Engineers and Work in Global Design Networks of the Semiconductor Industry

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I am very happy to write these lines as it means that I have finished my research and writing. This would have not been possible if not for the help and understanding of some people that both encouraged and supported me during my doctoral thesis.

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1. Engineering work in the semiconductor industry – why?

Internationalization of production has become a big issue in both general public debates as well as more specialized deliberations of academic and technical manner. How is internationalization affecting us? Where are jobs offshored to and why? What labor conditions exist in the new industrial centers? How will the future of traditional industrial centers look like? These are only some questions put to debate pointing to the central question how processes on the global and the local levels are intertwined and co-developing. The relationship between the local and the global has been of interest for academic discussions since at least Smith's work on comparative advantages in the international division of labor, and was expanded by Marx and Engels towards questions regarding workers and their struggles for a better life. Today the relation between the global and the local has sprung directly into everyday life of many people that loose jobs, or find new ones, that buy commodities produced in different regions of the world, or that use the internet to communicate in a simple way around the globe. While the international perspective has been strengthened in our everyday life, the understanding of the dynamics and the evolving structures of the international division of labor seem to lag behind.

This study's main goal is to contribute to a deeper understanding of the current character of internationalization of capitalist production, its drivers and outcomes. To be able to do this a highly specific object of inquiry was chosen. The work of engineers combines two fundamental dynamics of internationalization. First, engineering work was considered for a long time the part of the production process that could not be easily moved out developed countries. It was held to be spatially sticky (Pavitt 1999) and thereby non-globalizable. Many academic debates revolved around this idea, sketching an international division of labor in which developing countries would focus on production, while developed countries would keep the creative parts of product and technology development. This perspective was in its basic assumption the continuation of quite traditional ideas about the international division of labor (Fröbel et al. 1977). However, internationalization of capitalist production and distribution has moved on and it was not only expanded towards a broader base of operation but also its character has developed further. Simple models of center and periphery are now insufficient to describe the current status of the international division of labor. Companies from China and India are developing leading edge technology for international markets, while companies from developed countries locate design centers for technologically highly complex products in countries of Central and Eastern Europe (CEE), as well as in China or India.

As the picture of the international division of labor is becoming increasingly blurry research is necessary that is taking a closer look on the specific character of work and how it is organized. Here engineering work's second fundamental dynamic of internationalization comes into play. Work and the organization of the labor process are the places where the global and the local meet. Where global strategies of internationalization have to touch down in the local field and cope with all of its contingencies. Engineering work is then an object of inquiry that epitomizes the newest phase of capitalist internationalization, while it helps to understand how the global and the local are co-developing, enabling and constraining each other.

The electronics industry in general and the semiconductor sector in particular have been the vanguard of internationalization and industry restructuring towards vertical specialization (Lüthje et al. 2013). Labor intensive parts of semiconductor manufacturing were offshored to Southeast Asia for the first time in the late 1960s, with more technology intensive wafer manufacturing following in the early 1980s (Angel 1994). While some semiconductor companies began to build up product development capabilities in developing markets in the mid-1980s, the industry wide internationalization of innovation started in the late 1990s. This long history of internationalization of manufacturing and development renders the semiconductor sector very interesting for the analysis of the dynamics of an internationalized labor process. The already mature processes of internationalization allow to move the study beyond the initial phases of building up new oversea locations. With at least partly stabilized relations such locations experience processes of upgrading that are of fundamental significance for both the industry organization as well as the engineering labor process

Debates on internationalization, both academic as well as public, are focusing mostly on Asia, and here especially on China. However, the complexity of the new phase of internationalization lies not only in the increasingly blurred distinction between traditional center and periphery but also in the emergence of various locations integrated by the global networks of production and development. CEE, Mexico and Brazil are regions with major manufacturing operations of multinational companies. Countries in CEE also house product design operations of the semiconductor industry. Both the manufacturing and development operations in CEE are neither developing as dynamic nor have the same scale as in Asia. However, the CEE development centers of the semiconductor industry are specializing in the development of analog chips. Analog chip design is often referred to as the 'black magic' of chip design as only the best and most experienced engineers are able to tackle the development of these electronic components. The location of such technical capabilities in peripheral locations points to a very specific form of internationalization that will allow us to shed some light on both the relation of the global and the local as well as the emerging new and complex international division of labor.

In contrast to Asian countries Poland, Czech, Slovakia and Romania were already industrialized when they were integrated into the global networks of production and development. Manufacturing as well as research and development capabilities existed, the necessary infrastructure was in place while vocational schools and universities were providing the necessary workers. As a local semiconductor industry was existing since the 1950s multinational chip companies could put local wafer manufacturing operation to use and employ highly experienced chip design engineers. Simultaneously, these countries shared an important characteristic with countries in Asia as they were and often still are so called low-cost countries. This opposition between industrial capabilities and their price contributed to the way how CEE developed in the last two decades.

Describing CEE as a peripheral region where extended workbenches are established much in line with a complementary international division of labor (Berger et al. 2001) is not anymore a valid analysis. Although socio-economic development is never homogenous and pockets of such outdated forms of international division of labor can exist, what becomes evident in this study is that the already existing centers for product and technology development have evolved towards integrated design centers that often perform highly important functions in the global networks of manufacturing and design. The high levels of functional integration of these design centers establishes a new phase in the development of the international division of labor, where the categories of center and periphery become increasingly blurred at least from a functional perspective. However, hierarchies do not cease to exist with this new phase of internationalization, as the fundamental strategic and product related decisions are still concentrated in the headquarters. What is important is that the differences in technical expertise and experience and the recognition of these capabilities through the integration in decision processes and through an appropriate labor process organization are withering.

Internationalization and industry organization are processes that are intimately interconnected. As industry organization has developed towards vertically specialized structures, or in the terminology of the modularization approach, the modularity has increased, the location of particular parts of the supply chain in different regions of the world become possible. Debates on industry organization focus on required level of control within a specific industry and its correspondence to the technology and products it is producing. Some scholars of modularization are assuming such a narrow correspondence between technical and market modularization in the electronics industry that control between the various parts of the modular supply chain is reduced to processes of simple market coordination (Langlois 2003; Sanchez 2000). Their argument follows the line that the complexity of relations between the various modules in the supply chain is lowered by effective interface design to such a level that the market as mechanism of control will suffice. This study follows scholars that argue against this radical market modularity thesis (Brusoni 2003; Chesbrough 2003; Ernst 2005d), while it tries to expand the view on the growing control requirements that are developing driven by the increasingly complex organizational structures of the electronics industry as well as the exploding complexity and costs of technology. The process of modularization is characterized by highly contradictory developments and retracting dynamics of re-integration leading to new forms of vertical integration which can be observed on various levels of the vertical electronics industry in recent times (Lüthje/Pawlicki 2009; Lüthje et al. 2013).

Despite these increasing control requirements, manufacturing and development are organized in global supply networks and a re-emergence of the Chandlerian highly vertically integrated firm is not imminent. The global character of manufacturing and development has been used as a perspective for the analysis of economic development both on national, regional as well as sectoral level (Coe et al. 2004; Ernst 2005a; Gereffi 1994; Henderson et al. 2002). This research was initiated by the Global Commodity Chains approach (Gereffi 1994) and the subsequent Global Value Chains (Gereffi et al. 2005) approach but from its onset its analytical framework lacked important variables that were only gradually developed by critical scholars in the last years. Global networks of production and design need to be understood in a complex way regarding both actors, locations and dynamics. This study approaches this demand towards complexity as it integrates historical analysis of networks and specific network nodes and puts a major focus on local characteristics. How a network is integrating a specific locality into the international system of manufacturing and design is only in parts determined by the global strategies of companies. Local factors such as the institutional framing, labor market characteristic and the locations industrial history are of fundamental importance for the forms of its integration into the global networks of production. This study takes these factors, that were called for by critical scholars of globalization, into account but expands its analytical perspective by providing an analysis of the labor process organization evolving in particular locations of global networks of design in the semiconductor sector. The labor process is where the local and the global intersect and have to develop a working relation. The understanding of such local factors and localized dynamics is fundamentally important in the current phase of internationalization.

The labor process analysis of this study is essential for the discussion on how engineering work is developing. Some scholars have been analyzing the internationalization of engineering work from the perspective of industrialization. For them the internationalization of engineering work is resulting in processes of standardization, formalization and global fragmentation (Boes 2004; Chang et al. 1999; Kämpf 2008; Schmiede 1996). This industrialization of engineering work has fundamental effects on the labor process of engineers constantly reducing levels of autonomy. This is seen as necessary to enable the establishment of international teams and intra-organizational international design networks. They argue that through abandoning integrated task profiles of engineers and increased specialized and segmented work differentiated roles within the labor process are developed which then are used as starting point of internationalization dynamics. Although many of these shifts in labor process organization are visible they are not the prelude to the demise of autonomy in engineering work. What scholars of the industrialization of engineering work regularly seem to overlook is that the described developments are often intermediate states during industrial re-organization processes. Many of the standardizations, formalizations and fragmentations are retracting after a relatively stable form of international division of labor has been found. To enable an effective and efficient international process of product and technology development integrated design locations are necessary that allow smooth experience build up and knowledge sharing. A highly industrialized development process allows for easy re-location of capabilities, however it simultaneously obstructs consistent build up of experience and knowledge thereby reducing dynamics of innovation in the medium term. Furthermore, many standardization processes are welcomed by engineers when they allow them to cope with the constantly rising technological complexities. Using computer aided design was initially viewed also from an industrialization perspective. However, today chip engineers would not be able to design chips consisting of millions of transistors without the help of these highly complex software based tools for computer aided design.

The industrialization perspective is also often missing out on the processes of workers' resistance. Engineers have not been known for massive resistance, or Luddite like upheavals. However, engineers are exerting resistance both in open as well as covert forms and are able to influence the development of the labor process organization. Most of this resistance is highly individualized as engineers exhibit traditionally rather low rates of unionization, driven both by their specific class position as well as characteristics of their labor process. Some of the industrialization instruments such as knowledge management methodologies and systems are in the main focus of resistance from engineers. Not using a global knowledge database but relying on one's own local knowledge pool is one way. More interesting are strategies where such global databases are misused to develop personal networks that help to circumvent these instruments. With such strategies industrialization instruments do not cease to exist, and thereby can emerge in some analyses, but engineers were able to invert their function for their own good.

Labor process often has been analyzed in a very structuralistic manner, where the specifics of the capitalist logic act as a framework that is determining every aspect of work organization (Braverman 1974). Worker's resistance is one major factor that is putting such a perspective into question and calling for a more dialectic view on the development of labor process organization and has been the starting point for a long ranging debate (Thompson 1983). Managerial strategies (Friedman 1977) are offering an even more dynamic view on the development of control in the labor process. With the notion of managerial strategies control systems are perceived as processes where various factors come into play. The capitalist imperative of control (Thompson 1983) has to adapt to the specific dynamics of workers' resistance, technological dynamics and local market characteristics. Managerial strategies of control are also affected by processes of internationalization and industry restructuring. As upgrading takes place managerial strategies need to accommodate for the changing functional as well as product and process roles that a specific location plays.

Upgrading, or the process of improvement on various levels, is in the center of this study. Discussions about upgrading are set on various scales from the interrelation between industrial upgrading and the national economic growth (Ernst 2001) to inter-firm relations (Bair/Peters 2004; Pavlinek/Zenka 2010). Upgrading has been categorized diversely. Ernst (2001) defines five types of industrial upgrading – inter-industry, inter-factorial, demand, functional, linkages – while Humphrey and Schmitz (2002, 2004) have identified similar types of firm-level upgrading and expanded on them. Process upgrading introduces new production methods and better technology. Through product upgrading a firm is moving to more sophisticated and higher value-added products. With functional upgrading firms establish new functions. Upgrading is a way to describe the development of the international division of labor both on the level of nations and firms. Upgrading can also be used to analyze intra-firm networks of international locations for manufacturing and development. With these perspectives the concept of upgrading allows to understand the dynamics driven by the internationalization and changes in the industry organization. However, the concept of upgrading has until now only rarely been used for the analysis of effects internationalization has on work. Where upgrading has been applied for the study on work and globalization the perspective was mostly general, concerned with shifts in work roles and overall pressures on labor conditions and rights (Gereffi 2005; Palpacuer 2008). This study attempts to expand the perspective and trace the role of upgrading in the development of labor process organization. The labor process of chip design engineers at CEE design centers of multinational companies is developing in parallel with processes of upgrading. Functional and product upgrading constitute the hinges between the global and the local level, i.e. between the sector wide developments of the international division of labor through triangular restructuring and the dynamics in the labor process. Such a perspective on upgrading in this study allows us to understand how the global and the local are intertwined.

The study's aim is to find answers to the following general questions that are constituting the horizon of this research:

a) What is the current status of industry organization and international division of labor in the semiconductor industry?
b) What role is CEE playing in the global networks of manufacturing and design of the semiconductor industry?

c) How is the labor process of engineers in CEE organized and how did local factors drive its development?
d) Does the specific position in global networks of design affect the engineering labor process in CEE?

The fundamental hypotheses in this study are the following. The semiconductor industry is characterized by a dynamic development of industry organization that is moving towards an increasingly network style organization. However, as technological and economical constraints rise the requirements for control within these networks are expanding. Simultaneously, the location from where control is exerted is moving towards the manufacturing side. CEE has moved from its initial role as low-cost extended engineering workbench towards a highly specialized location for research and development, where the most challenging forms of chips – analog chips – are being developed. The engineering labor process in CEE is very similar to the ones in developed countries, with high levels of autonomy and the ability to technically and organizationally influence the design projects. However, the high customer focus coupled with the low network position of the respective companies is taking its toll on engineering work as extra-organizational dynamics often heavily influence its character.

This study has two main parts, the first consisting of chapter 2 and 3 focused on the global and sectoral dynamics, and the second consisting of chapter 4 and 5 focused on local and labor process related developments. However, both parts constitute the two sides of a coin and therefore considerations in one part are always related to the other. The separation between the global and the local is not possible. This study on engineers and work in Global Design Networks of the semiconductor industry is structured as follows. Chapter 2 outlines the theoretical debates on the development of the international division of labor along the lines of the Global Commodity/Value Chains, Global Production Network and Global Design Network approaches. The concepts of modularization and triangular restructuring will be introduced to be able to understand the dynamics of industry organization in the electronics industry. To get a first glimpse of the role of work in internationalization both concepts on categories of work, as well as on international R&D centers will be discussed. These strands will be merged at the end to formulate research questions and hypotheses that will guide the analysis of empirical data in chapter 3. Here we begin with a general and historical discussion on the internationalization and industry organization of the semiconductor industry. The second part of this chapter is based on three case studies of chip companies with design centers in CEE countries. How these centers are integrated into global networks of production and design and how they have been able to upgrade will enable a first thorough assessment of the dialectical relation between the global and the local. Chapter 4 returns with a theoretical discussion, now focused on the labor process theory that directly aims on work. Characterizing the labor process organization allows to understand how the international division of labor is evolving. Using both the labor process as well as the knowledge management perspectives an analytical model is developed for the empirical data in the following chapter. Chapter 5 returns to the three company case studies to analyze the engineering labor process. This very close look gives a detailed picture on the concrete workings of global strategies and dynamics and their constraints. Chapter 6 discusses the results from an integrated perspective developing the idea of the importance of upgrading for sector wide developments as well as labor process related dynamics.

1.1. Short remarks on methodology

The pillars of this qualitative study are three case studies on semiconductor companies that maintain chip design centers in CEE. These three case studies allow to depict how engineers and their work are affected by the integration into global networks of production and design of the semiconductor industry. Although three case studies do not produce wide ranging results for the entire industry, their focused high level of detail enables an analysis of central aspects of the dynamics of internationalization. By choosing companies with very different business models and functions within the industry it was possible to carve out important differences and similarities. The chosen business models are representative for semiconductor design centers in CEE, allowing for some extrapolation on the regional level. The choice of two analog chip design companies enables the study also to move towards extrapolations on the global level, as the highly specific labor process of analog chip engineers is until now limited to only a number of locations worldwide. Taking these sectoral, regional and global perspectives together these three case studies make an informed analysis of the Global Design Networks of the semiconductor industry possible.

The major part of the data used for the case studies has been gathered through 38 semi-structured expert interviews. I travelled to the particular design centers and talked directly to the respective engineers and managers. These interviews were between 60 minutes to 120 minutes long, always dependent on how much the particular engineer or manager was able to carve out of his schedule. All of these interviews were recorded for later transcription. The interviews were transcribed by myself mostly in full, although a minor number has been only summarized. The interviews in the Czech Republic, Slovakia and Romania were all conducted in English, while interviews in Poland were conducted in Polish. Visiting the design centers always included a guided tour through the various R&D facilities. This gave me the possibility to not only talk to engineers but also watch them work. These tours were especially interesting where the integrated character of the design centers came into play. Test and measuring facilities where chips are probed were helping in understanding how diverse the work of analog chip engineers is in design centers in CEE.

Additionally, I conducted a number of interviews with other companies, lecturers and academic researchers as well as industry journalists. While visiting Romania I was invited to the National Institute for Research and Development in Microtechnologies (IMT-Bucharest), where I spent an entire day talking to semiconductor researchers and was invited to visit their cleanroom and other research production facilities. These general interviews were very important to learn more about the background of the industry, local industry history as well as to get a broader perspective on the dynamics in focus.

Data regarding broader industry aspects was gathered through continuous and broad monitoring of industry periodicals, SEC filings as well as annual reports of companies in the industry. Here, I was able to access data that I have collected in previous research projects[1]. With this I had access to a huge archive of information on the sectoral level going back around seven years and comprising of data on brand name companies, contract manufacturers, R&D cooperation initiatives, component/chip companies as well as

[1] "Innovation, Global Production and Work: Global Design Networks in the Semiconductor Industry and the Relocation of Science-based Work to China and East Asia", lead by Dr. Boy Lüthje and Dr. Dieter Ernst. This project was financed by the Volkswagen Foundation. "New Models of Production and International Division of Labor in the Electronics Industry - Contract Manufacturing in the Pacific Rim and Central and Eastern Europe", lead by Dr. Boy Lüthje and Prof. Dr. Wilhelm Schumm, financed by the Deutsche Forschungsgemeinschaft – the German Research Foundation.

various policy organizations and initiatives. This data was especially crucial for the more historical analysis of the organizational and geographic shifts in the industry.

Throughout the study I use the male form when I talk about the engineers and managers and their situation and actions. Engineering as a male dominated field has been my research reality in this project. In all of my research on engineering work I was only able to talk to one female engineer. Hence, although I am aware of the various achievements of women in hardware and software engineering and of the fact that a number of female chip design engineers exist, I chose to use the male form to have a realistic representation of the situation in design centers in CEE.

2. Industry, internationalization and innovation. Work and industrial restructuring

Research on the spatial dimension of capitalist development initially focused mostly on trade relations, as production was organizationally and spatially integrated. Vertically integrated firms established international linkages mostly to secure raw materials necessary for their production and to develop sales markets for their finished products. However, organizational innovations, technological development, such as ICT technologies, and regulatory changes, facilitated a globalization where production is increasingly fragmented and dispersed globally. This led to the development of the theory on the New International Division of Labor (Fröbel et al. 1977) that described a shifting of major manufacturing operations from developed nations to newly developing countries. Such offshoring was highly hierarchical, developing distribution patterns along the divide between low value-add and high value-add manufacturing activities. Labor intensive work was shifted to newly developing countries that provided large pools of low-cost labor, as well as highly underdeveloped industrial relations, favoring the interests of foreign investors. Similar to dependency theories of unequal development (Frank 1966) the New International Division of Labor theory presumed the formation of trade and production linkages that would continuously reproduce the divide between developed and developing countries. The idea of a complementary internationalization was one of its major theoretical pillars. These ideas were resurrected in discussions on the role CEE would play after its gradual integration into the capitalistic world market after 1989 (Berger et al. 2001).

Besides developmental and economic issues the New International Division of Labor theory included discussions on the situation of labor, helping to develop awareness about often inhumane labor conditions in so called sweat shops. However, as the perspective was focused on manufacturing jobs, higher qualified work such as engineering was often missing in the analysis of labor. This was founded in the empirical data and inscribed in the theoretical models that analyzed internationalization as a process resulting in complementary divisions of labor, where core activities such as research and development were regarded as non-globalizable.

Technological and organizational innovations are at the heart of the electronics industry, driving and limiting opportunities of internationalization. Technology and its fast paced development in the semiconductor industry is subsumed in the notion of Moore's Law (Moore 1965). Despite being only a lucid analysis of empirical data Moore's Law[2] has been the benchmark of the industry, driving technological innovation and organizational endeavors. The increasing complexity of electronics systems and their modular organization has facilitated the development of new organizational forms as the industry differentiated and specialized. However, as wee will see technical modularity driven by technological innovation does no determine organizational modularity. The separation of manufacturing from R&D poses great organizational and technical problems that need to be tackled. One of the main aims of this study is to show how this is being organized in the electronics industry in general and the semiconductor industry in particular. For this we need to turn to theoretical concepts that allow us to understand the geographical and organizational development of capitalistic development and its fundamental drivers.

2.1. Globalization of work. Dynamics of production and innovation in theoretical perspective

2.1.1. Global Commodity Chains

Earlier perspectives on the spatial development of capitalism that focused on the evolving international integration of national states and markets through trade were challenged by Hopkins and Wallerstein (1977), who postulated that any analysis of the globalization of capitalism could not merely be based on exchange processes but had to integrate production processes, distribution processes and investment processes. They proposed the concept of commodity chains incorporated the various inputs and processes by which these inputs are being transformed into a finished consumable item, defining a commodity chain as a 'a network of labor and production processes whose end result is a finished commodity' (Hopkins/Wallerstein 1986: 159). Hopkins and Wallerstein formulated a research agenda that was well-received by many scholars leading to a first summary of the ongoing research in Gerreffi's and Korzeniewicz's publication of *Commodity Chains and Global Capitalism* in 1994. In this volume Gereffi (1994) laid out his ideas and concept for the study of global commodity chains (GCC).

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[2] In 1965 Gordon Moore, one of the founders of Intel, made the prediction that the economical density of integrated circuits will double roughly every two years (Moore 1965). This prediction has been updated since then several times, but its basic description of a very fast paced, however quite stable innovation path in process technology still holds up to day.

However clear the lineage between GCC and the world-systems tradition is, there are significant differences in the concept that Gereffi has been developing with fellow colleagues since its initial publication. Firmly based in the world-system approach Hopkins and Wallerstein focus in their commodity chain concept on the state as the main actor in the process of shaping global production systems through tariffs and local content rules. The reproduction of a stratified and hierarchical world-system through commodity chains is one of the central assumptions for world-system theorists. Gereffi's GCC approach refocused research on firms – their actions, strategies and inter-organizational linkages – as the main actors and drivers of globalization and industrial development (Sturgeon 2009). Gereffi (1994) argued that while trade liberalization enabled growth of international trade, this potential was only realized by firms from advanced economies through their investments in as well as, cooperation and trade links with developing countries. The concept of upgrading developed in the GCC approach is the second main difference with the initial commodity chains concept, as it describes possible changes of relative positions of particular firms and countries in the stratified and hierarchical relations between advanced and developing countries (see: 1.1.6) .

The focus on the firm in Gereffi's concept reflected his aim to analyze the organization of global industries by identifying all the actors involved in producing and distributing a particular good or service and characterizing the specific relationships existing between these actors. This relational perspective was set to determine where, how and by whom value is created and how it is distributed along the commodity chain, opening a way to understand how global strategies take effect on the local level through the actions and capabilities of specific companies. Gereffi (1995) developed four main dimensions that were to lead the GCC analysis: (1) the input-output structure – encompassing the whole value-chain across the relevant industries; (2) geography – as the spatial patterns of production and distribution; (3) governance structure – depicting the power structures within the specific GCC; (4) institutions – frameworks regulating the activities of the GCC on the various levels of local, national and international. The dimension of institutions has played only a very minor role in GCC research leading to critique and frequent calls for a sharper focus on institutional frameworks in the GCC research (Bair 2005; Henderson et al. 2002; Raikes et al. 2000).

Students of GCC focused in their subsequent research on governance structures aiming to answer how firms organize cross-border production arrangements. Gereffi

(1994) provided a basic GCC governance typology based on capital-intensity as a main driving factor. Producer-driven commodity chains are capital-intensive, such as in the automotive industry, where high entry barriers allow for high levels of control of the production system by brand manufacturers. These lead firms are able to draw their profits from the effective development and manufacturing of complex final marketable systems. Buyer-driven commodity chains are more common in labor-intensive industries such as garments and agriculture. They are based on complex subcontracting networks that are being managed by designers, retailers and other brand-name firms (Gereffi 2001). In Buyer-driven commodity chains the main sources of value lie in the development of products and the brand-name as well as marketing capabilities.

While this typology was initially a helpful heuristic model for empirical research, its applicability and utility is disputed since several years based on theoretical considerations as well as empirical evidence (Henderson et al. 2002; Lüthje et al. 2013; Sturgeon 2009). For the analysis of technology intensive sectors that are characterized by constant restructuring processes, such as the IT-industry, the GCC governance typology is too crude. Here a distinct differentiation between buyer-driven and producer-driven commodity chains is not possible as Wintelistic restructuring dynamics rendered leading firms of the IT-industry to be neither pure brand-name companies nor pure producers (Borrus/Zysman 1997; Lüthje 2001; Sturgeon 1997). Here lead firms are technology leaders driven by cost explosions in R&D and manufacturing as well as financial markets interests to reorganize their R&D and manufacturing activities through outsourcing and offshoring. The GCC approach is neither accounting for the underlying processes of technological innovation driving this dynamic (Ernst/Lüthje 2003; Sturgeon 2009). Nor able to grasp the complex processes of vertical re-integration at the level of manufacturing, both in the system integration sector with EMS companies such as Foxconn, as well as in the chip industry, where foundries such as TSMC as providers of wafer manufacturing have grown to considerable importance (Lüthje/Pawlicki 2009).

The GCC analyses zero in in their research on governance structures on the lead firm and its relations to its suppliers that form the power structure allowing the lead firm to ‘drive’ (Gereffi 1994) the GCC. The heavy emphasis on the lead firm as well as the concept’s quite limited scope further problematizes its use in the analysis of the semiconductor industry. The term lead firm is associated in the GCC approach with either system manufacturers or brand-name companies, which seems to be linked both to the empirical evidence on which the concept is based as well as the chain terminology, that drives a very hierarchical and sequential perspective on production processes, with system integration and manufacturing as well as branding activities as the major characteristics that define lead firms through which they can constitute their power within GCC. In technology driven industries such as semiconductors the lead firm needs to be understood in a much more complex way. The setting of parameters and standards that form the basis of a power structure within inter-firm networks is a process driven by more than only one firm. The highly vertically specialized industry structure of semiconductors locates such standard setting oftentimes in cooperation relations between foundries, as providers of wafer manufacturing technologies, and EDA companies, as providers of chip development systems, that can be perceived from a knowledge perspective as highly elaborated and automated knowledge codification systems. Such set standards are then again enforced both by the above standard setting companies, as well as their customers, such as chip design houses, who need to have their suppliers of silicon IP to be aligned with the technology processes of their foundries. The quite simple linear relation of the GCC approach between lead firm and supplier is being expanded into a complex network of cooperation and power relations.

2.1.2. Global Value Chains

The Global Value Chains (GVC) approach has been developed as a reaction to both empirical evidence of the limited applicability and utility of the GCC approach as well as theoretical considerations that favor more economically driven models of industry organization (Gereffi et al. 2005; Bair 2005; Sturgeon 2009). Grounding their deliberations heavily in international business management literature and transaction cost economics Gereffi et al. (2005) expand the typology of various GVC governance structures and attempt to explain them by identifying key determinants. The major theoretical basis of the GVC concept is formed by considerations on transaction cost economics (Coase 1937; Williamson 1975, 1981) used to model the make or buy decision of firms more formally. The key variable in transaction costs economies is asset specificity (Williamson 1981), formulating the idea that firms make transaction specific investments that tend to lock partners into relationships by creating opportunities to take advantage of the other firm. As Williamson (1985) has also expanded his model towards networks as an intermediate organizational form between market and hierarchy, GVC perceives the three basic organizational forms firmly established.

For a more differentiated analysis of networks GVC scholars turned to economic sociology's critique of the opportunistic view of human nature implied by transaction cost economics. Granovetter (1985) showed how economic activity is embedded in social relations. The social embeddedness of inter-firm relations allows them to be sustained in face of asset specificity, driving networks as a distinct organizational form based on trust and long-term relationships, social and spatial proximity. Along this line industrial geographers have argued for an even stronger emphasis of social and spatial proximity with local and regional networks as foundation for technologically innovative or highly adaptive industry clusters and districts (Goodman et al. 1989; Grabher 1993a, 1994; Saxenian 1994). Expanding its perspective beyond economic sociology and industrial geography towards strategic management literature and evolutionary economics and their concepts of firm capability and learning (Nelson/Winter 1982) the GVC approach tries to contain the shortcomings of the asset specificity concept further by integrating ideas about positive effects of the access to expertise and capabilities through business relationships.

Three main variables have been developed by the GVC scholars as basis for a dynamic and operational theory of governance structures (Gereffi et al. 2005; Sturgeon 2009): (1) the level of complexity of information that is being exchanged between firms, (2) the codifiability of this information, (3) the capabilities that supply base is providing. GVC perceives asset specificity as limited by dynamics of process codification and standardization and the development of modular production equipment. Linking asset specificity and codification provides a very interesting explanatory model in which the various governance models of the GVC approach are based. Gereffi et al. (2005) developed a highly differentiated view on industry organization expanding network governance into three distinct forms. Modular network governance is based on complex transactions, high codifiability of complex information and high capabilities of the supply base. With these characteristics modular linkages constitute a network governance type that is very close to market governance. Relational linkages govern complex transactions based on hard to codify tacit information exchanged between buyers and highly competent suppliers. When complex transactions need to take place but only less competent suppliers exist that need detailed instructions on highly codifiable information captive type linkages are being adopted. Captive value chain governance is therefore quite close to the hierarchical governance form.

Despite this very elaborate typology, both the high focus on lead firms and their relations towards suppliers as well as too mechanic understanding of the consequences of codification lead the GVC scholars to an oversimplifying perspective on inter-firm relations. Gereffi et al. (2005) argue that as codification and standardization processes take effect increasingly complex information can be exchanged between suppliers and lead firms. This correct observation leads them to deduce that high levels of codification drive relations that are much like market based relations, rendering costs for switching to new supplier partners low. However, the opposite process can be observed in the semiconductor industry with increasing complexity of involved process technologies and product design methodologies. EDA companies, selling the complex software based tools for chip development, are cooperating with wafer manufacturing service providers to provide chip design companies with so called Process Design Kits and chip design tools that are developed specifically for a particular process technology. This involves codification of knowledge linked to both specific process technologies and design methodologies, to enable the efficient development of chips as well as easy exchange of complex information over organizational borders. As every wafer manufacturing service providers is increasingly providing this codified knowledge in highly proprietary formats the need for transaction specific investments are rising on the side of their customers. Here higher levels of codification are linked to more captive forms of governance. Codification needs to not only be taken into account as a parameter of governance forms but also analyzed as a complex process in itself, pointing to questions about the changing interfaces of innovation (Lüthje/Pawlicki 2009; Pawlicki 2010). The level of technological complexity is of great importance both driving the costs of codification as well as raising proprietary elements within specific process technologies simultaneously lowering the possibility to second sourcing strategies.

The GVC perspective substituted the broader term governance with the concept of coordination loosing the ability to identify power relations already on the semantic level (Coe/Hess 2006). This new angle privileges structural characteristics of particular sectors, constituted by organizational and technical variables (Bair 2005). This almost structuralistic view of inter-firm relations reflects key assumptions of transaction cost economics leading into a theoretical pitfall. Here organizational forms seem to be only efficient solutions to structural changes associated with problems of asset specificity, rendering power relations both in the definition as well as governance of a particular GVC irrelevant. With this, almost any agency in form of strategic actions of firms is missing. However, the development of GVC within industry dynamics of vertical specialization and globalization, is the outcome of strategies and decisions of actors within a developing structural framework (Gibbon et al. 2008) and the institutional and regulatory environment of the chains. The GVC approach is unable to account for wider structural constraints as discussed in the varieties of capitalism literature (Hall/Soskice 2001). However, local characteristics and the possibilities for lead companies to tap into these resources that are being shaped by the social, cultural and political environment embodied in e.g. state policies, local labor markets or historically determined technological capabilities and knowledge sources, have to be integrated as constitutive variables for GVC analysis (Bair 2005; Henderson et al. 2002).

The automatism of the GVC approach, however dynamic and differentiated its explanations are, is concealing a major characteristic of capitalistic development and fundamental driver of industry organization. The periodically reoccurring economic crises, both on the sectoral as well as global level, lead to shifts in industry organization and geographies that cannot be grasped by a transaction cost based framework. The IT-industry, and especially the semiconductor sector, is characterized by constant crises that are able to change inter-firm relations fundamentally without having obvious effects on asset specificity and other major variables of the GVC framework (Lüthje 2004). The problem seems to lie in the GVC quite narrow focus on sectoral dynamics, leaving issues of global capital dynamics with it processes of over-accumulation and valorization bottlenecks unconsidered (Brenner 2002). These processes cannot be regarded as external as especially constant over-accumulation is a direct result of the industry's vertical specialization and competitive structure.

The disregard for structural characteristics that go beyond the particular sector and transaction between firms leaves out the process of financialization which is both a constitutional element in the development of GVC as well as a variable that is driving changes in the global chains. The enforcement of shareholder rights since the beginning of the 1980s has shifted power away from managers with fundamental effects on corporate governance. Strategies of publicly traded companies increasingly focus on rising shareholder value and short-term return on investment through downsizing of operations, focusing on core competencies, and profit distribution to shareholders (Milberg 2008). To be able to develop shareholder value positively companies look increasingly towards international offshoring and the effective management of GVC, causing a constant restructuring of chains to accommodate for financial market interest.

The constantly rising levels of financialization, coupled with the periodically reoccurring economic crises lead to an increasing assertion of a distribution of profits towards lead firms by transforming the ways in which power, risks and wealth are being distributed among firms and workers. Changes in sourcing patterns such as supply base reduction policies, stringent supplier selection criteria, continuous price reduction pressures, risk transfer programs and pressures to rise production flexibility have been frequently linked with increasing levels of financialization (Palpacuer 2008) as well as economic crises (Lüthje 2007b). These requirements formulated and exerted by lead firms are driving a constant rise of the entry barriers, as these policies are best met by big suppliers with the necessary organizational and managerial capabilities. Additionally they reduce profits retained by suppliers and raise uncertainty of future orders. These economic pressures are passed on to the weakest participants of the GVC – the workers – who have no possibilities to guard themselves against them, as most of the suppliers have built-up their manufacturing operations in so-called low-cost locations where labor laws are lax and labor unions are weak (Palpacuer 2008; Sproll 2010).

The value chain framework not only focuses on the organizational patterns and power dynamics but also defines geographical possibilities – i.e. clustering vs. dispersal of industries, rapid vs. gradual relocation of work – that are enabled by each governance form. Modular forms are linked to highly dispersed geographies as the high codifiability of exchanged information allows for communication over distances. Relational governance types require increased proximity through co-locating suppliers with lead firms, as codifiability is lowered by low levels of standardization and a frequent need to exchange tacit information. Again the GVC provides some insights but with a too simplistic and too focused view on industrial geographies that are always linked with patterns of industrial organization. As we can observe in the electronics industry modular production networks, epitomized by the central organizational form of contract manufacturing companies, a huge variety of geographical organization exists ranging from highly vertically and locally integrated manufacturing locations such as Foxconn City in Shanghai to the regionally integrated networks of Flextronics (Lüthje et al. 2013). On the level of supplier networks for these 1st tier suppliers, economies of scope drive geographical proximity. Similar varieties of geographical organization can be found in the semiconductor industry. Foundries cooperate both with local companies as well as globally dispersed ones on products with similar technological complexities. Low codifiability can also lead to processes of integration of functions both within one organization as well as one location, which could be interpreted as establishing proximity to exchange tacit knowledge. However, this is not only leading into a co-location but towards refocusing of interfaces along the lines of value chains implicating different geographies.

2.1.3. Global Production Networks

In critical response to GCC/GVC authors Henderson et al. (2002) developed the Global Production Network (GPN) approach based on insights from economic geography and network theories to move the research on the spatial development of capitalism beyond the highly linear and unidirectional perspective of GCC/GVC. The notion of network allows to integrate both actors other than firms as well as a more polycentric way to approach and analyze inter- and intra-firm networks (Coe et al. 2008). Each stage of the production chain is embedded in a much wider set of non-linear, or horizontal relationships, constituting a multiscalar network that integrates various actors and places. The polycentric perspective of the network approach enables a research that moves beyond focusing mainly on lead firms and their relations to big suppliers. GPN conceives the relation between networks and spaces as deeply dialectical, where places are being transformed by flows of capital, labor, knowledge, power, etc. but in the same instance transform these flows as they have to materialize in the ever specific places constituted by historical, institutional, economical, cultural and regulatory developments.

The social constitution of GPNs is established on several levels, from lead firms and their network partners with corporate cultures heavily influenced by home country origin and capabilities required and used in the cooperation locally constituted, to regulations and institutions, both as outcomes of historical social processes and instances of exerting influence as well as cultural variables (Coe et al. 2004). This socio-spatial embeddedness is modeled as driven by strong processes of path dependency that facilitate the development of own local identities of different places in the same firm. The ability to integrate such local differences is one of the major challenges of GPN, especially when intra-firm networks are in question, determining the success of the particular lead firm organizing the network (Lüthje et al. 2013). To cope with locally disparate and historically evolved local characteristics firms are constantly standardizing interfaces, processes and labor organization through global strategies. However these standardization attempts are processes characterized by constant negotiation as they need to conform to local regulations, labor market requirements as well as limits set by organized labor and intra-organizational power structures. The dialectical view of global-local relations of the GPN approach makes the inclusion of all relevant major actors beyond the producer firms necessary, not only as exogenous variables but as constituent parts of the respective network (Hess/Coe 2006). The institutional framework is extended to actors such as nation-states, labor(-unions), NGOs, educational and research institutions and consumers as well as structural characteristics defined by multi-scalar regulatory systems and international standards (Coe et al. 2008).

The notions of the social construction of networks as well as their socio-spatial embeddedness increase the importance of a historical perspective on the various levels of GDN (Henderson et al. 2002). The reconstruction of the history of chains, of their development with regards to path dependent processes, is a major concern of the GPN approach, allowing to describe how production networks have changed their organizational and spatial characteristics as well as how power structures have changed over time. The assets and competencies of firms are regarded as dynamic. Firms do not only react to structural changes, but also have room for autonomous actions and strategic decisions within historically evolved boundaries. This autonomy is central to the upgrading process as it defines a way in which companies can change their relative positions within GPN.

The integration of this complex institutional framework is paralleled by the idea of GPN as contested terrain (Levy 2008), where every actor and institution has an own agenda, with variable levels of power and different strategies to realize it. Power relationships within GPN are neither fully structurally determined nor unidirectional. Each actor is involved in relations characterized by cooperation and collaboration as well as conflict and competition. This duality of relations is, as we will see in the account of the development of the semiconductor industry, an increasingly important mode of organization, as the costs of process technology R&D are moving beyond the financial capabilities of single companies. The term coopetition is used by industry experts and analysts to describe the situation where companies cooperate on the R&D focused on specific technologies, which form the basis for competing products.

The black-box view of the firm within GCC/GVC is one of the critical concerns of the GPN approach. To describe and analyze in a consistent way the continuous development of GPNs through processes of restructuring and of constant reconfiguration of organizational boundaries through internalization and externalization of functions, intra-firm relations are of fundamental importance. As GPN are perceived as consisting of local and functional sub-networks the firm needs to be approached more as a network with internal power structures and functional geographies than as a monolithic entity (Coe et al. 2008). The power relations within firms have a strong territorial dimension and render the intra-firm relations as contested fields similar to the level of GPN. The level of competence determines the strength of influence in intra-firm negotiation processes about strategic choices of investments and location of specific functions. Local competencies are driven, at least partly, by environmental factors (Dicken/Malmberg 2001) such as labor markets, competing companies, local customers and suppliers, universities and other R&D cooperation as well as locally available management talent.

To be able to assess a place's location within a commodity chain, both as part of intra- and inter-firm networks, the perspective on labor and work is very helpful (Smith et al. 2002) and needs to go beyond issues of labor costs. Yet the GPN perspective is focusing mainly on the strategies of labor struggles and organizational efforts (Coe/Hess 2006; Coe et al. 2008), however important these struggles are, this does not provide insights into the everyday work in globally integrated companies.

However, in its initial formulation Henderson et al. (2002) provided a very helpful perspective for integrating the analysis of work into GPN research. Value is differentiated with regard to how it is created, how it is captured and how it can be enhanced. The creation of value provides an intimate perspective on labor, as the question of how value is created within the labor process, i.e. through the utilization of labor power, is the fundamental dynamic of this process. Aspects of employment, skills, working conditions and the production technology come into focus as well as the broader social and institutional context framing the reproduction of labor power. Besides this micro perspective on the labor process the value creation category is also integrating considerations about industry wide processes of rent generation. Technological, organizational, relational and brand capabilities drive value creation differences between companies. Both forms of value creation show socio-spatial embeddedness, as well as structural dependencies underlining the dialectical nature of global-local relations in GPN.

The same applies to value enhancing and capturing, which can be basically translated as processes of upgrading and regional development.

2.1.4. Global Design Networks

The concept of Global Design Networks (GDN) developed by Ernst (2005a), referring to observations in the semiconductor industry, runs counter to standard assumptions in innovation and knowledge research, that assume a high geographic stickiness of knowledge and knowledge related tasks. Especially forms of tacit knowledge that are the basis of learning processes and innovation are seen as less mobile and therefore requiring proximity on a much higher level than e.g. manufacturing tasks (Markusen 1996). From an innovation approach perspective, the complexities, both cognitive and organizational, that underlie innovation processes are so high that this part of the value chain was seen as non-globalizable (Pavitt 1999).

The basic idea of GDN is to further develop the GVC and GPN approaches, which were firmly based on manufacturing networks, to cope with developments that increasingly drive the offshoring and outsourcing of innovation (Ernst 2005b, 2008a). This new perspective on the increasing changes of innovation on both the geographic as well as organizational level, is highly important for this study, which is concerned with the organizational forms of product development in the semiconductor industry. The GDN perspective is focused on the dynamics of integration of regions that until recently were not found on maps of innovation locations such as Asia (excluding Japan), or CEE. As vertical specialization and geographic dispersion in the semiconductor industry have moved beyond production tasks (Lüthje 2007a; Lüthje/Pawlicki 2009) the manufacturing driven chain and network approaches need to be broadened towards innovation specific issues. The main question Ernst (2004) wants to answer is why and how GDN can develop despite the necessary geographic and organizational proximity of innovation processes and how this new organizational model, despite being highly hierarchical and requiring high levels of coordination, allows for upgrading that helps to overcome traditional patterns of international division of labor.

Ernst (2005b, 2006) integrates a historical and institutional perspective in his analysis of the development of GDN. The development of GPN in the electronics industry integrated developing countries from Southeast Asia, such as Taiwan, South Korea and Malaysia since the late 1960s, facilitating the growth of a thriving local industry. Regulatory regimes and dense institutional patterns provided by the particular nation-states point to the constitutive role of state polices in the formation and development of global networks of production, and in recent times, of innovation. The historical perspective helps to understand how industry wide organizational and geographic restructuring facilitated the development of local characteristics that are seen as pull factors, but also evolved into dynamics enabling the relocation and dispersion of offshoring.

The pull and policy factors help to understand why innovation offshoring is taking place with an increased focus on Asia. However, the enabling factors, dubbed by Ernst (2004) as push factors, are the variables that allow to analyze why innovation can be relocated and dispersed geographically as well as organizationally. Sectoral dynamics of technology development paths, economic pressures and ongoing organizational restructuring enable innovation offshoring. Technology development in the semiconductor industry is characterized by a very high and quite stable speed summarized by Moore's Law. The ever increasing number of possible transistors and gates that can be manufactured on one chip has forced extensive changes in the design methodology, moving towards a more modular design. The modularization of design was the first step to enable its relocation. Changes in the design methodology are not only driven by the need to cope with the exploding technological complexity but also with basic economical considerations about cost structures and the return on investment. From this perspective changes in the design methodology, pushing for an increasingly modular design that enables higher levels of division of labor facilitating both outsourcing and offshoring, are linked to broader aspects of the fundamental economic dynamics of capitalistic accumulation.[3] The dynamics of design methodology are embedded in a wider social context as they require specific institutional framing and have practical implications for the engineers' labor process. The modularization of design is based on the hope for an increasingly segmented process that allows to outsource and offshore parts of the design ending the more artisan-type labor process where one local team was responsible for all design steps of a development project.

The increasing modularization of innovation and the global organization of engineering work have fundamental effects on knowledge forms and flows of knowledge

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[3] The financialization and the increasing ability to compare financial and industrial assets through financial market arbitrage puts the semiconductor industry, with its extremely high investment requirements under a high pressure. Short term shareholder value considerations can run counter to the quite long cycles of technology R&D and product development in the semiconductor industry.

(Ernst 2004, 2008b). Interfaces that allow and enable the exchange of knowledge across organizational boundaries as well as across distances become fundamental prerequisites of functioning GDN. The ability to design, organize, formalize and manage knowledge interfaces is the main objective for successful GDNs, as knowledge sharing is the glue that keeps GDNs stable and allows for growth. Complex tasks, such as chip design with its highly dynamic technological development, are characterized by high levels of tacit knowledge. Tacit knowledge is a form of very personalized knowledge making it spatially sticky and seen by many researches as quite resistant to geographical dispersion (Pavitt 1999). Hence, the main issue of interface design and management lies in structuring and formalizing knowledge to make it easily exchangeable across organizational and geographical distances. Although this de-personalization of knowledge involves some level of degradation of work (Braverman 1974; Friedman 1977) it is not a one way process of deskilling, as highly codified complex information needs knowledge and experience on the side of the recipient to be able to translate them into applicable knowledge. This points to changes of required skill sets and necessary skill and experience levels that involve contextualizing and translating capabilities, opening up upgrading possibilities for supplier firms and low-cost design centers. Using complex design automation systems, the so called EDA software, the semiconductor industry tries to create modularized knowledge packages of various abstraction levels perceived by the industry as a promising detachment of the design implementation from the creation of a particular block (Chang et al. 1999). However formalized this kind of knowledge exchange is, it still requires high levels of coordination and trust, to drive down risk.

Ernst (2005c) points to positive effects of knowledge communities, where rules, codes and idioms as well as trust are shared, on the exchange of more personalized knowledge forms. Following Pavitt (1999) on his distinction between cognitive and organizational complexity, Ernst (2005d) suggests that knowledge communities are a way to establish cognitive proximity, even if members of the design community are scattered around the world. However, establishing and maintaining effective knowledge communities is by far not as easy as Ernst's account would suggest, as especially in intra-firm GDNs the workloads that engineers need to master due to ever too short project schedules, impede an easy and almost self-propelling creation of such communities. The development and maintenance of such knowledge exchanging organizational structures is a very important managerial task, both to activate it as well as to give the engineers enough room in their schedules. A balance between highly formalized and standardized and more open interfaces has to be found to enable knowledge flows that are not regarded by engineers are exclusively utilitarian and beyond their control.

The objectives of innovation management that fuel the internationalization of R&D determine what types of R&D are performed in overseas location (Ernst 2008a). The idea of motives that structure internationalization and the development of GDN not only driven by sectoral dynamics but also by strategic choices that form and are driven by the particular firm's business model, gives room for agency in the GDN approach. Motives for R&D offshoring and outsourcing can change over time as learning processes take place and trust relations are developed. Initially low-profile design location within intra-firm GDNs can develop strategic capabilities as central management is changing perception of local capabilities and also needs to retain engineering talent through increasingly more complex design projects. Trust relations are even more fundamental in the perception of capabilities to execute projects within set timeframes and quality demands.

2.1.5. Modularization

Perceiving business dynamics from the perspective of modularity opened the way for scholars to move beyond Chandler's vertically integrated firm (Chandler 1977) and provided an analytical concept for economy wide dynamics in industry organization. Technical modularity – the division of labor in design – and modular architectures, defined as architectures with a one-to-one mapping between functional and physical components based on standardized interfaces (Bargigli 2005), created new opportunities for the disintegration and geographical dispersion of the value chain and processes of vertical specialization, or market modularity. Within several years these opportunities, backed by financial market interest in rising profit margins through re-organizing capital intensive manufacturing operations, lead to the proliferation of outsourcing and offshoring dynamics in manufacturing in a wide range of industries. Although the electronics industry and especially the PC sector are prototypical for modular architectures and highly internationalized production systems, examples of vertical specialization can also be found in more traditional industries like garments (for electronics industries see: Lüthje 2001, Sturgeon 1997; for the garment industry see Gereffi et al. 2002). In recent time modularity has expanded into the very process of innovation, resulting in the internationalization of design work (Ernst 2006) as well as into information services.

Advocates of modularity (Langlois 2003; Sanchez 2000) share the assumption that technical modularity will almost directly lead to changes in the organization of firms and markets, i.e. to market modularity. Langlois (2003) assumes that in the age of modularity the need for hierarchical coordination is dissolved in arm's length market relations. The interaction between specialist suppliers and system integrators is coordinated by the market. The codified information embodied in the modular components is enough to achieve coordination (Sturgeon 2002). Each of the suppliers is able to focus on the innovation, development and production of a specific module, which then will be integrated by the system company. The definition of interfaces within specific systems becomes one of the major instruments in the establishment of market control, as these quasi-standards define innovation dynamics.

Ernst (2005d) and other revisionist scholars (Brusoni 2003; Brusoni/Prencipe 2001; Chesbrough 2003) show, how the claim of a convergence between technical and market modularity takes arguments based on the concept of modularity uncritically too far. Although there is empirical evidence in the electronics industry for industry wide dynamics leading to market modularity, Chesbrough (2003) and Ernst (2005d) show that there is no simple translation of modularity in technical structures into modularity in organizational structures. Furthermore, vertical specialization does not develop permanently towards higher levels. The process of modularization is characterized by highly contradictory developments and dynamics of re-integration leading to new forms of vertical integration, which can be observed on various levels of the vertical electronics industry in recent times (Lüthje/Pawlicki 2009; Lüthje et al. 2012). However, these new forms of vertical integration are not a return of the previous model known from the 1960s.

Technical modularity is a necessary precondition for market and organizational modularity but there are further criteria that must be met for both types of modularity to converge (Chesbrough 2003), such as knowledge diffusion, shared language and verification. One of the most important requirements for market modularity is a capable and broad-based supplier base that allows flagship companies to switch suppliers (Ernst 2005d). As we will see, the supplier base argument can also be reversed, i.e. high levels of modularity call for capable system companies, pointing to possible fundamental shifts in the vertical electronics industry, where system knowledge is shifting its location within GDNs.

Brusoni (2003) argues that most modular literature focuses on what firms do, deriving the convergence argument out of this perspective, and leave aside what firms know and need to know to be able to coordinate the development of the underlying technology and to integrate systems. The competitive position of firms may depend on their ability to introduce radical innovation in products and components, which are mainly fueled by in-house technological capabilities. The differentiation between product design, i.e. designing and manufacturing the modular systems, and technology development, developing the knowledge bases needed for innovation, is seen by Ernst (2005d) as a major argument against the assumption that technical modularity translates directly into market coordination. System integrators need to know more than they should in the light of modularity arguments, as it is their role to pick the one possibility out of the almost infinite variants offered by modularization. These broad knowledge bases are the foundations for coordination power of system companies in "framing" (Brusoni 2003) problems and identifying key interdependencies. The distinction between technology and product development leads to a two stage model, in which the first step, technology development, or in the words of Brusoni, framing, calls for a highly coordinated process which is carried out either within one company or by highly controlled innovation networks. The second step, the designing and manufacturing of the respective product, can be carried out in a highly modular fashion with little or no coordination necessities. However, even within the design stage, technological and organizational complexities coupled with high economic risks make coordination as well as relations that are based on trust necessary.

These arguments are based on the traditional innovation model, where the system knowledge is directly linked to and derived from the top position within a supply chain, with brand name system companies possessing both the broadest and deepest technological understanding and market knowledge of the particular product in question. However, the picture of the industrial organization within the electronics industry is changing rapidly and new innovation models are developing in system integration and the development of central components – semiconductors – which are redefining the interfaces between particular network participants as well as the roles they are playing within these networks. These changes in the innovation model influence dynamics of modularity and control in the electronics industry pointing to new limits of vertical specialization. Processes of triangular restructuring as described by Lüthje (2007) are driven by these changes in the innovation model, increasing the complexity of the innovation process overall as well as the structure of the industry's organization. The hitherto known hierarchical structure of modular production and design networks, that developed in the last two decades in the electronics industry when the meeting of Chesbrough's (2003) preconditions allowed for a convergence between technical modularity and market modularity, was characterized by more or less dyadic relations of brand name system companies with high levels of system knowledge and a technologically capable supplier base. The development of suppliers with high levels of system knowledge – ODM and chip companies –, contract wafer manufacturers as well as brand name companies with almost no system knowledge capabilities has changed the situation profoundly, making innovations in the models of design and production necessary.

2.1.6. Upgrading

Both chain and network approaches are based on the idea that firms, regions and nations integrated into global structures of production are enabled to dynamically develop through the process of upgrading. This perspective is turning against traditional notions in developmental studies that emphasize the reproduction of the core-periphery opposition, that leads to a constant gap between developed and developing countries (Hopkins/Wallerstein 1977; Wallerstein 1986). Although criticism of a developmental illusion were formulated (Wallerstein 1994) proponents of upgrading have some hard empirical evidence on their side. Southeast Asia's rise, especially in the electronics industry cannot be denied, from a mere provider of cheap labor used for low value-added work to a technology powerhouse providing innovation and design services with local brand name companies developing in the last several years. However strong arguments can be brought up pointing to a unique situation that provided a window of opportunity for the countries in Southeast Asia, the process of upgrading is also observable, at least on the level of particular firms, in other regions.

Upgrading is defined as innovations that are producing an increase in value added (Morrison et al. 2008). The concept of upgrading is understood as a relational category placing the specific developments in a context to be able to assess how a particular firm, location or cluster is developing (Ernst 2001; Morrison et al. 2008). By qualifying how a specific innovation is relating to competitors as well as participant of the same network it is possible to identify upgrading (Kaplinsky/Morris 2001). However important this relational perspective is, as it is making a distinction between innovation and upgrading, a historical view that allows to asses how the specific object of inquiry – firm or design location – has been developing its capabilities over time needs to be taken into account.

Debates on upgrading are set on various scales moving from a macro level, where scholars look at the interrelation between industrial upgrading and the national economic growth (Ernst 2001), to the meso level of inter-firm relations (Bair/Peters 2004; Pavlinek/Zenka 2010). As the GVC, the GPN and the GDN approaches are mostly concerned with inter-firm relations that establish the global production structures, the perspective on upgrading is located mostly on the meso level, analyzing how lead firm-supplier relations are fostering learning and upgrading processes at the level of suppliers (Schmitz/Knorriga 2000).

There are various typologies of upgrading that reflect the various levels on which the process can be analyzed. Ernst (2001) defines five types of industrial upgrading – inter-industry, inter-factorial, demand, functional, linkages – defining functional and linkage upgrading as the most important for his analysis as they are located on the firm and sector level. Humphrey and Schmitz (2002, 2004) have identified similar types of firm-level upgrading. Process upgrading takes place when more efficient production methods and better technology are introduced leading to an improved quality of produced goods and also an increased flexibility of producers. Product upgrading occurs when the firm is moving to the production of more sophisticated and higher value-added products. With functional upgrading firms acquire new functions, moving increasingly towards R&D, marketing and service-related tasks, generating higher incomes involving the increase of the overall skill content of the firm's activities.

The re-organization of industries, especially dynamics of modularization, are facilitating upgrading as lead firms constantly push suppliers to lower prices and increase quality (Palpacuer et al. 2005) as well as look for possibilities to outsource and concentrate on their core capabilities. However, this does not mean that upgrading is an automatic as well as conflict free process. In particular, functional upgrading can lead to frictions and conflicts within GPN/GDN as lead firms see future competitors arise. The prospects of upgrading are linked to the governance structures of GPN (Pavlinek/Zenka 2010). Less captive relations allow and demand higher functional upgrading from suppliers, who need to compete to stay in the supply chains of brand name companies, by offering increasingly integrated complex services and products. Upgrading within GPN is highly hierarchical, as the position of the suppliers within the network defines the level of intimacy of their connection to lead firms in the areas of R&D, which facilitates upgrading. Suppliers from lower tiers do not have a direct connection with lead firms, which is impeding their ability to learn as technology transfers are not frequent. Upgrading is linked to strategic decisions of firms making cognitive barriers an important variable. As Grabher (1993b) has shown for regional development, cognitive capabilities are path dependent and can impede the ability to recognize necessary strategic choices. Similar cognitive barriers can be found on firm-level, where historically developed divisions of labor can lead into barriers for functional upgrading, as specific functions required for innovation activities are not taken into account as important.

Although upgrading is providing firms, networks and regions with possibilities to move towards higher value-added functions, this is not a stable process generating definite outcomes. As upgrading processes are taking place within globalized structures, global dynamics can change the context as well as strategies of lead firms leading to decreases of local upgrading dynamics or their full halt (Lüthje et al. 2013). Upgrading has to be perceived as a precarious process, where local capabilities are put into use and developed as long as global strategies see this fit. Only if locations can develop an appropriate importance through their scale as well as local institutional and regulatory characteristics the process of upgrading can be stabilized.

Discussions on upgrading rarely focus on the dynamics within firms that underlie the process of upgrading (Morrison et al. 2008). However it is important, for this study and for the more general understanding of upgrading, to understand how processes within the firm are driving and enabling upgrading. The upgrading of locations within global intra-firm networks can be both a top-down as well as bottom-up driven process, where strategic choices, customers' requirements, talent sources as well as local managerial initiatives are of importance (Fuchs 2008). From this perspective also local characteristics can play a decisive role, providing capabilities and resources fitting into global corporate strategies. However, as already mentioned, the local linkages are increasingly fragile and need institutional and regulatory catering, otherwise only 'cathedrals in the desert' (Grabher 1997) will develop. To be able to analyze upgrading as a process within a particular firm where dynamics of GPN and in-house activities have to come together (Morrison et al. 2008), the notion of capabilities, as routines and knowledge resulting from the process of organizational learning (Nelson/Winter 1982), is helpful. Technological change through technology and knowledge transfer and diffusion needs a recipient that is capable to identify, assimilate and exploit knowledge external to firm or location. This absorptive capacity is linked to technological capabilities, or skills that firms need to utilize technology efficiently, both in form of equipment as well as information, to accomplish any process of technological change. Such skills are located on managerial, technical and organizational levels and are firm specific resulting from individual skills and cumulated experience pointing to both a purposeful process of investment and activities that defies any automatism in upgrading processes, as well as highly path dependent developments (Morrison et al. 2008). Capabilities in firms are not some kind of abstract processes but are inscribed in the everyday work of the firm's employees, management and organizational structures. What kind of work is performed and how it is organized are the major factors that define the routines and knowledge within a firm or particular design location. To understand the upgrading within a firm it is necessary to take a closer look at the work performed at the particular location and how it is changing over time.

2.1.7. Work

Questions concerning work and the labor process were initially not in the focus of most GVC and GPN research. However, recently labor related questions have been increasingly discussed by GPN scholars, especially in the context of ILO's Decent Work strategy (Pegler 2010). Most of the new studies are focusing on the relation between upgrading and changes in labor conditions as well as representational opportunities (Bair 2005; Bair/Peters 2004; Pegler 2010; Pegler/Knorriga 2007) or the link between economic and social upgrading (Barrientos/Gereffi/Rossi 2011), leaving out almost any considerations of changes in skill requirements driven by the integration in GDN. The newest endeavor in extending the GCC approach with a labor perspective is Selwyn's (2012) very informed critique and effort of extension. His main idea is to model GCC investigation along the ways how capital-labor relation co-determine processes of capitalistic development and change.

To combine labor studies with the GPN approach Knorriga and Pegler (2006) underline similarities by conceptualizing relations as characterized by power asymmetries, either between workers and employer or between various firms in the value chain. One of the results of these power asymmetries is the continuous passing of growing flexibilities and risks in form of higher precariousness on the lower end of the value chain (Pegler

2010), which translates into deteriorating labor conditions for workers, especially in peripheral companies. Although upgrading and improvements in labor conditions are seemingly related, Knorriga and Pegler (2006) identify such development only in the initial phases of GPN integration where companies need to develop compliancy with international standards for quality management and technology development. However, these temporary positive changes are being continued if certain work characteristics exist. Highly skilled, relatively scarce talent focusing on work characterized by relative high levels of tacit knowledge can count on relatively positive labor relations that will develop over time (Pegler/Knorriga 2007). Work in chip design is exhibiting these very qualities with companies being anxious to retain specialists with the help of acceptable labor conditions.

Labor conditions are not the most problematic issue in engineering work, as companies are quite avidly trying to cater for their highly specialized talent. This tilts the necessary focus of analyses more in the direction of skill content and skill change. Compared to the highly Taylorized and segmented manufacturing labor process, skill levels in the labor process of engineers are affected in a different way by firm level upgrading. For engineers, functional upgrading can lead to a shifting of required skills towards e.g. increasingly frequent customer cooperation or can add new technological capabilities necessary to organize and manage emerging interfaces, as these functions need to be integrated into the engineering labor process.

However, functional upgrading is not an automatic process driven only by economic factors and global strategies of offshoring and outsourcing. As employment relations are based on control, conflict and consent (Burawoy 1979) the development of trust is necessary for labor relations to develop towards a working level. This build up of trust is impeded by the highly precarious labor conditions that characterize manufacturing work in the globalized value chains (Knorriga/Pegler 2006). As engineering work in the semiconductor industry is characterized by more stable labor relations the build up of trust based relations is enabled and necessary for a complex knowledge based labor process. Trust continues to be a highly interesting category in this context as it is not only the base for relatively positive labor relations, but also for building up capabilities in knowledge creation, absorption and retention, establishing a direct link to skill development.

A major contribution to the ILO related debate on the development of work in the globalizing economy is Gary Gereffi's 2005 study on new qualities in job offshoring. In this study Gereffi calls for detaching job analysis from location and conceptualizing work and jobs by their role in GVC. His argumentation is initially convincing. This conceptualization of work in a globalized economy enables to move towards a new idea of globalization and international division of labor characterized by functional integration on the global level which is increasingly overturning the New International Division of Labor (Fröbel et al. 1977). This shift is evident in the process of more and more work traditionally regarded as located exclusively in core countries being offshored to peripheral locations. Ideas about complementary divisions of labor (Berger et al. 2001) are put into question, as increasingly peripheral locations either develop into nearly independent entities that take over lead roles or build up unique capabilities within companies. But discarding location all together as a variable in the concept of work (Gereffi 2005) is inhibiting a differentiated analysis that can reach beyond economistic and highly structuralistic analyses. The institutional and regulatory patterns, as well as local market conditions, existing in the location where a global value chain touches down have effects on the way how firms can act within their own offshore location in regard to labor and work issues as well as how local suppliers are being integrated into global networks. The particular local design of global strategies is affected by labor laws, labor markets, educational systems and investment incentives. While Gereffi's (2005) job concept is leading to a quite mechanistic picture of jobs and work in GPN, where things like skill levels seem to be easily derivable from a position of the firm in the GPN, a more dialectical view on the process seems necessary (Henderson et al. 2002). This is not to say that multinational companies are not able to push the development of local institutions and regulations in favor of their interests (Bohle/Greskovits 2004), especially through the increasingly global competition between investment locations.

Gereffi (2005) is proposing a typology of work, which despite being heuristically helpful has severe shortcomings, especially as offshoring increasingly affects also knowledge-intensive work. The typology is developed almost exclusively in relation to manufacturing, proposing only one category of work – knowledge-intensive work – that is not directly linked to manufacturing activities. Although this reflects globalization with its initial high focus on manufacturing and related operations, since about 15 years the reality of offshoring has been changing as non-manufacturing tasks are being located also increasingly in low-cost locations. Such an undifferentiated typology misses many characteristics of the diverse offshoring landscape and the developing international division of labor. Not only is little attention paid to knowledge-intensive work, but the typology is also prone to mingling the levels of value-add and knowledge-intensity within different job categories. The question whether work at a specific location is characterized by high levels of knowledge-intensity cannot be answered in a general way, but needs a sector specific perspective. Work seemingly knowledge-intensive such as in call centers can only be conceptualized in such a way if perceived from the vantage point of industries that are not so knowledge-intensive. Comparing knowledge-intensity of call-center work to work performed within the ICT industry the level of knowledge-intensity is being put into perspective.

An opposing perspective on work is being developed in studies such as Huws and Ramioul (2006) that analyze service work and its changing situation in the global knowledge economy. Here white-collar work, or roughly set knowledge-intensive work, is being detached completely from any manufacturing relation and viewed only in its service work form. The missing link to material production is pushing into the background technology changes affecting production processes, knowledge forms and also the way how knowledge workers need to innovate and develop new products within these changing variables. This limits the ability to integrate sector specific technological and economical constrains for the development of knowledge intensive work. Only a sectoral analysis, making industry specific factors such as capital accumulation dynamics, technology development and industry structure comparable, allows to sketch a differentiated picture facilitating a distinction between core and peripheral workers across organizations as well as within them.

A sectoral perspective integrating the dialectical relation between the local and the global allows also to develop a much more appropriate perspective on the work. Although processes of rationalization, de-qualification and increasing precariousness tend to emerge throughout all industries in the capitalistic system (Braverman 1975; Friedman 1977) the specific forms may differ extensively. As Gereffi's (2005) concept is mostly focused on manufacturing related work it is necessary to develop a specific typology, which is more applicable for knowledge intensive development work. Taking Gereffi's (2005) knowledge intensive category as well as considerations about the importance of location as points of departure, four categories of work within the innovation and product development process can be developed.

(1) Architectural and research related positions are focused on the development and design of specific (internal) standards, knowledge resources and architectural decisions that are guiding the actions of their engineering colleagues within the firm. These engineers are representing the interfaces between various knowledge fields as well as organizational units, requiring high levels of technical knowledge and long experience with the technical aspects of their work. As their role is also characterized by the technical direction of development projects, high levels of management skills, especially in communicating and integrating of disparate interests and viewpoints is necessary. Traditionally architectural and research positions have been located in the core countries, especially near the headquarters, as they require insight in both strategic decisions as well as central R&D processes. However, as dynamics of integration are increasingly driving the international division of labor, the shift of such positions to initially peripheral locations and countries can be observed.

(2) Integrated positions situated in development projects that locally comprise all, or most of the functions required to implement the project in question. Dependent on the characteristics of the development and labor process the particular functions that comprise the whole value chain of development can vary. For chip design, functions such as logic design, design implementation, physical design and layout, verification and test come into focus. The local integration of these functions enables engineers to both develop extensive knowledge pools through contact with other engineering functions, as well as offers broader possibilities for career development. Integrated positions also involve project management, mostly performed by local engineers, shifting the required skills increasingly towards managerial capabilities. From an upgrading perspective such positions are the result of functional upgrading and are extremely important for further upgrading dynamics as they allow to develop high levels of capabilities in a specific location.

(3) Managerial positions relate mostly to the management of the particular design location, the program and the project team. It is of considerable importance whether local managerial positions are being filled in with expats, who are rotated frequently, or with local managers that not only have a better grasp of institutional and cultural specifics, but also have a higher impulse to drive local interests. Other managerial functions, especially those linked to sales and marketing are highly important for the long-term development of

a design center, as these functions allow to actively influence broadly product and technology strategies with regards to future customer needs.

(4) Auxiliary work is performed either when projects are not integrated and specific tasks are offshored, or when specific auxiliary functions, such as in-house software tool development are located in low cost locations, mostly in line with cost optimization strategies. This is often based on a complementary division of labor rendering these positions precarious, as the required capabilities can be found also elsewhere. Possibilities for upgrading are impeded as the missing systemic overview of projects is rendering learning processes much longer than with integrated projects.

These four categories of work enable a differentiated analysis of knowledge work in global design networks while the relation between upgrading and skill dynamics in engineering work is facilitated by this detailed perspective on knowledge work. To move beyond a generalized view of capability distribution within GDN, based on particular functions assigned to design centers, it is necessary to take a look into the centers and on the specific character of work performed. This broadens the basis for analyzing the position of a specific design location within a GDN. This typology of work enables an analysis that traces the historical development of local capabilities in a particular design location. With the relatively long history of internationalization of engineering work in the semiconductor industry this is an important analytical perspective.

2.2. The changing face of innovation. Architectural innovation, capabilities and industry organization in globalizing markets

As the organization of innovation has changed over time, so have the concepts about its role in economic development and its main actors. The creative destruction through the combination of existing resources was initially viewed as a highly focused process driven by the entrepreneurial inventor (Schumpeter 1997) who conceived a new way to do things, be it either a new good, a new method of production, a new market or a new organizational structure. However, innovation is neither to be equated with invention nor R&D, although these are the initial phases of an innovation process. For an invention to become an innovation, the new creative combination has to upset the equilibrium state on the specific market it aims for, making it necessary that users perceive an advantage justifying a higher price.

The ongoing transition towards a knowledge society has changed the demands posed towards the organization of the innovation process, broadening it from the mere operational translation of a specific idea into a commodity. The traditional view on innovation conceptualized the process as based on static resources of technologies and means that need to be recombined. As innovation has become increasingly the integral part of economic development, it had to move from a unique and singular act to a planned permanent process. Today companies can to stay competitive only through the systematical development of the production means, based on assumptions and extrapolations with regard to future market demands that drive a consistently organized process. This conception of planned out innovation can have its drawbacks. As it is trying to perpetuate the sometimes erratic process of creativity, which lies at the base of every innovation, a too narrow planning can stifle innovation, making innovation management a walk on a tight rope between the necessary freedom and the required reasonably predictable business results.

Viewing innovation as an ongoing and planned process of the development of the production means is also broadening the view on the various actors involved. The initial narrow focus on the entrepreneurial inventor has separated the function of production from innovation (Kocyba 2000). However, not only does innovation comprise the manufacturing and marketization of an idea, but, within a perpetual process, innovation draws heavily from knowledge created within the production process. The essential detachment of production and innovation can therefore cause fundamental problems in the innovation process that need to be taken care of through the development of appropriate organizational forms of coordination and control (Ernst 2005d). The broader view on actors involved in innovation is also spurred by deliberations on national and regional innovation systems (Nelson 1993) that conceptualize innovation processes embedded in a historically developed institutional and regulatory framework.

The electronics industry in general and the semiconductor industry in particular are characterized by a high level of innovation dynamics, where innovations on various levels such as process technology, design automation software, design methodology and industrial organization are intricately intertwined. Combined with financial market pressures, the high technological dynamics have facilitated a very specific model of organization where production and innovation were increasingly decoupled. Wintelism (Borrus/Zysman 1997) was based on the possibility to define and control new markets, technologies and production capabilities through quasi-standards[4] based on break-through innovations that were enabled by an increasingly modular system structure. Although this new way to organize innovation, production and markets has been perceived as the model of the future for industrial organizations in the 1990s, both economic as well as technology crises have shown its limits (Ernst 2005d; Lüthje 2007b; Lüthje/Pawlicki 2009). However, as constraints such as ever decreasing product life cycles coupled with exploding innovation costs and permanent financial market pressures still exist and need to be accommodated for in the historically developed industry structure, innovation cannot be re-organized as a closed intra-firm system. R&D consortia and alliances need to cope with the situation providing firms with resources of talent, production means and pooled knowledge with shared risks and costs.

It is helpful to identify various innovation models, as they rely on different knowledge forms and corresponding capabilities as well as opportunities to learn. Henderson and Clark (1990) distinguish between components and the architecture of a product to develop their four models of innovation.[5]

In an incremental innovation both core concepts embodied in the components as well as the architecture of the product are taken as given, while focusing on the optimization for cost, performance or time-to-market. The idea is to introduce incremental improvements to the existing product or process. In this innovation model leading-edge knowledge and intimate relations to fundamental research is not important. However, managerial capabilities such as market knowledge or innovation process management are of big importance paralleled by experiential knowledge linked to production.

Modular innovations keep the architecture of the product intact while developing new components. Modular innovations are only possible across organizational boundaries if the innovation process can be modularized, based on interface standards. This model opens up markets for business latecomers, as they can focus on the development of highly specialized knowledge and capabilities without the need of deep system knowledge. This does not directly translate into low entry-barriers, as the technological complexity of these

[4] Quasi-standards are standards that are not linked to specific standardization bodies and deliberation processes but base their existence on market domination. Both Microsoft's Windows as well as Intel's x86 microarchitecture are such quasi-standards through their almost monopolistic market position, that forces other companies to comply with specific technological standards set by these two companies.

[5] A component is a part of a product, or service, that embodies a core design concept and performs a clearly defined function. The architecture is the way in which the various components are linked together into a functioning product.

modular innovations can be very high, furthermore linked to extreme capital expenditure requirements.

Changing the way how components of a system are linked together while keeping the component design and with this the dominant design concept stable, constitutes architectural innovations. With components' design fixed the associated scientific and engineering knowledge remain the same, lowering the need for high science inputs and financial investment in contrast to radical and modular innovations. Architectural innovations are based more on knowledge about the requirements of markets and users within the confines of already existing technological possibilities. This is why Ernst (2008b) points to the development of new business models as an important form of architectural innovations.

Radical innovations introduce fundamental shifts by breaking with the dominant design via changing core design concepts. Breakthrough innovations of both architecture and components require broad and deep research and product development capabilities, with intimate linkages to various leading-edge sciences. Mastering radical innovations not only requires huge capital expenditures but is also based on high levels of experience in the various technological areas the product is encompassing. To be able to assess the possibilities of the various technological variants a completely new designed system can have, even broader technological knowledge needs to be accumulated (Brusoni 2003). Besides being extremely expensive radical innovations have a high risk, as completely new systems take a long time to develop and need to be accepted by the market.

The specific technology and economic dynamics of the electronics industry, especially in the Wintelistic characteristic, have put a high focus on leading-edge technology development to define new markets associated with high profit rates. Coupled with the existing and further developing technical modularity, the Wintel model favored and facilitated both the radical and modular innovation models. However, both the organizational and spatial dynamics inscribed in this model of industry organization and innovation put an increasing focus on architectural innovations, that cater for markets in the developing countries based on a deep understanding of their customer's specific needs, as well as help to keep costs down by using already existent modular IP in a new way (Ernst 2008b). Architectural innovations allow for an easier entrance of new companies in incumbent markets, as their demands towards both financial as well as knowledge resources and capabilities are manageable. Companies pursuing architectural innovations have the capability to challenge incumbents, which have been focusing on incremental innovations. Contrasting incremental and architectural innovations Henderson and Clark (1990) show how knowledge forms and the linked capabilities evolve in a phased model of dominant design assertion.

Vertical specialization, with Wintelism as its extreme form, is based on the idea that the innovation process can be clearly detached from manufacturing, making it possible to outsource and offshore manufacturing activities. However, vertical specialization is being paralleled both by processes of re-integration (Lüthje 2007a; Lüthje et al. 2012) as well as a rising in the complexity of the outsourcing services, reaching now complete system integration and development. What has started at contract manufacturing companies as manufacturing near engineering to optimize interfaces to customers as well as manufacturing processes has developed over the last years, driven by the last two global economic crises, into full-fledged system design capabilities. A similar process, driven more by technological pressures and possibilities, has taken place in the semiconductor industry, where system integration on one chip forces semiconductor companies to move increasingly towards system design (Lüthje/Pawlicki 2009).

These dynamics facilitate fundamental shifts in the interface of innovation within GPN and GDN drawing it nearer to manufacturing and with this pushing it away from lead companies to lower levels of the value chains. At least the tier 1 suppliers within the particular value chain, increasingly become solution suppliers, often putting both their financial as well as innovation resources to a test. As these suppliers are often assigned with the development and manufacturing of highly commodified consumer products, the product differentiation is not focused on technological break-through innovations. Rather the re-use of existent technologies, with a high focus on cost competitiveness, as well as the ability to quickly re-organize the own supply chain are the fields where the companies are focusing their innovation. Providing pre-developed systems to lead firms requires high levels of intimate knowledge about both the consumer market, where the commodities will be sold, as well as the lead firms that will brand the system to be able to organize product development in an efficient way while lowering financial risk. This drives the development of new business models, which try to integrate both market and technology complexities within the economic limits of the crisis laden global economy.

Innovation interfaces are further changed through the modularization of innovation that facilitates a fragmented innovation process with many organizations involved.

However, as we will see in the next chapter, there are not only limits to this model of open innovation, but even dynamics linked with knowledge and learning, the organization of interfaces and economies of scales, that cause processes of re-integration on the level of design service providers, following the pattern of triangular restructuring (Lüthje 2007a). These developments lead into a more complex system of innovation and production, where system companies and their suppliers are increasingly linked by interface supplying firms. Integrating knowledge from manufacturing and product development these interface suppliers offer standardized knowledge modules which are highly customizable and allow lead firms to use their innovation capabilities in a flexible way, while lowering implementation and production risks.

The geographic dimension of the outsourcing and offshoring developments in the last 30 years has a far reaching important impact on shifts between the four innovation models. Developing markets for consumer goods, especially in the BRIC states, gain importance due to market saturation in developed markets and a dynamic expansion of consumers in these developing countries driven by the industrialization related to the integration into GPN. Although the financial resources of these new consumer groups is rising it is still quite low, putting severe limits on product development, as developing markets also ask for a high variety in the range of products as well as a constant supply with new product. This shifts the innovation focus away from costly leading edge technology, to more market oriented products that cater for the specific needs and limits of these new consumer groups.

2.3. The place of innovation work. R&D locations and their various functions in Global Design Networks

The internationalization of R&D, or the offshoring of innovation, through global design networks has various drivers resulting in differentiated patterns of international division of labor. For years firms have been operating R&D facilities in regions abroad that were the main locations of technology development in their respective industry, such as the Silicon Valley for electronics. Such R&D centers were the firms' interface to these highly localized knowledge pools, easing up the access to leading edge knowledge and scientific results. However, the sheer need for a big engineering labor force seems to be increasingly more important for the process of building up design centers abroad. This driver of R&D internationalization is quite new, superimposing on the traditional strategy of knowledge access. The need to access engineering talent is driven by shortening product life cycles, diversification of product ranges and cost pressures. The sheer numbers of graduate engineers in developing markets such as China and India can provide for this demand for talent.

Besides these quite general demand and supply factors for the internationalization of R&D, industry specific dynamics promote this development to unprecedented qualities and levels. The sophisticated vertical specialization of the electronics industry, paralleled by technical modularity allows for a high level of modularization in the innovation process, easing up the process of offshoring development tasks crucially. Technological limits and requirements shaping the innovation interfaces throughout the industry make specific strategic changes necessary, to cope with the developing international division of labor. As manufacturing and some important engineering tasks are located in Southeast Asia electronic companies from Europe and the U.S. need to build-up design locations to develop, organize and manage interfaces to their customers, suppliers as well as their own increasingly capable manufacturing locations.

A quite simple, however significant typology splits R&D centers into two general categories with regards to their particular functions and primary objectives linked with specific capabilities and information flows, making a hierarchization of foreign R&D operations possible (Kuemmerle 1997). Home-base augmenting R&D locations aim at tapping knowledge pools in specific high-tech regions, where universities and competing companies have established dense local knowledge networks. Information is flowing from these sites to the central R&D unit, making high level engineering and science capabilities necessary to be able to keep up with the local leading-edge technology developments. Formulated on a broader basis the output of home-base augmenting R&D operations is used worldwide throughout the whole firm in various applications for different countries. The location of these sites is promoted by existing high-tech regions as well as the geographies of specialized engineering talent.

Home-base exploiting sites are set up to support already existing manufacturing facilities or to adapt standard products to the local market needs and help to commercialize them in foreign markets. These sites are dependent on knowledge and information from their central R&D organization. In the face of increasing technical complexity and shortening product life cycles the geographical separation between product development and manufacturing has to be organized by setting up such offshore engineering operations in proximity to manufacturing facilities to smooth out the knowledge transfer and make production more efficient. Their location is therefore driven by the geographical pattern of manufacturing, as well as important new markets.

Kuemmerle's (1997) typology is a good starting point, but his model is not allowing for any dynamic development in the roles assigned to specific R&D locations. Upgrading is not only taking place on the national and company level. Development locations in intra-organizational GDN are also upgrading and changing their relative positions in the hierarchy. This prospect is rendering international cooperation so problematic, as engineers in central locations are fully aware that they are training their possible future substitutes in peripheral design centers. Just as in manufacturing, complementary divisions of labor are becoming obsolete in the internationalization of engineering work. A very important drawback seems to be the typology itself, as it only allows for two highly disparate forms, which even if treated as ideal forms are not able to map the diversity of R&D locations and their operative aims.

Following Kuemmerle (1997) in his typology of home-base augmenting and home-base exploiting R&D labs Sachwald (2008) adds a new category[6], the global development center. With this Sachwald aims at adapting the model to the developing empirical reality. The existence of global development centers has to be understood before the background of the ongoing modularization of innovation. These centers are carrying out R&D tasks that can be easily separated and fed back into the parent company's innovation process. This includes back-office tasks, tests, and software coding. Viewed from the point of GDN in the semiconductor industry physical design, documentation, test and library development could be added. The fundamental characteristic of these R&D units is their quite visible detachment from their location, as neither an important knowledge community, nor a market that could be tapped for sales or information exist. The locational determinant for this type of design centers is cost-efficiency, driving the location of such engineering units in low-cost countries such as India, China or CEE.

Global development centers differentiate the typology of R&D units in a very important way, as the category is expressing specific structural developments that keep the internationalization of innovation in flux. This category helps to take into account the new level of internationalization that is moving to a more systemic level, where global structures become fundamentally vital for innovation processes. Such centers are neither

[6] Sachwald (2008) renamed Kuemmerle's (1997) home-base exploiting R&D locations local development centers, and the home-base augmenting units global research laboratories.

augmenting nor exploiting the home base as they both use and produce valuable knowledge that can be applied worldwide in various development projects. The local integration of such centers is quite low, compared to the high levels of local integration of home-base augmenting and exploiting locations, which have either close relations to local knowledge communities or to local manufacturing, suppliers and markets. With regards to upgrading it is very hard to predict how such an highly internationalized character will take effect. As their function within a specific GDN is not closely determined from the onset, it both opens up future possibilities but at the same time can result in precarious or even aborted development. Using the global development center category as a possibility to integrate fundamental shifts in the organization of innovation through modularization in the discussion on R&D locational choices, it is possible to both characterize the internationalization of R&D in its developing variety as well as underscore the increasingly fluid functions of design operations within the global innovation architecture.

However, design centers often seem to integrate functions related to both home-base exploiting and global development center categories, as their relations to the central and other R&D units are highly differentiated ranging from simple execution of work packages within a particular international development projects through locally integrated projects to leading international projects. High local integration facilitated by functional upgrading is calling for an extension of Sachwald's (2008) global development center category for the present study. The development of a location to more mature stages can be taken into account in this way, as the initially detached global center is increasingly being embedded locally. In this perspective the global development center category is describing a highly dynamic unit in between global strategies and local characteristics.

2.4. Complex relations. Summary and development of guiding questions

The electronics industry is at the forefront of the ongoing dynamics of globalization and organizational innovation. Driven by economic and technology pressures and opportunities electronics system companies and chip manufacturers were among the first to internationalize their manufacturing operations substantially (Angel 1994). Since the 1990s semiconductor companies are also increasingly organizing their R&D operations globally. The ongoing internationalization of the industry has been facilitated by dynamics of vertical specialization that push the industry towards a horizontal organization, based on global production and design networks, advancing fundamental changes in the international division of labor. This renders the electronics industry in general and the semiconductor sector in particular a formidable object of inquiry for questions regarding industry organizational and geographical dynamics and their effects on engineering work. The electronics industry is characterized by an industry organization that is in constant flux. Although technical and organizational modularity are high and elaborated, coordination requirements are increasing due to complexities on both levels. These dynamics seem to facilitate, at least on some levels of the industry, centripetal forces both regarding organizational and geographical patterns. It will be the task of the present analysis to trace current developments in relation to economic and technology dynamics as well as their historical background, to be able to understand how firms organize their production and innovation and how this is affecting work.

Offshoring and outsourcing of manufacturing and innovation, or the spatial and organizational modularization of the whole production process are the fundamental forces behind the ongoing globalization of work. This leads to the following questions and hypotheses that will be addresses in this study. As these questions are addressing the complex interrelated dynamics of industry, firm and local development they are more of a guiding framework through the study, than aiming at separate answers.

1) *How can the major shifts and their drivers in the organization of the electronics and semiconductor industry be characterized and is a dominant organizational model emerging?*

   - The development of industry organization is not a straight and smooth process leading to one best solution of either market or hierarchical organization. It is a crisis laden process of vertical specialization and re-integration.

   - The global crises of capitalist development shift both investment, consumption and geographical patterns impacting the way how vertical specialization and integration shape the industry organization.

   - Financialization is a major factor driving vertical specialization increasing the emphasis on a positive and growing return on investment, forcing companies to focus on core capabilities that generate high profit margins.

- Sector specific cost pressures, originating from the extremely high capital expenditures necessary to support wafer fabs, are pushing companies out of manufacturing. The development costs of IC products are also reaching levels that are often beyond the financial limits of smaller IC companies, driving processes of specialization and cooperation within the development process.

- Technology is a major driver of vertical specialization as its dynamical development is the fundamental basis of technical modularity. System knowledge increasingly is shifting towards component suppliers making intimate development relations between lead firms and system suppliers necessary. Semiconductor suppliers need to cooperate with various other partners to be able to organize their product development efficiently.

- A network based industry organization is emerging as the dominant model. While incumbent integrated chip companies still are important, foundries as manufacturers, technology suppliers and network organizers are becoming fundamentally central.

2) *In what way is the location of innovation shifting – organizationally and geographically – in the global production and design networks of the electronics industry?*

   - System knowledge is increasingly moved towards component suppliers making intimate development relations between lead firms and chip suppliers necessary. Cooperation with various other partners are necessary to organize product development efficiently.

   - The evolved division between manufacturing and product development is increasingly generating problems as complexity rises. Previously quite simple patterns of customer-supplier relations reach their limits driving shifts in the innovation interface.

   - Increasing dynamics of re-integration on the manufacturing side, foundries for semiconductors and contract manufacturers for systems have fundamental effects on the organizational and geographical level. Innovation is moving towards Asia and out of system companies into networks driven also by suppliers.

- Shifts in the innovation model have implications for knowledge and capabilities stimulating further changes within global production and design networks.

3) *What are the major geographical dynamics in the electronics industry and what role can states play in the development of local resources and capabilities required by globally organized industries?*

- Locations with regard to both policies and regulations as well as formal and informal institutional frameworks co-shape processes of vertical specialization and internationalization.

- State policies financing technology transfers have been essential for the development of integral parts of the vertically specialized semiconductor industry.

- State policies that lower overall costs help to stabilize the increasingly fragile process of technology development.

- Previously peripheral locations are increasingly developing importance in manufacturing as well as product development capabilities. The development of local markets, supplier networks and technical capabilities is often additionally backed by technology oriented state policies.

- Southeast Asia has emerged in the last four decades as a manufacturing location and was able to upgrade its technical and organizational capabilities substantially.

- Emerging brand name companies, re-integration on the manufacturing level as well as new dynamic end markets are important factors that drive the shifts of innovation interfaces to Asia.

4) *What is the current status of offshoring of engineering work in the semiconductor industry of CEE and how did it develop?*

- The firm is the most important perspective to understand how internationalization is developing. Processes of learning, knowledge transfer and build-up as well as upgrading are driven by local and global factors that come together within the firm and its location where it is touching down in the local.

- How the organization of work and work itself is being affected by the integration of design center locations and firms into GDN analyses within the black box of the firm is important.

- Upgrading is not and automatic process but involves considerations regarding trust as formally verifiable capabilities do neither guarantee required quality levels nor expected time-to-market. Learning is taking place on both sides to enable local capability build up as well as strategic decisions to further grow the importance of a particular location.

- Functional upgrading is increasingly driving local integration of various work categories in design centers in CEE. The initial relations characterized by a complementary division of labor have been developed through the years towards more integral and important.

- Local skill levels within GDN are driven by processes of specialization and integration. The development of design centers in CEE is characterized by a broadening and deepening of skill levels on both technical and managerial levels.

- Product upgrading and process upgrading are driving technical requirements as well as the organizational capabilities. In inter-organizational networks quality management standards are an important factor of process upgrading.

- The process of local integration has replaced micro-modularization in CEE design centers of the semiconductor industry.

5) *Which local characteristics are important in the emergence and development of design locations and how do they take effect?*

- Opportunities for functional upgrading are linked to the specific character of intra-firm design network as well as environmental characteristics such as the labor market, research institutions and other historically developed resources. The industrial history of CEE was an important factor in the integration of the region into GDN of the semiconductor industry.

- Local labor markets provide experienced engineers and well trained engineering graduates. The drying up of the local labor markets forces companies to deepen their local integration by cooperating with universities and extending their recruitment focus.

- Low turnover rates are important for an upgrading process that is not backed by external factors such as local content rules or local standards. Long tenures allow to develop high experience and trust levels.

- The importance of local knowledge communities is changing in the development of design centers, as firms are increasingly cooperating with local universities.

6) *How is the position in intra- and inter-organizational global development networks affecting the development of particular firms and design locations in CEE?*

- Upgrading possibilities are linked to problems of visibility in intra-firm networks. Peripheral network positions can translate into a lowered perception of results originating at peripheral locations.

- Direct customer involvement is key for small firms in inter-organizational networks as mediated communication is limiting the build up of required market knowledge.

3. Organization and Geography of the Semiconductor Industry

The electronics industry is at the heart of the industrial revolution of the last 50 years. The industry's technological drive as well as its organizational innovations are intimately connected with the segment providing its hearts and brains – the semiconductor industry. Within only years of its existence the semiconductor industry lead fundamental changes in industry organization as well as internationalization. Semiconductors, or integrated circuits, are the technological building blocks that enabled miniaturization, computerization as well as the all encompassing telecommunication.

The following chapter is divided into two main parts. The first part analyses the development of the industry's organization and geography on the sectoral level. Processes of vertical specialization, triangular restructuring and the ongoing internationalization are the main focal points in this account. A historical perspective on the development of the semiconductor industry sketches the initial development of the industry and is extended by the analysis of the role of the state in this industry. The semiconductor industry, its initial development, its internationalization, as well as its current technological dynamics depend in great measure on the state both as provider of subsidies and institutional frameworks as well as source for research funds. As a knowledge based industry the chip industry is an interesting example of the ongoing commodification of knowledge which is a major driving factor of vertical specialization. The technology dynamics in the semiconductor industry will be analyzed as major drivers and at the same time major limits for the development on both the organizational as well as geographical level of the industry. The shifts in markets, business models as well as geographies are the background for a general analysis of development of the industry's organization. The first part will be concluded by a short case study about the Taiwanese chip design company Mediatek that is an epitome of the sketched developments.

The second part of this chapter is based on my field work in CEE. The focus shifts from the sectoral level to the firm level, to be able to grasp the intricate dynamics of triangular restructuring and internationalization on the level where is actually happens – the firm, and more precisely the particular design center. Three case studies offer a differentiated view on the integration of design centers into the global design networks of the semiconductor industry. The analysis shows that for the internationalization of innovation too, ideas on a complementary international division of labor have to be revised. Although GDN are highly hierarchic it is not possible to deduce the role and position of a particular design center only from its geographical location. Functional upgrading and local integration are developing the complementary international division of labor further, towards a system of self-confident, independent as well as technologically capable and distinguished design centers in peripheral locations. Two multinational integrated chip companies that both develop and manufacture their own chips will give us insights in the processes within intra-organizational development networks. The third case study is focused on an independent IP developing company from Poland. It gives an impressive example on the hierarchies and power structures within Global Design Networks.

3.1. The Semiconductor Sector – organization, geography and technology

3.1.1. Formation and internationalization of the semiconductor industry

After the transistor has been invented at AT&T's Bell-Labs the semiconductor industry has been thriving since the late 1940s in the U.S. The developments of semiconductor technology were largely related to the research system of the big armaments, aerospace and computer companies supported by the U.S. Department of Defense. The ongoing technological development made the integration of many components into a single device possible. The integrated circuit (IC) has many fathers, ranging back to the late 1940s in Germany and Great Britain. However, Jack Kilby is generally credited with the invention of the IC at Texas Instruments in 1958. Robert Noyce also invented the IC almost in parallel. Noyce moved on to develop fundamental solutions for the production of the IC, such as the planar process[7], that revolutionized semiconductor manufacturing.

In its beginning the semiconductor industry was almost entirely dominated by electronics companies from the U.S.. Vertical integration was the fundament of these corporations that were striving to develop extensive and complete supply chains as control instruments over value added. R&D, manufacturing as well as sales and marketing were organizationally integrated through a high focus on the role of manufacturing in the whole system. Lüthje (2001) describes the U.S. electronics companies acquiring an increasing relative specialization and distinguishes four industry branches: the capital equipment and

[7] The key innovation of the planar process was to conceptualize a circuit in its two-dimensional projection. This view allowed to use photographic processing technologies such as film negatives to mask the projection of light exposed chemicals.

consumer electronics, aerospace and military electronics, computer industry, and telecommunications. Although initially the major share of investments in the semiconductor industry was concentrated at already established firms such as General Electric and RCA, they only cautiously moved into this new technology field, ceding the market to smaller companies (Angel 1994). AT&T, IBM, Texas Instruments and Motorola were vertically integrated electronics companies that were developing and manufacturing the components, the systems as well as the necessary software for their hardware. The vertical integration was perceived as an important market strategy that allowed to develop long-term customer relations. Customers were dependent on the initial supplier as the only provider of upgrades and extensions for systems centered on proprietary interface and technology standards.

Central for the U.S. electronics industry was a regulatory framework that allowed AT&T's telecommunication monopoly under the condition of a very licensing policy institutionalized in the Bell Labs (Lüthje 2001). This developed into a nation wide technology transfer system based on licensing, conferences as well as a very high mobility of the research personnel from Bell Labs. The extensive technology transfer opened up the access to leading edge technology for smaller companies not able to invest major financial resources in the R&D necessary for the new semiconductor and IC technology. With their R&D work the Bell Labs were able revolutionize and disseminate the fundamental production processes for an industrially organized IC production.

The U.S. electronics industry, with its very specific organization, regulation as well as technology transfer system was tightly integrated while simultaneously providing the structural gaps that allowed new start ups to develop in a quite dynamic fashion (Angel 1994). From the technological perspective it was the commercial development of the planar process that facilitated the development of specialized semiconductor companies such as Fairchild Semiconductor. These first specialized semiconductor companies marked the initial step to vertical specialization. Vertically integrated electronics companies started to source some of their electronic components from independent suppliers. However, the breakthrough of vertical specialization only occurred with the second generation of chip companies, like Intel and AMD, that started to appear at the end of the 1960s. Intel and AMD, founded by former Fairchild Semiconductor engineers, established the model of the integrated device manufacturer (IDM) and spearheaded the technological revolutions of the microprocessor and memory chips in the 1970s. These merchant chip companies promoted the standardization of previously proprietary components to enable their mass production.

The IDM integrates development and manufacturing of semiconductor devices, from simple analog ICs to digital logic ICs. The IDM are the "classical" vertically specialized chip companies acting as merchant chip companies, as their products are available on the open market. With their vertical specialization and role as merchant chip companies, IDMs are able to profit from Cost reduction through the exploitation of economies of scale. Only increasing volumes of mass production as well as long production runs allows chip companies to increase their yields through learning processes and improve their unit costs as they are able to fine-tune the initially unstable production process (Brown/Linden 2009). This learning curve translates into the situation, where the high-volume production is one of the major factors that enables low cost products.

Fabless chip companies are the second key model of the vertically specialized electronics industry (Lüthje 2007a). The design knowledge available through commercial Electronic Design Automation or EDA systems (see: 3.1.3.) combined with the development of the new Application Specific Integrated Circuit or ASIC design methodology facilitated a further vertical specialization in the semiconductor industry. LSI Logic was a precursor of the fabless design house in 1981, focusing on the design of application specific chips that were manufactured by utilizing excess capacity at Toshiba's wafer fabs.[8] As the basic CMOS process technology used to manufacture digital chips was already highly standardized it allowed for a separation between product design and manufacturing. Fabless chip companies developed in the beginning of the 1980s and saw their heyday start in the 1990s paralleled by the ascension of independent chip foundries.

Fabless chip design companies are a further step in vertical specialization as they focus only on the development and design of IC products, while sourcing their manufacturing capacities from contract manufacturers – the foundries, as well as assembly and test specialists. Companies like Qualcomm, Broadcom and Nvidia started as small niche players, for highly specialized applications. However, with the shift in end markets and the growing importance of consumer and telecommunication electronics these niches

[8] LSI Logic was a precursor of the fabless design houses as it initially had own manufacturing operations as well as proprietary design tools. However, using outside manufacturing capacity as well as making EDA tools accessible for customers sketched the future way for fabless design houses.

grew to multi-billion markets, allowing some of the biggest chip design houses to enter the top ten rankings of the semiconductor industry.

Driven by the microelectronic revolution both IDMs and design houses were remarkably successful as key models of vertical specialization. Financial markets highly valued this success and perceived the organizational forms as blueprints for future industry organization. Vertically specialized chip companies raised the competition standard for incumbent vertically integrated electronics companies in the U.S. that started to imitate the model. However, the market modularity driven by the commodification of knowledge has limits. The codifiability of knowledge is in a constant tension with technological dynamics and organizational innovations (see: 3.1.5). Arm's length relations are not providing the necessary complex and stable interfaces that are increasingly required. The levels of control are rising despite a further vertical specialization in the industry.

The industrialization and routinization of semiconductor production was fed by the emerging mass-markets in the 1960s. Profitability required the industrial organization of manufacturing and the standardization of the necessary processes. The classical linear model of production was established that allowed to break down the manufacturing process into discrete stages. Mass manufacturing was necessary to drive the technological dynamics through the ongoing stabilization of wafer manufacturing. As the interfaces between the particular process steps became stabilized and increasingly standardized, ideas of modular production leading to supplier relations and a broader geographic organization of the industry became viable. Semiconductor manufacturing was still very labor intensive. The assembly and test of chips was based on highly routine work of soldering pins to the semiconductor device by hand. Chip companies started to offshore labor-intensive manufacturing stages such as assembly operations to Southeast Asia in the 1960s. This internationalization was enabled by export oriented development strategies of Asian countries based on export processing zones. With the opening of its assembly plant in Hong Kong in 1961, Fairchild Semiconductor was the first U.S. company to establish offshore operations. Throughout the 1960s major U.S. chip companies followed suit and build up extensive networks of assembly operations in countries such as Korea, Mexico, Singapore and Taiwan (Angel 1994).

3.1.2. The state as driver in industry development

The role of the state has been essential in the development of the semiconductor industry. U.S. defense and space programs had substantial effects through both direct R&D support (DARPA, Air Force) and more importantly through extensive military procurement programs. The military market was the key market for semiconductors, until it was replaced by the markets for industry applications in the 1970s. U.S government employed also regulatory and trade policy as well as fiscal measures to help the industry thrive and overcome sector driven crises (Angel 1994). However, to illustrate the importance of state policies and initiatives in the development of the semiconductor industry, its organization as well as national upgrading processes we will turn to Taiwan.

Taiwan has come a long way in the last 60 years developing from a late comer economy to one that is based on high-tech industries. The country has been aptly described by Amsden and Chu (2003) as a "neo-development" state, that linked market liberalization with import-substitution as a new way of industrial policy. Taiwan's role as a small country latecomer and its ambitions to develop high-tech industries made high levels of international technology transfers necessary (Fuller 2002). Taiwanese industrial policy focused on multi national companies from the beginning, directing its efforts towards the access to technologies and knowledge. This was paralleled by policies that facilitated the development of dense local supplier networks that enabled the development of local lead firms.

The international integration of Taiwanese economy began with the establishment of an export processing zone in Kaohsiung in the 1960s (Lin/Trappey 1997). Just as the semiconductor industry started to offshore the most labor-intensive parts of production to Southeast Asia, Taiwan provided ample possibilities for investment, especially a low-wage labor force (Angel 1994). Kaohsiung Electronics Company, an U.S. led investment, was the first IC semiconductor assembly and packaging company in the new export processing zone. Shortly after, numerous U.S and European chip companies opened shop. With these investments Taiwan's government saw a future in further developing a local IC industry. However, local companies were neither interested nor able to venture into IC manufacturing with its huge capital expenditure requirements (Liu 1993; Fuller 2002). To facilitate the development of local wafer manufacturing the Taiwanese government had to step in and build up R&D capabilities that would allow further technology transfers as well as offer a stepping-stone for the development of local companies. The Industrial

Technology Research Institute (ITRI) was founded in 1973 by the Ministry of Economic Affairs as a government R&D agency aiming at applied research, technology transfer, new product development and consultancy services. In 1974 ITRI launched a program to develop a local IC industry by establishing the Electronic Research Service Organization (ERSO). The U.S. company RCA was chosen as the initial technology partner as it tendered a complete offer comprising design, process, manufacturing management, cost accounting as well as extensive engineering training (Chang et al. 1994).

By 1980 these successful local wafer manufacturing operations were privatized into the IDM United Microelectronics Corporation (UMC). Since then spinning-off successful R&D projects has become one of the major principles in the development of the Taiwanese IC industry. ERSO trained personnel in acquired technologies after which it allowed them to take its equipment and found private companies (Fuller 2002). Initially UMC was operating with quite outdated process technology limiting its ability to provide VLSI[9] manufacturing capabilities for the planned Taiwanese IC design projects. Morris Chang, a returnee from Silicon Valley recruited for the position of president of the ITRI, introduced his idea of a semiconductor manufacturing service supplier that was to be formed through a privatization of ERSO's already existent VLSI fab. What was later dubbed the foundry business was a revolutionary organizational innovation pushing the level of vertical specialization in the semiconductor supply chain a huge step forward. The idea to establish a semiconductor company that would not design its own chips but only manufacture them for other companies was initially perceived as highly problematic both as the market seemed too small, as well as a close link between product development and manufacturing was still regarded as important for process technology as well as product development. The fabless chip design firms, the natural customers for foundries, were in their infancy and viewed by many industry experts critically, also because design houses were highly dependent on IDMs and their excess wafer manufacturing capacities.

In 1987 ERSO spun off its 6-inch VLSI fab into the Taiwan Semiconductor Manufacturing Company (TSMC) choosing Philips as joint venture partner to acquire 2-micron volume production and improved process technology (Tu et al. 2006). For over a decade TSMC as well as other foundries that followed suite, were operating in a niche market with IDMs occupying the leading positions in the semiconductor industry both from the perspective of market share as well as technology leadership. However, as the

[9] VLSI is the acronym for Very Large Scale Integration and was the industry term for semiconductor technologies of one-micron and below.

sectoral technological and economical dynamics have shifted over time and the industry's organizational patterns have developed, foundries have become major manufacturing partners and technology providers.

The establishment of TSMC as a wafer manufacturing service provider considerably lowered entry barriers for new fabless design houses, especially for companies from Taiwan. This allowed for a highly dynamic development of fabless design companies in Taiwan that grew to around 55 companies in 1990 (Chang et al. 1994). Today Taiwan is the second most important location for fabless design houses worldwide after the U.S. The development and success of the foundry model facilitated a further development of the vertically specialized semiconductor industry.

Taiwanese IDMs such as UMC ran into fundamental problems in the simultaneous organization of design and manufacturing by the mid-1990s. At the core of their problems were the rapid innovation cycles as well as huge capital expenditures that were very hard to synchronize. The following restructuring was carried out either by focusing on lucrative niche markets with lower innovation dynamics or through further vertical specialization. In 1998 UMC transformed into a pure play foundry by spinning-off its design functions and focusing its manufacturing operations solely on foundry services. Some of Taiwan's major design houses emerged from UMC's spin-offs, such as Mediatek (see: 3.1.8.), Holtek Semiconductor, Novatek Microelectronics, AMIC Technology, ITE Technology. UMC is still a major equity holder in most of these companies organizing a so called design ecosystem.

By 2010 the foundry business developed into a major part of the semiconductor industry. TSMC, dominating the foundry market with about 50 percent market share, reported revenues of around US$ 14bn for 2010. Compared to the top ten semiconductor vendor lists, which mostly exclude foundries, TSMC would rank on third position after Intel and Samsung. The next two biggest foundries UMC and GlobalFoundries would rank among the 20 biggest semiconductor companies. The economic strength of foundries is also visible in their expansive capital expenditures. In 2011 TSMC alone planned to spend around US$ 7.8bn on capital expenditures, trailing only Intel with planned capital expenditures of US$ 9bn (Deffree 2011). However, foundries are not only investing huge amounts of money in manufacturing operations. By 2010 TSMC was reported to be among the top ten biggest R&D spenders of the semiconductor industry. This development shifts leading-edge foundries from mere manufacturing service companies towards technology providers and R&D cooperation partners. Although TSMC is still lagging behind Intel with the release of leading process technologies, the company is able to compete with other large IDMs. In the beginning of 2007 Texas Instruments announced a cooperation with TSMC that illustrated this increasing importance of foundries as R&D partners. One of the oldest and largest IDMs of the industry decided to abandon the costly development of digital process technologies and transfer it to TSMC completely. Texas Instruments will outsource the development of technologies for 32nm processes and below moving to a fabless model in its digital business (see: 3.1.6.).

Driven by the participation in global networks of manufacturing and design this functional upgrading on firm as well as sector level shifts foundries towards research intensive positions within the semiconductor value chain. For discussions on innovation this is a highly interesting development, as it clearly shows that manufacturing is not a dead end distancing companies from leading edge research. The idea that only product development is driving innovation has to be put into question as the innovation models are changing fundamentally (see: 3.1.7.).

On the national level the development of local manufacturing and design capabilities were major upgrading processes for Taiwan and its economy. The initial integration into the emerging global production and design networks of the electronics industry set the country on a development path that allowed for substantial relative changes of its position within the international division of labor. However, as the country's focus on manufacturing and manufacturing services enabled a rapid initial development it also set a development path that limited capability development within the local economy that is necessary for further upgrading. The lack of Taiwanese brand name companies translates into lower profit margins than other system companies in the electronics industry. As the first brands such as HTC are evolving and presenting possible upgrading paths it will be interesting how Taiwanese companies will be able to move further up the value chain.

3.1.3. Commodification of knowledge and increased modularization

The semiconductor industry with its high levels of knowledge dynamics has to cope with the process of constant knowledge commodification. Company and cooperative R&D efforts provide increased miniaturization through new process technology generations. Specific functionalities that hitherto only incumbent companies were able to develop as well as the design methodologies and instruments themselves become tradable goods as the complexity of systems is advancing. This process is fundamental for the development of vertically specialized companies. Fabless design houses, that focus on the development of specialized chips do not have the resources for internal design tool development. The constant shift of system knowledge requirements towards chip companies is generating a situation where also big IDM need to shift their focus and rely on commercially available design tools and IPs.

Electronic Design Automation

Developing an IC requires various design instruments that help the engineers to deal with the complexities of chips. Chips can be described as miniaturized electronic systems that today consist of up to several million components, or transistors, which are linked in specific ways to perform various functions. Through the history of the semiconductor industry the design and the verification of design experienced an increasing automation. Electronic Design Automation (EDA)[10] are software tools that enable IC design and verification engineers to handle the growing complexity by both rising the abstraction level on which they work as well as making specific bits of complex knowledge available in form of software algorithms.

Layout, the last steps of IC design before manufacturing, was the first design task in the focus of automation efforts. Chip layout, or the physical design, is a tedious task that mostly does not call for creative engineering work but consists of transforming of the existent design into specific physical representations. The functionality of an electronic system is in most parts determined by the design of its circuitry not the circuit's physical design, leaving room for variability of the systems final layout.[11] Initially physical design tools were developed mostly as internal tools by big system companies like IBM or the emerging merchant chip providers. In the early 1970s the first independent design tool companies emerged offering tools that were focusing on physical design. Calma, one of the first generation EDA companies, still influences the IC industry as it provided a de-facto standard widely used until now. Its GDSII (Graphic Data System) layout design computer systems established the GDSII format, consisting of all necessary layout information, designed to control IC photomask fabrication. The commercial availability of this format allowed for data transfers between the design tools of different chip vendors that operated with proprietary data formats and were one important facilitator of vertical

[10] EDA is often described as complex toolboxes of Computer Aided Design (CAD) tools for the design of electronic systems.

[11] This is true for digital ICs. As we will see in the part on analog design, layout and the material structure of the chip can have fundamental influence on the chips workings.

specialization. The first EDA companies were system vendors, developing both the hardware workstations as well as the proprietary design software. This integrated model proved to be too expensive and slow to keep up with the technological dynamics of the technology development. While in the 1980s an increasing number of independent EDA companies were offering commercially available design tools, Mentor Graphics was the only one to specialize only on EDA software development.[12] The company did not have to invest engineering and financial resources in hardware development. From the perspective of vertical specialization it is very interesting, how the emergence of a fundamental part of the modularized IC development value chain is linked to a further specialization within the only just established design automation sector. Mentor Graphics is the only survival from the 1980s becoming, one of the so called big three of EDA, besides Synopsis and Cadence.

Throughout the last 30 years commercially available EDA has rapidly increased in importance both as process technology development is moving on as well as the IC industry is becoming increasingly organizationally modularized. The emergence of complex EDA systems facilitated the development of independent design houses. The de-facto standards that govern the design within the specific EDA tools enable the organization of design in a much more modular fashion, as designers both in different locations and different organizations can exchange highly codified information. Although EDA software is very expensive, with license costs that can exceed several hundreds of thousands of US$ per year per engineer, it offers independent design houses the access to automated design knowledge without the need to support own design automation departments.

EDA tools are a way to codify complex information to make transactions possible over organizational as well as spatial distances. However, as the innovation dynamics of the semiconductor industry are quite high this is a constant process that is not developing permanently in the same direction. Industry wide developments increasingly limit modularization driven by codifiability. Design for Manufacturing, or DFM, is describing the technical problems that occur in modularized design and manufacturing supply chains. As process technologies become smaller designs need to become aware of problems in manufacturing. This knowledge flow needs to be organized and is quite problematic as foundries need to open up the access to their process technologies. Furthermore, the

[12] From a technical perspective the 1980 saw a broadening of automation from layout towards synthesis and verification.

increasing alignment of EDA tools with foundry specific process technologies can develop into a barrier of modularization. The codifiability of information is being raised considerably while simultaneously transaction specific investments for the design company are growing. To be able to source from two different foundries design houses need to port their designs to match the different process technologies and design software standards.

Perceived from the perspective of design work EDA companies are translating specific parts of engineering knowledge into complex software algorithms that form the base of their EDA systems. This objectification of knowledge through automation cannot be easily grasped with notions of deskilling and control (Friedman 1977). This ambiguity of design methods and automation on engineering work has already been described for software engineering by Beirne et al. (1998). The development of EDA systems is a process of abstraction where the design of ICs is increasingly moved away from the fundamental building block – the transistor (Sangiovanni-Vincentelli 2003). To be able to deal with the increased number of transistors IC, that process technology development is making available, designers need tools for translating their functional concepts onto the transistor level in an automated fashion. These shifts in technical knowledge consist of a parallel process of objectifying knowledge and creating an imperative to acquire new knowledge about both new software based tools as well as new design approaches. Engineering skills are also shifting, as the complexity of IC design projects is increasing, the technical ability of engineers has to be augmented by organizational capabilities to be able to work in increasingly bigger projects with various other technical and functional fields. The imperative of new knowledge is also driven by the dynamics in the roles that chip suppliers and system companies have in system development. With its ability to integrate almost entire systems on a single chip, System on Chips or SoCs have shifted the place of system design at least partly towards chip companies. This technical possibility is amplified by the ongoing restructuring of value chains, where system companies are narrowing their focus on core capabilities, increasingly pushing major parts of systems development to their chip suppliers (see: 3.1.7).

Semiconductor Intellectual Property – re-using knowledge

The ongoing miniaturization of transistors facilitates the development of increasingly complex electronic systems. The so called SoC, or system on a chip, design methodology (see chapter 3.1.5) is based on the idea that a complete system, such as a mobile handset, can be put onto a single chip. Development of such complex chips is based on semiconductor IP (SIP) to both lower costs and make the complex task of such system development possible. SIP blocks, or functional blocks, are sourced from third-party suppliers allowing the chip company to focus on the development of differentiating functions and the final integration. SIP blocks represent specific functional parts of a SoC design such as processor core, memory or interconnect cores previously integrated as separate chips.

From a knowledge perspective SIP blocks are a specific form of commodified knowledge. Where EDA is enabling the diffusion and general usage of specific design related knowledge, IP blocks allow companies to source electronic functions for their future systems. A fundamental concept in SIP based design is the re-use of both in-house and third-party SIP blocks, through which cost of design can be lowered considerably (Chang et al. 1999).[13] Rationalizing chip design through higher levels of re-use requires chip design companies to build up consistent in-house SIP re-use methodologies and standards, thus directly influencing changes in the organization of work.

Third-party semiconductor IP does not involve the transfer of ownership but is based on specific licensing fees or royalty payments (Tuomi 2009). Additionally, SIP providers also offer complementary services such as technical support, training, customization and development tools. The semiconductor IP industry does not have a single business model as various companies offer IP blocks. Foundries increasingly offer semiconductor IPs to both enable a smoother design hand-off as well as tie their customers to their specific process technology. These in-house and third-party SIP cores and standard cell libraries are often available for foundry customers without license and royalty fees, leading to extreme pricing pressure on independent SIP providers. Similarly, EDA companies offer SIP blocks as so called add-ons for their EDA systems. Commercially available IP blocks are offered by independent SIP companies, but also increasingly by IDMs and design houses, which license their in-house SIP blocks. Most SIP companies provide blocks of highly commodified nature, i.e. on chip functions that do not provide a differentiation for chip companies. Relying on SIP blocks is in line with the increased focus of major chip companies on core capabilities and parts of the production process that allow for high

[13] The idea of re-use is not new to the chip industry. Already in the 1980s the standard cells design methodology developed for the design of ASICs was based on the ideas of standardized modular design and re-use. However, standard cells were only the basic building blocks used to design specific on-chip functions. The abstraction level of IP block based design is much higher, allowing for the design of much more complex systems.

value add and high profit margins. Companies can focus on the development of IP, either on silicon or software level, that will help them to develop differentiating functionalities.

However, the use of silicon IP is not working in such a smooth way as the industry has hoped for. The development of SIP is based on complex EDA software systems that allow for relatively high levels of automation. But the process of qualifying and integrating third-party IP is still lacking extensive automation, rendering productivity gains smaller than expected (Wilson 2010). SIP deployment is very often characterized by high levels of manual engineering work, underscoring the importance of the interface between SIP supplier and chip company. Although on chip interfaces are relatively well standardized, question regarding performance of third-party SIP remain fundamental. Quality management becomes a central issue, affecting directly the labor process of engineers through standardization requirements.

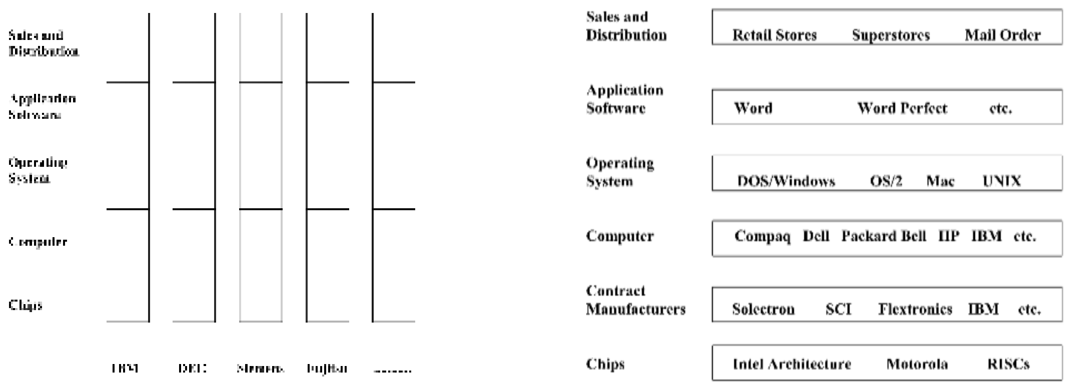
As the qualification of SIP is not well automated, engineers would either need to laboriously check performance and specification consistency or simply trust the supplier. Both strategies are not blindly acceptable for chip design projects that range in the tens of millions of US$. The build up of trust through long term relations between supplier and chip company are one way to cope with this problem. Interpersonal relations between the design engineers of both companies are important as they allow for easier communication. Direct integration of the SIP supplier into the design team is yet another possible strategy. Chip companies are tied to their suppliers in a much stronger way than the idea of a highly modularized arms-length market relationship for silicon IP based chip development was promising. Changing IP providers in a constant manner from project to project would limit cost savings enormously as trust relations could not lower the need for IP qualification on the side of the chip company. IP providers, mostly small to medium companies, are facing a much more difficult situation. They need to invest major parts of their resources to develop and maintain customer relations. Although these provide revenues they simultaneously limit resources required for product development.

3.1.4. Geographical and organizational dynamics of the electronics industry

Overall dynamics of the electronics industry and end user markets influence the organizational and geographical developments of the semiconductor industry. Processes of vertical specialization and new specific forms of integration on the manufacturing end of the value chain, transform the innovation interface as system companies shift increasingly away from system design. The geographic organization of the electronics industry is changing as both production locations and key markets are shifting towards Asia. Contract Manufacturers, or companies providing so called Electronic Manufacturing Services (EMS) as well as Original Design Manufacturing (ODM) are a result and major driver of these developments.

The roots of the EMS industry can be traced back to the 1980s when specialized companies like Intel, Microsoft and Cisco started to become increasingly important. Focusing on key components of the PC they contradicted the traditional model of innovation and market control. This led to a massive shift in the industrial structure as they extended vertical specialization towards the whole electronics industry. The traditional model of vertically integrated production, centered on the control of the various key elements of the computer systems through proprietary standards, was superseded by new more modular production system. Based on open but owned quasi-standards defined by Intel’s x86 microprocessor architecture as well as Microsoft‘s DOS/Windows software, entire systems such as PCs could be assembled using standard components such as microprocessors, memory, motherboards, disk-drives, displays and operating systems (Cusumano/Gawer 2002). This modularization lead to the development of the “horizontal computer industry” (Grove 1996; see: Figure 2.1.) where the various parts of the whole value chain developed into vertically specialized industries, integrated by increasingly complex global production and innovation networks.

Figure 3.1: The dynamics of industry organization



The vertically integrated computer industry (ca. 1980)

The vertically dis-integrated computer industry (ca. 1995)

Source: Grove (1996)

Borrus and Zysman (1997) coined the term Wintelism to describe this specific model of production and innovation. It involves more than plain vertical specialization, as firms located somewhere in the disintegrated value chain developed the ability to define terms of competition and restructure innovation through their control over the evolution of key standards. This potential is not anymore linked to the ownership of assets of production. Wintelist innovation systems formed the basis of the restructuring of production within global networks of production and lead to the disintegration of the industry's value chain into discrete functions. These functional blocks, or production steps, can then be contracted out to independent producers located somewhere in the global economy. In the 1990s, the heyday of Wintelism, formerly small companies specializing in assembling printed circuit boards grew into multibillion enterprises with global operations. They are performing integrated manufacturing services through turn-key production networks (Sturgeon 1997), ranging from systems manufacturing to components purchasing and inventory management, global distribution and logistics and after-sales and repair services (Lüthje et al. 2013). Foxconn and Flextronics are today the two biggest EMS companies, with revenues of billions of US$. However, as the EMS companies are focusing on manufacturing their profit margins are both very low as well as highly precarious.

The restructuring of the electronics industry and the financial market driven concentration of OEMs on their core capabilities, called for an extension of production capabilities on the side of EMS companies. This went far beyond the manufacturing capacities acquired from OEMs as well as beyond traditional production locations in the U.S. and Europe. EMS companies started to build up advanced manufacturing locations in Asia, Mexico and CEE. China with its very low cost structure, specific institutional framing as well as an initially shear infinite work force was the location where the main investments of EMS companies were directed to.[14] Through the development of a differentiated location structure EMS companies created low-cost, mass production capabilities on a global scale and enabled OEMs to organize parts of their production activities in form of a "one-stop-shopping" (Lüthje et al. 2002).

The crisis of the electronics industry 2000/01 led to a restructuring of the EMS industry through the relocation of production to China as well as industry level centralization and integration. The crisis driven geographical as well as structural shifts were amplified through the growing importance of the ODM contract manufacturing

[14] The fast economic development of China based mostly on manufacturing operations has led to a fundamental change in the labor market situation. Now increasingly labor shortages characterize the situation in the developed regions of China, causing major social frictions as well as driving wage levels.

model. Original Design Manufacturing goes beyond providing manufacturing services by enabling system companies to source out product development. Taiwanese contract manufacturing companies developed this model in the notebook market already in the late 1990s. With product portfolios growing and product life cycles shrinking system companies increasingly faced problems to keep up with competition on product markets and to fulfill demands of financial markets for profit growth. Sourcing out the development and manufacturing of parts of their product portfolio, mostly entry level systems, allowed OEMs to focus their resources on leading edge products with higher profit margins.

On the geographical level the growing importance of Original Design Manufacturing entailed a further shift towards Asia, as ODM companies have most of their operations in Taiwan and China. With ODM not only manufacturing but also product development is moving to Asia. Hence chip companies also have to refocus their development interfaces and design operations towards this region. EMS and ODM have expanded the focus of the whole electronics industry towards the global level, developing global networks of manufacturing and design by integrating low-cost locations into the developing international division of labor. With the rise of China in the last ten years the focus of the industry has shifted definitely towards Asia, where the most important manufacturing locations and important innovation interfaces as well as new and important key markets emerge.

Market shifts and changing product characteristics

Since the 1960 the semiconductor industry has seen a gradual but fundamental shift in its end markets. The U.S. defense sector was the initial focus market with around 70 percent of the industry's production. By mid 1960s the end markets diversified as both corporate and consumer electronics grew in importance (Tuomi 2009). Corporate computing remained the main market until the 1990s, driving technological innovations focused on performance improvements. Initially mainframes and later also PCs and servers were the dominant markets for the semiconductor industry, putting memory and multi-purpose chips, such as CPUs and MCU[15], in the center of attention. Since the 1980s

[15] The Central Processing Unit (CPU) is the heart of every computer or other processing devices. Microprocessor CPUs carry out the instructions of a computer program. The most renowned CPUs are based on Intel's x86 microarchitecture. The Microcontroller Unit (MCU) is a small computer on a single integrated circuit comprising of processor core, memory and input/output peripherals. MCUs are designed for embedded applications.

the consumer market is growing in importance. In the mid-1980s consumer market accounted for around 30% of the semiconductor consumption, while the corporate market had around 60% shares, while the government market was at around 10%. By 2005 the consumer market share has grown to more than 50% while the corporate market fell under 45% (Brown/Linden 2010). This shift of end user markets was paralleled by a growing diversification of markets. While until the mid 1990s the PC was the most dominating market segment, the last 15 years saw its relative decline as mobile phones, MP3 players, digital cameras and other digital consumer devices became ubiquitous (Macher et al. 2007).

The shifts of end user market in the last 40 years have fundamental implications on the level of market dynamics as well as technical requirements. Tuomi (2009) notes how the initial shift from military to corporate markets resulted in a rapid price deterioration, as the new markets had a much higher price sensitivity, while they simultaneously offered rapid growth of market size. Today, the increasing dominance of the various consumer electronics markets is driving the average prices further down, while again expanding the total available market. In historical perspective these market shifts had adverse effects on average profit margins, despite the still existing high profit margin opportunities for first movers. Market differentiation as well as rising market competition facilitate the tendency to lower profit margins additionally. The high price sensitivity in consumer markets is paralleled by decreased product life cycles. The time before a new model is introduced has constantly shortened. Mobile phones, currently the most dynamic growth market for consumer electronic systems, have seen product life cycles reduced from around two years to currently less than 8 months. This is putting system and chip companies under stress to be able to develop new products in time and to generate enough sales to stay profitable.

The increasing vertical specialization within the electronics industry lowered the barriers of entry for newcomers both on the system as well as chip level. The markets became thus more and more fragmented, rising the risks for new product development constantly as the competition for the fast changing chip slots in the systems is growing. During the PC revolution, general purpose chips allowed for the ability to generate high and quite stable premiums for companies like Intel or AMD. As consumer electronics are not based on the Wintel standard but the particular system companies try to differentiate amongst others through various standards, chip market are becoming fragmented.

The shift in the organization of manufacturing and product design as well as the growing importance of consumer electronics markets put chip companies under pressure making organizational innovations necessary. The ongoing growth of product development capabilities in Asia, mostly due to ODM as well as new genuinely local Asian system companies, are forcing semiconductor companies to internationalize their development to be in close contact with their customers. As Asian markets for consumer electronics, with their specific demand characteristics, become more important chip companies need to gather more knowledge to be able to offer adequate products.

3.1.5. Technology dynamics – costs, differences, opportunities and draw-backs

In his seminal article "Cramming more components onto integrated circuits" Gordon Moore (1965) made some observations regarding the development of semiconductor manufacturing that would later come to be called Moore's Law. Moore's Law has two aspects: first, it states that about every two years the developments of semiconductor process technology double the amount of transistors that can be integrated into the same space on a silicon wafer. This miniaturization through the ongoing downscaling of transistor size enables increasingly complex ICs. Second, and more in line with Moore's original statement is the financial aspect: the cost per transistor that can be used for an IC is being lowered constantly. Moore's observation was and still is a benchmark that the semiconductor industry is striving to reach. The Technology Roadmap for Semiconductors was established as a framework to organize and align technology development within an increasingly vertically specialized industry. With the International Technology Roadmap for Semiconductors (ITRS), defined by several hundred semiconductor companies, this planning and control have been internationalized since the late 1990.

The production of chips is a highly complex process that involves several hundred of different production steps. Front-end manufacturing is focused on the creation of electronic circuitry on a silicon wafer, while back-end manufacturing takes the finished die and assembles it into a protective package with necessary connections and tests its functioning. Front-end manufacturing is more complex and more capital intensive. Photolithographic techniques are used to transfer transistor patterns from masks[16] onto the

[16] Photolithography uses light guided through masks as its main transmission tool. In its most basic understanding it shares some principles with photography as the pattern on the etching resist

wafer surface while chemical and mechanical treatments are used to engrave layer by layer the material structure of the future chip. Photolithography equipment is one of the most important parts of front-end manufacturing. Advances in photolithography are at the central focus of the industry to be able to follow Moore's Law consistently.[17] This equipment is a major driver of fab costs. Typically photolithographic equipment accounts for around 20 percent of the fixed costs of an advanced wafer manufacturing facility. Complex chips are made with up to 30 mask layers and need several weeks to process from start to finish (Turley 2003). These steps need to be carried out in highly controlled clean rooms as single dust particles can damage a wafer.

Besides transistor density, wafer size is an important factor in the economics of semiconductor fabrication. The silicon wafer on which chips are manufactured are round slices of silicon material holding from several to thousands of raw chips depending on the size of the wafer as well as the size of the chip. Since the beginning of semiconductor manufacturing wafer sizes have grown constantly, to increase throughput and reduce costs. Larger wafer sizes allow more chips on their surface lowering the costs per chip considerably. The last shift in wafer sizes occurred in 2000 when 12-inch (300mm) wafers were introduced and started to replace 8-inch (200mm) allowing for a 2.5 increase in wafer area.[18] However, these gains in cost reduction require huge and constantly growing investments.

Semiconductor manufacturing is characterized by economies of scale and processes of learning through experience (Brown/Linden 2009). These two factors are constantly driving the scale of wafer fabs that manufacture chips using the most advanced process technologies. The rising cost of manufacturing equipment as well as the need for increasing size of the manufacturing operations translate into a cost explosion for semiconductor manufacturing. Although unit costs go down, the fixed costs for so called leading edge gigafabs, that are able to process more than 50,000 wafers per month, have

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applied onto the silicon wafer is created through its exposure to light. These patterns then are uncovered by chemical etching.

[17] These advances are of overwhelming technical complexity. Current state-of-the-art photolithography tools use deep ultraviolet light that has wavelengths of 245nm and 193nm. This requires the development of intricate techniques to be able to manufacture transistors that have a size of 45nm.

[18] The next step will be the transition to 450mm, or 18-inch wafers. However, as the costs for equipment are exploding only a very small number of industry leaders will be able to generate enough revenues to offset the enormous investment costs. This is making semiconductor equipment companies wary, as both the risk to develop and market such tools is rising while the total available market is shrinking considerably.

skyrocketed. To operate such a wafer fab with a profit extreme manufacturing volumes are required to offset the incurred costs. Table 3.1 shows how the costs for building a leading-edge fab have developed over the last 25 years. In 1983 a leading edge fab required an investment of around US$ 200 million. To be able to build an advanced fab of minimum efficient scale a company had to invest around US$ 5 billion in 2007.

Table 3.1. Rising costs of building leading-edge fabs, 1983-2007, in US$

Year	1983	1990	1997	2001	2007
Wafer (inches in diameter)	5	6	8	12	12
Linewidth (microns)	1.200	0.8	0.250	0.130	0.065
Cost (US$ million)	$200	$400	$1,250	$3,000	$5,000

Source: Brown/Linden (2009)

The cost explosion is not only limited to building leading-edge fabs, but affects the whole semiconductor industry, from research to manufacturing. Table 3.2 comprises the cost development of three main R&D steps of the semiconductor industry linked to three different process technology generations.[19] The development costs for a new process technology have doubled between 2006 and 2010, reaching now around US$ 3 billion. Developing a process technology does not include the ownership of a fully equipped wafer fab. Costs for chip design and masks are important indicators for market entry barriers for fabless design houses. Although these companies do not need to invest in manufacturing operations and the corresponding process technologies, their costs for a single design project are also rising fast. Mask costs are an important proxy for risks in chip design linked to design re-spins. As the complexity of ICs is rising, the possibility is growing that a design flaw is discovered only after mask production. The resulting design re-spin can translate into costs ranging in the millions of dollars.

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[19] Process technology generations in the semiconductor industry are generally described by the average length of a transistor gate that can be build with this technology. Since the early 1990s this average length is in the nanometer range, where a nanometer (nm) is a billionth of a meter. At the time of writing leading edge semiconductor process technologies used in mass manufacturing are on the 45-nm node. However, the ramp-up of process technologies that allow finer structures is ongoing, with 28-nm technology nodes being the state of the art in 2011. Products manufactured using 32-nm process technologies started to be shipped by Intel in the beginning of 2010.

Table 3.2. Rising costs of semiconductor R&D, in US$

Linewidth (in nm)	65	45	32
Process R&D costs (in US$)	1.5 billion	2.4 billion	3 billion
Chipdesign costs (in US$)	NA	20-40 million	75 million
Mask costs (in US$)	3 million	9 million	NA

Source: EE Times, Synopsis, VLSI Research and own data

The extreme costs for process R&D have pushed the semiconductor industry towards a specific mode of innovation, which is tellingly termed by some industry analysts as coopetition. Although R&D alliances have been known for some time in the semiconductor industry, the extent of the alliances seen in the last 10 years has a new dimension. Competing companies are working together on design related topics as well as in specific areas of fundamental research but in the development of specific process technologies, which all partners will put into use in their manufacturing operations.

One of the first major R&D alliances between IDMs with this new characteristics was Crolles II, which evolved out of an initial alliance between Philips Semiconductor and ST Microelectronics in 2002. Motorola's Semiconductor Division (now Freescale) and TSMC later joined Crolles II. The aim of Crolles II was the cooperative development and ramp-up of digital CMOS process technologies for the 90nm technology node and below. The interesting and new feature in this R&D alliance was the development of a common design platform. In 2005 the alliance went even further and created a high-level SoC IP block library to enable the re-use of specific blocks. However, in 2007 the Crolles II alliance split, partly due to restructuring at NXP, the former Philips Semiconductor division. ST Microelectronics and Freescale joined IBM's common platform group.

The IBM common platform group evolved out of a cooperation between IBM and Chartered, a foundry from Singapore. In 2002 IBM started to offer foundry services and planned to align its 90nm process technology with that of Chartered to be able to offer mass-production and second sourcing capabilities. In 2003 the German chip company Infineon joined the process development platform to participate in the development at the 65nm technology node. After the breakup of Crolles II, ST Microelectronics and Freescale joined the development alliance. Infineon, ST Microelectronics and Freescale are joint development partners taking part only in the technology development and then transferring the results into their own fabs. Chartered, which is now part of GlobalFoundries, as well as Samsung form the manufacturing alliance that provides almost completely aligned process technologies among three companies. To be able to organize the interfaces between design and manufacturing such as tools and libraries, an extensive ecosystem has been developed by the common platform group, consisting of EDA companies, IP providers as well as packaging and test service providers.

Digital and analog – two different sides of semiconductors

The summarized economic issues and organizational dynamics of semiconductor manufacturing apply in their most striking characteristics to the production of digital ICs. However, the semiconductor industry is also concerned with the design and manufacturing of analog and mixed-signal ICs that face different problems. Analog and mixed-signal devices are often used as interfaces between the analog world of e.g. speech and the digital area. Sensors are an important part of analog devices allowing for the translation of real world information into digitally processable signals. Analog chips are also important for the regulation of power allowing to lower the power consumption of electronic devices. This is essential for the increasingly complex mobile, as well as stationary devices. The next generation power infrastructure, called smart grid, requires analog devices to both control and regulate power production, distribution and consumption.

Digital components are based on the basic difference between one and zero, where 1 denotes a flowing current of electricity and 0 stands for no current. Digital transistors work in a way like on-off switches. Computers are based mostly on these digital or logic components. In contrast analog components treat electricity as a continuously variable stream, their function is in smoothing, shaping and modifying the electricity that is passing through them (Turley 2003). As in analog circuits variances cannot be distinguished from the signal itself, miniaturization in a similar fast pace as in digital process technologies is limited. Shrinking the components always results in various issues linked to phenomena of electronic currents such as noise and impedance, which are negatively influencing the signal. It requires then a constant readjustment of the interference relations between the various parts of the chip to stabilize the whole functionality of the device. These complex interdependencies renders analog chip design the most demanding form of chip design and being often called black magic of chip engineering.

"[Analog is] tough because it's unpredictable. It's not like in digital, where you can draw a truth table or different other approaches to predict how the design you are building will behave. Now designers are not using truth tables on paper, they have synthesis machines and software and stuff like that. Nevertheless the behavior is somehow predictable, you can simulate very early with the computer how the design will look like. In analog it is not quite like this, because from the start we have a lot of effects, of loops, of feedback, everything is influencing everything. We cannot build something and then put together with something else and hope it will behave like when it was alone. No, it will influence everything around and will be influenced by the environment. Building a very complex analog system is very tough. And we cannot match the complexity of microprocessors in digital. (Senior Analog Design Engineer – BuDC)

Analog devices are produced in process technologies that are few generations behind leading edge digital CMOS technologies. This is the result of problems in shrinking analog circuitry, as well as the fact, that required performance levels can be met with 'older' process technologies. The result of the much slower pace of process technology development translates into much lower capital expenditure requirements. Additionally, analog devices are produces in more specialized process technologies than CMOS, the staple process technology of the digital field. The link between analog process technology and design is much closer than in the digital field, as signal integrity is influenced by the material structure and physical properties of the technology. Here, market competition as well as differentiation still lie as much in design capabilities as in process technology innovation. The tweaking of process technology into highly specific characteristics that enable better product quality or peculiar functionalities, is an important technical capability for the analog chip market. Organizational integration allows to communicate the necessary knowledge about the specifics of the process between manufacturing and chip design more efficiently.

The complexity of a device is both important to be able to assess how developed the technical capabilities of a certain company or design center are. For digital ICs measuring the complexity is quite straightforward, based on two main factors. The number of so called gates[20] on an IC is indicating the level of integration of various functions onto a single device. The technology node – e.g. 40nm, 32nm or 20nm – in relation to the current technological development stage, is the most widely used measure for complexity. For analog ICs the measurement of complexity is far more complicated. Although the number

[20] In digital chip design gate or logic gate, denotes the most basic function put together through linking several transistors. Out of only four different available logic gates highly complex systems such as microprocessors can be designed through linking them based on Boolean logic into specific complex functionalities.

of integrated functions can also indicate complexity, devices which might seem to be less complex due to their size and technology node, can require much more knowledge to design and manufacture. As in analog ICs the various parts on the silicon are interfering with each, other the ability to limit these interdependencies is a complex design task. Also many analog ICs are being deployed in extreme environments, such as the engine of a car, or its brakes. The design and manufacture of an IC that will be able to work in temperatures between 180°C and -40°C reliably for many years is a highly complex task. If one takes into account the fact that some of these systems are critical, it is quite obvious that complexity in analog devices can not only be measured by gate numbers and technology nodes.

Design automation – its limits as drivers of internationalization

The differences between analog and digital ICs in manufacturing are also present in chip design. Although a highly complex task, involving knowledge from different fields, the design of digital circuits is often described as somewhat of a Lego construction kit, where complex functions can be quite easily developed by linking various components together. This almost mechanical design procedure[21] allows for high levels of automation based on EDA tools (see 3.1.3), necessary to be able to cope with the ever increasing number of available transistors on the same silicon wafer. Analog chip design on the other hand is often described as black magic, involving intricate knowledge about both specific design strategies and choices as well as about how these will be affected by the specifics of a particular process technology. The automation of such highly experience based knowledge is much harder, hence analog design is the least automated field of chip design. Various automation efforts have already been undertaken, however the poor quality of results exceeded the possible cost reduction through automation.[22] This resistance to automation of analog chip design translates into some peculiarities in industry organization as well as a much more artisan work and work organization.

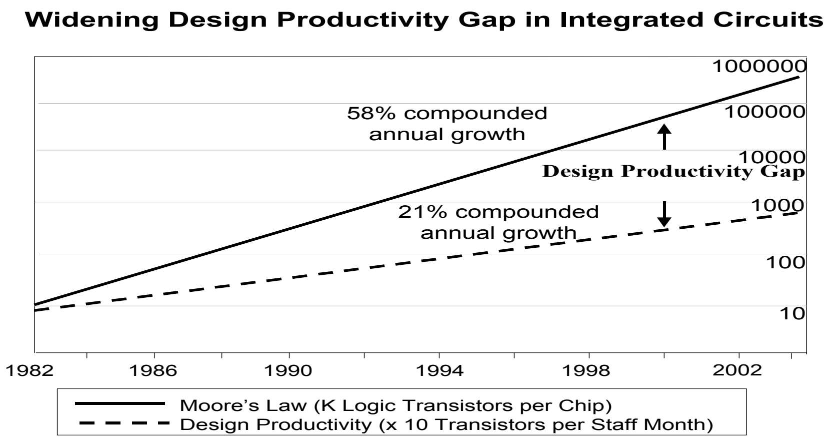
Although the automation of digital chip design is developing since several decades it is always in tension with the ongoing miniaturization. This tension has increasingly developed into a fundamental problem termed the design productivity gap (Figure 3.2.).

[21] Of course designing digital ICs is far from an easy and mechanical task. However, for the sake of the argument we need to abstract from the complexities involved.

[22] The results of automated digital chip design are also inferior to custom digital design – have a lower performance and are bigger. However, the incurred quality and cost drawbacks are more than compensated by the productivity gains of automated chip design.

The productivity of semiconductor manufacturing has been growing in the last two decades with a compounded annual growth rate of 58%, while the design productivity has only developed with a compounded annual rate of 21%, leaving a huge gap between the possibilities provided by process technology and the ability to use them in chip designs economically. This design productivity gap already surfaced officially in 1997 in the ITRS (Rowen 2004) but was covered up by the New Economy boom.

Figure 3.2. Design Productivity Gap



Source: International Technology Roadmap for Semiconductors 2002

The semiconductor industry has developed several rationalization strategies to cope with the costs as well as organizational issues. The increased level of R&D cooperation in process technology alliances as well as the extensive use and development of EDA tools were already mentioned. The internationalization of work, both through outsourcing and offshoring, is a way in which the industry tries to close the productivity gap by tapping into hitherto unused talent sources providing cheap engineering work. The internationalization strategies of semiconductor companies vary strongly – from attempts to realize the idea of design factories in low cost locations and the build up of a complex structure of offshore design labs, to very focused and long-running internationalization strategies that enable the build up of local human resources and a firm local ecosystem. A considerable part of design work is increasingly outsourced to third party companies driving the internationalization of design work even further. Although chip design work is not only outsourced to Asia, the design service industries in Taiwan, India and China have seen enormous growth during the last several years.

However, this increasing modularization is gradually limited by its very own enablers and drivers. As the development of technology in the semiconductor industry is moving forward, considerable problems of so called design for manufacturability, or DFM, emerge. The separation of design from manufacturing was based on the idea that these are two different processes that can be linked by standardized interfaces. As the development of process technologies moved on towards the deep sub-micron era[23], specific design choices require deeper knowledge about the process technology in use, to limit design related defects (Hutcheson 2007). Only in this way chip companies are able to keep yield rates on profitable levels. This problem calls for a much better and more systematic development of inter-organizational interfaces, that allow to transfer this kind of knowledge between the foundries and the chip design houses. However, this kind of information potentially allows to learn more about the characteristics of process technologies than acceptable for foundries. This is one of the driving forces behind increasingly proprietary formats of foundry data, that is at least in parts locking in their customers, making second sourcing strategies more costly.

Rationalization through design methodologies revised

The development of new design methodologies, the way in which the chip design process is being organized, is another major rationalization strategy of the semiconductor industry. An early major step to rationalize chip design was the ASIC design methodology in the 1980s (Chang et al. 1999). As miniaturization moved on, new possibilities emerged in the late 1990s subsumed under the concept of System-on-Chip (SoC). The idea of SoC was to combine onto one single chip the various subsystems that make up a specific electronic system previously integrated on a printed circuit board. One of the main pillars of this paradigmatic shift in design methodology, or „SoC Revolution“ (Chang et al. 1999), was the idea of re-use. Although the ASIC design methodology was already based in some parts on re-use it was only working on a very basic level. With the SoC design methodology re-use was shifted to a much higher abstraction level – the level of components. SoCs are designed through the integration of blocks of IP, or complex virtual components, such as processor cores, memories, Bluetooth, and other functionalities on one silicon die. The different IP blocks can be used for the design of various SoC products, transforming IC design to a seemingly simple process of stitching together pre-

[23] Sub-micron designs are designs far smaller than 1 micron. Mostly designs in the 90nm node and smaller are grouped together under this term.

designed standard components. The SoC design methodology promised substantial increases in the automation of chip design and a transformation of the organization of engineering work. Ideas of an industrial organization of chip design emerged, based on a strict division of labor with hopes of huge savings in engineering labor costs. However, as we have seen (in 3.1.3) the integration of IP is not as easy and automatable as planned.

The SoC design methodology resulted in very big chip design projects that expanded the complexity of design tasks and project management problems. Technical issues occurring in the design process stretch from architectural decisions, regarding the partitioning between hardware and software implementation, to almost unmanageable verification complexities due to exploding transistor numbers. The sheer size of these SoC design projects broadened the already strained schedule and time to market issues of chip design projects, especially as products in development were targeting consumer electronics markets with their ever reducing product life cycles. The doomsday scenario „building the chip wrong“ was expanded by problems of „building the wrong chip“ (Rowen 2004). Thus verification became one of the most important design processes.

Another way of coping with the design productivity gap is to broaden the range of possible applications in which IP blocks can be re-used. Similar to the car industry, chip platforms focusing on mobile communication, consumer electronics or automobiles, allow building a number of different products using the same IP blocks. Although the development of application platforms is a very expensive task, NXP spent around US$ 1 billion for the development of its Nexperia platform (Arensmann 2004), a chip platform considerably raises volume levels and the stretches product live cycle of the architecture, enabling to easier set off the very high initial development costs.

Both SoC as well as platform design methodologies are rising the abstraction level of chip design up to the point, where semiconductor companies are increasingly becoming involved in system development and design. (see: 3.1.7). A very instructive example of this shift towards system knowledge are reference design kits (RDK). Initially RDKs were used by chip companies to sell the components used in the design. Although the term RDK is quite ambiguous in the industry, it typically refers to an almost completely designed system, e.g. a mobile handset, that a chip company is offering its customers to enable operations and tests of the chip company’s components on a running system (Cravotta 2007). RDKs are costly to develop, limiting both the amount of RDK a single company can offer as well as the possibility for small companies to offer them at all (see: 3.1.8).

The SoC and RDK give evidence to a growing need put forward towards chip companies to deliver solutions, instead of single components. This development is driven by the technical possibilities provided by increased miniaturization, the development of industry organization driving further specialization on top of global design networks, as well as economic pressures that system companies face. Although solutions, i.e. complex components, are prevalent in the digital field, analog chip companies gradually are required to provide solutions that go beyond single components.

3.1.6. Fab-light and the disposal of manufacturing capabilities

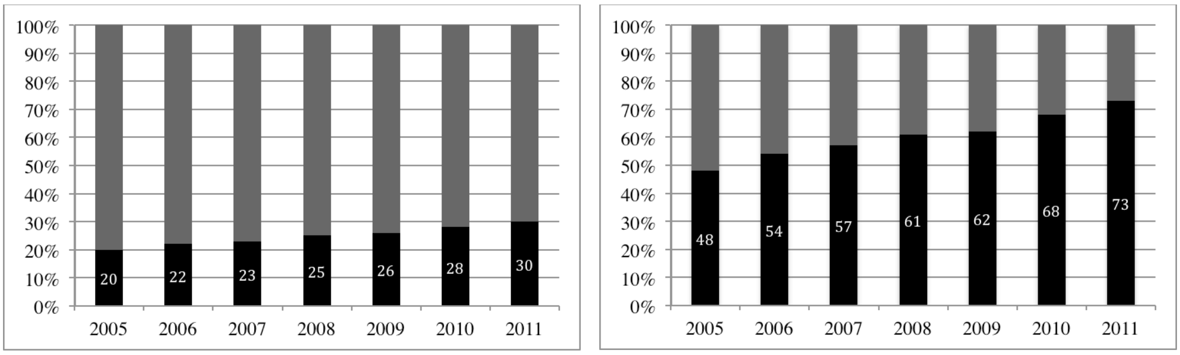
Since AMD founder's Jerry Sanders formulated, that "real man have fabs", both economic limits as well as technical and structural possibilities have changed the entire landscape of the semiconductor industry. Between 2005 and 2009 average selling prices of chips were falling by around 2.8 percent per year, while the global market grew between 2004 and 2009 by only 1.1 percent (Clarke 2010a). The financialization of the chip industry was nevertheless developing, with private equity firms entering the market. One of the major deals was the take over of Philips' semiconductor business by a consortium of private equity investors, consisting of Kohlberg Kravis Roberts & Co. and others. With private equity firms cost awareness grew even more, as high capital expenditures lower profit rates and the cash flow. The already discussed extreme financial resources necessary to operate leading edge manufacturing facilities mark an increasing fundamental problem for mid-size companies. Only companies like Intel and Samsung with revenues around US$ 40 billion and US$ 32 billion respectively in 2010 are able to set off capital expenditures of US$ 5 to 8 billion.

The relatively long history of foundries has helped stabilized the business model as well as allowed leading companies TSMC and UMC to develop extensive technological capabilities. TSMC is ramping up mass production of leading edge technology nodes only several months after Intel, the industry's technology leader. This provides fabless design houses and fab-light IDMs with hitherto unknown early access to leading edge process technology. As the EDA based interfaces have been developed further, the hand-off between design and manufacturing is working quite smoothly, although the organizational and technical hiccups never stopped and with DFM problems only grew in the last years.

The outsourcing of wafer manufacturing has steadily increased in resent years. The share of wafer manufacturing outsourcing has grown from 20 percent in 2005 to 30 percent in 2011 (Figure 3.3). Analog manufacturing, with its different economics and the outsourcing possibilities, is an important part of the semiconductor industry distorting outsourcing ratio in the overall industry. However, in the market for digital application-specific ICs, already more than 70 percent of wafer manufacturing is performed by foundries (Figure 3.3). Here foundries already gained the role of dominant manufacturers and technology suppliers.

Figure 3.3. Overall and specific wafer manufacturing outsourcing, in %

Trend towards front-end outsourcing… …especially in application specific logic ICs

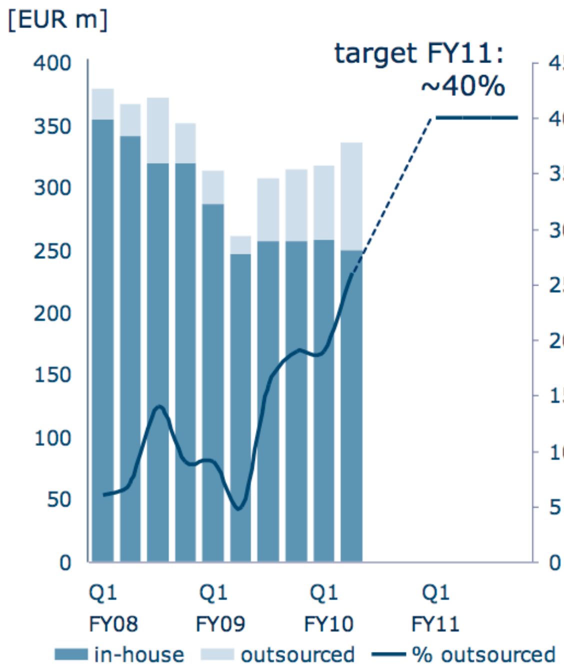


In-house fabs Foundries

Source: IC Insights

The importance of foundries has grown in the last ten years as mid-size IDMs started to shift towards the fab-light model. This development started to gather momentum through NXP's and Infineon's growing outsourcing of manufacturing capacities. At the end of 2005 Infineon announced its retirement from manufacturing below the 90nm technology node. The existing manufacturing operations in Europa and Asia were still to manufacture products in trailing edge technologies for both digital and analog products. As Infineon offers many analog and mixed-signal chips such older manufacturing operations can be used profitably. Infineon's starting point for the fab-light strategy was the company's process technology development partnership with IBM's common platform that existed since 2003. In the beginning of 2006 Infineon demonstrated its first products based on a 65nm manufacturing process. The test phase for these chips was carried out at IBM's facilities in East Fishkill, New York, and then the same tape-out could be used to reproduce the chips at Chartered's wafer fab in Singapore. In 2009 Infineon extended its outsourcing cooperation towards TSMC. Until 2010 Infineon had outsourced around 25% of its front-end manufacturing and was planning to raise the outsourcing level to around 40% (Figure 3.4.)

Figure 3.4. Infineon front-end outsourcing 2008-2011, in EUR and %



Source: Reinhard Ploss presentation at the IFX Day 2010, Campeon June 24 2010

Figure 3.4. reveals how chip companies such as Infineon use the fab-light strategy as a flexibility instrument for volatile markets. Quite parallel to the crisis driven reduction of industry activity during 2008 and 2009 Infineon radically cut down outsourcing of wafer manufacturing. This allowed the company to keep its manufacturing operations utilized, limiting incurred losses. However, this flexibility is only possible as long as the company's revenue is derived mainly from products that are manufactured by both its own fabs as well as foundries. After the crisis Infineon not only resumed the pre-crisis outsourcing levels very quickly but extended the outsourcing share considerably.

Since the Philips Semiconductor business was spun-out into the privately held NXP, the new company used the fab-light model also both as restructuring as well as flexibility instrument. NXP's decision to quite the Crolles II alliance was a strategic move to lower the costs for process technology R&D. Although initially NXP reduced the outsourcing ratio from 18 percent to around 10 to 15 percent, this was more due to market developments than for strategic reasons (Walko 2007). The long time strategy for the company's advanced digital CMOS production was an increase of outsourcing to TSMC to 30-40 percent. This strategy has been extended towards the company's mixed-signal business in 2010 when NXP announced the close down of overall three wafer fabs in Europe that were specializing in mixed-signal manufacturing processes. For its leading edge mixed-signal products NXP is sourcing wafer manufacturing from outside, as it is not able to manufacture mixed-signal product in its remaining facilities (Clarke 2010b).

For many industry observers the fab-light strategy is the protracted process of moving chip companies from IDM to fabless status. This seems quite conclusive as long as mid-size IDM keep their focus both on the analog as well as digital markets. Product differentiation and profit source in analog is still based on the ownership of the manufacturing process. Although there are already some analog foundries the main business for leading edge products will be based on relatively high levels of integration. Infineon is again a quite graphic example. In 2010 the company announced that it would sell its mobile chipset business to Intel. With this quite radical restructuring the company disposed of almost entirely products based on leading edge digital process technologies. This lead to an apparent drastic reduction of its outsourcing ratio down to less than 10 percent. However, as the company is now mostly focusing on analog and mixed-signal products this is by no means a reduction of outsourcing, just a sell off of product lines with high outsourcing levels.

After using the fab-light strategy for several years, Texas Instruments moved completely out of process technology R&D in 2007. The company announced to source process technologies finer than 45nm completely from technology partners to focus its R&D resources on its analog business. In 2010 Texas Instruments was already outsourcing 60 percent of its digital wafer manufacturing and planned for a further increase in the outsourcing ratio (Form 10-K 2011). As products based on 65nm and 45nm processes still account for the biggest market share, the transition towards a fabless model for its digital business will take another few years. As of 2010 cooperation partners are responsible for Texas Instruments' whole 40nm and lower technology production capacity. However, Texas Instruments has not developed into a fully fabless or fab-light chip company as with its analog products it is still highly integrated. Texas Instruments is developing its in-house analog wafer manufacturing capabilities further investing in the industry's first 300-mm analog fab.

The most radical move out of manufacturing was made by AMD when it spun out its manufacturing operations – much in contrast to Jerry Sanders' idea – into the independent company Globalfoundries in the beginning of 2009. AMD became a fabless design house focusing on microprocessors supporting by this strategic decision the understanding of fundamental economic issues linked to ownership of digital manufacturing operations. At the same time a major player in the foundry market was established with Globalfoundries. After the company took over the Singapore foundry Chartered Semiconductors it became the third biggest wafer manufacturing service supplier worldwide.

The increased demand for foundry services coupled with the extreme costs for maintaining leading edge manufacturing operation is pushing big IDM increasingly to consider entering foundry services. This is often a strategy to smooth out cycle dependent underutilization of existing fab capacities. Samsung is offering foundry services already since several years, especially through its common platform partnership with IBM. However, the company is still only on position ten in the worldwide rankings of IC foundries (LaPedus 2011). The relative independence of IDMs from their foundry business compared to pure play foundries can be a competitive advantage in the future. Especially small sized foundries are quite vulnerable during downturns loosing clients as well as slowing down their technology development.

The increased importance of the fab-light model can lead to severe issues influencing the competition of chip companies. Outsourcing wafer manufacturing operations adds an additional level of competition for the concerned company, as the suppliers are mostly much bigger than their customers. Now it not only has to compete on its end markets for customers but also needs to compete for manufacturing capacities at the foundry. Not all companies generate enough business to be regarded as important customers by their foundry suppliers. The status of preferential customer guarantees access to technology prior to other companies, also prior to competitors. Non-preferential customers can be delayed access to technology by up to six months (Clarke 2010a). In a market that is moving as fast as semiconductors, such a delay can be devastating. During growth periods relatively small companies also have problems to obtain enough wafer starts at foundries as utilization rates are very high, and preferential customers are guaranteed product capacities. This limits growth for smaller chip companies.

3.1.7. The changing place of innovation interface

The development of global networks of production and design in the electronic industry has facilitated dynamics of re-integration paralleled by shifts in the innovation interface. Innovation has not only moved along the value chain but it has been exploded into a complex organizational process involving numerous companies located around the world. After Wintelism has separated ownership of manufacturing from control of markets and innovation the development of the industry's organization has moved on. Economical, technological and organizational limits have proven a further separation of product development and manufacturing unfeasible. Although returning to historical vertically integrated organizational structures is unlikely, the need for higher levels of control call for a more integrated organization through networks. These networks are characterized by a specific new co-dominance of the manufacturing side, as the integration on the level of manufacturing goes on and the network interfaces between product development and manufacturing is increasingly being organized by the manufacturing companies.

Re-integration from the manufacturing side

The 2000/01 crisis had important impacts on the development of contract manufacturing. The already widely used outsourcing of manufacturing to EMS companies was extended and organized in a more systematic way. Centralization and re-integration of specific functions on the side of OEMs as well as a increasingly focused approach towards outsourcing lead to concentration dynamics. Company size was becoming even more important as a base for market success in the EMS industry. The rise of Foxconn towards dominance, with its extreme levels of integration, advanced the integration and concentration processes within contract manufacturing.

Regarding the innovation model in electronics industry, post-crisis effects within the model of contract manufacturing itself were fundamental. The EMS model involved engineering mainly as manufacturing near engineering, necessary for a smooth ramp-up of mass manufacturing. ODM in contrast provided both product development and manufacturing services. These system development capabilities both shifted innovation interfaces with OEMs as well as allowed for higher profit margins for ODM companies. ODM in mobile computers was primarily based on efforts of Intel's architecture lab focused on providing highly developed reference designs for PCs, that were to guarantee a fast adoption of the company's new microprocessors (Cusumano/Gawer 2002). This lowered the barriers for market entry, allowing companies with very limited system development knowledge to offer mobile computers to OEM customers. Within years these Taiwanese companies developed into ODM giants such as Quanta, Compal, Wistron or Pegatron. After the 2000/01 crisis the ODM model was adopted in other parts of the electronics industry, mostly mobile phones and consumer electronics. With these new very dynamic market segments the ODM model has outgrown the EMS industry for several years, establishing outsourced system design as a viable business model (Keith 2010).

The 2000/01 crisis also had an important impact on the level of system companies, especially with regards to their organization of innovation. Collapsing profit margins coupled with an increased financial markets focus on short-term efficiency, facilitated the deepening of the already ongoing consolidation of core-competencies. System companies restructured their R&D departments further, sorting out capabilities that were perceived as non-differentiating, as well as not providing a big enough return on investment. Technology that was available on the market was deemed to be sourced from suppliers. This had an ongoing impact on chip companies, that were gradually pushed to become providers of almost complete systems, in which system companies only have to insert their differentiating IP. The development of derivative as well as low-end products increasingly moved to ODMs as engineering capabilities at OEMs focused on high margin market segments.

The success of ODM has accelerated shifts in the innovation model. Although ODM companies own system development capabilities these are not comparable to incumbent OEMs. As an example, Nokia had extensive chip design capabilities that were regarded as leading edge. This allowed Nokia to both develop their mobile handset almost from scratch as well as coordinate technology roadmaps of their chip and other technology suppliers in a much more informed way. Nokia was not only a lead firm due to its brand, size and position in the global networks of production and development, but also based on its ability to drive the development of technologies and standards – its framing capabilities (Brusoni 2003). From this perspective ODMs are a new type of system companies, that lack extensive development capabilities. Their system development is based on the availability of commodified knowledge in the form of components and reference design kits. This translates into an increased demand for chip solutions that integrate both several functionalities as well as system knowledge (see: Mediatek case study).

System companies increasingly focus on solutions, ecosystems and services, driving the business model of ODM and EMS further. Chip companies are affected by this shift in several ways. The interface of component and system development become increasingly complex, as chip companies have to be able to work together with ODM, EMS as well as system companies that all have different system development capabilities. As systems are developed in cooperation between system companies and contract manufacturers chip companies need to cater for both partners at once.

ODMs are an example of specific re-integration dynamics on the level of system development. On component level the vertical specialization is advancing re-integration processes that do not result in a vertically integrated organization but in a more complex system of network integration. Companies like eSilicon, Open-Silicon or Faraday Technology have been developing ASIC or SoC turnkey design services since several years. These companies offer their specialized expertise in physical chip design and integration to OEMs, chip vendors as well as fabless chip design houses to enable more efficient chip development. However, this new model is not comparable with the hitherto known outsourcing of physical design to low-cost locations. Although the SoC design methodology offers a way to reduce difficulties through the modular design of IP integration, the ongoing vertical specialization of chip companies increased the number of specialized suppliers to such a degree that the management of the value chain is becoming challenging. The growing distance between chip companies and wafer manufacturing is also lowering their technical capabilities to evaluate and understand the manufacturing driven implications of their chip designs. ASIC design service companies not only provide simple physical design services but also organize the whole production process for chip companies and OEM.

Provisioning appropriate silicon IP through third-party suppliers and own development as well as the capabilities to integrate these blocks in a defect free design are the main objectives of these turnkey design services. With this the ASIC design service providers are organizing the interface between the design level and the manufacturing level. In a way resembling some aspects of contract manufacturing these companies use advantages of mass production, or at least high production numbers, for both building-up their technical and organizational expertise as well as a beneficial access to manufacturing services. With the complexity of ASICs rising constantly chip companies, both IDMs as well as fabless chip houses, develop fewer products each year. This impedes the constant development of the interface towards manufacturing, which is increasingly important as technical and economic issues increase. ASIC design service companies have a much higher number of tape-outs as they focus on the physical design part and the organization of the chip production. While previously the chip company itself organized the production of outsourced physical design, now these functions can be integrated into the services of ASIC design service providers.

Additionally, ASIC design providers can be at least a partial remedy for problems in the cooperation with foundries, caused by the lack of size of many fabless design houses. Specializing in production services ASIC design service providers have developed extensive relations to foundries that translate in a constant flow of orders for wafer manufacturing services. Although not being big companies they still can guarantee production lots at foundries, something small design houses often struggle with. Many of the ASIC design service companies are independent firms that offer their customers the access to a variety of foundries and assembly and package companies.

Architectural innovation

The ongoing shifts in the geographies and the organization of the electronics industry has favored the entrance of new system companies in the various markets for consumer and telecommunication electronics. Based on architectural innovation companies hitherto not known as technology powerhouses were able to compete with incumbents in the dynamically growing emerging markets, especially China. Their initial major successes in these markets, as well as their subsequent spread to markets in developing countries has not only raised the competition level for incumbent companies, but also challenged the model of radical innovation as a driving force for market success. Architectural innovation is based on an innovation model that is both combining existing technology with market knowledge as well as shifting innovation towards the organizational level. In contrast to incremental innovation the aim is not only to lower the overall costs but to use preexistent technology modules in a new way that will provide for demands until now not satisfied by other products or services on the market. Radical innovation is focusing on breakthroughs in technology that allow either for the creation of new markets or the possibility to garner extra profits through technology leadership. Radical innovations are very risky, as such projects are both long and costly and neither can guarantee a result nor the market success. Additionally, radical innovation need deep R&D capabilities that span several technology areas, initially not available for late comers from emerging markets. However, successful business based on architectural innovation can lead to the build up of such resources allowing late comers to develop into technology leaders over the years.

As architectural innovation lowers entry barriers for late comers it requires a specific industry organization where system knowledge is at least partially available as a commodity. Industries organized around highly vertically integrated companies are very much opposed to this innovation model as companies are not able to procure the necessary technology modules and system knowledge on the market. The decade long vertical specialization of the electronics industry has facilitated the development of companies specializing in the provision of important technology modules that allow the build up of a system in a relative easy way. However, as the commodification of knowledge facilitates the lowering of market entry barriers, it also rises the requirements put forward toward technology suppliers. While chip development has moved on to system integration on a chip, the technological fundaments for such requests are being reinforced since several years. One of the epitome of the ongoing triangular restructuring of the electronics industry as well as the rise of architectural innovation is Mediatek, a chip design house from Taiwan.

Reference Design Kits (RDK) are a well-tried marketing instrument offered by chip companies. Most basically RDK can be understood as information that educates engineers and allows to accelerate design cycles through the provision of various materials to customers, ranging from data sheets through demo boards to production-ready designs (Cravotta 2007). By showing in a RDK how the particular chip can be applied chip companies hope to generate business. The emergence of new companies from Southeast Asia, that do not have the necessary deep system knowledge and whose main business objective is a fast time to market within relatively constrained financial limits, is tilting the RDK model increasingly towards kits that offer almost ready systems where specific differentiated IP can be dropped in. These companies are brand name companies such as e.g. Huawei or ZTE that have seen remarkable success in the last years in telecommunication markets. Additionally, the raise of ODM companies is also extending the number of system companies that do not have extensive technology and system capabilities and need to rely on technology suppliers. However, the demand for ever more far-reaching RDK is also fueled by incumbent companies with decade long history in system and technology development. The ongoing restructuring of incumbent companies driven by financial markets to further focus their operations, lower time to markets and

R&D costs, while generating increasing model variety for new unknown markets, is stretching their development capabilities.

This ongoing shift of system knowledge towards chip companies is quite problematic. The development of entire RDK is related to high up front costs in general. Additionally the requirement to develop system knowledge pushes chip companies towards new knowledge areas that need to be tackled and organized. Former component suppliers are moving towards becoming system suppliers. However product life cycles are measured in months for consumer and communication devices further raising the pressure for chip companies.

Foundries as network organizers

Design service companies are not the only one who organize the interface between design and manufacturing as a service in an increasingly specialized semiconductor industry. Foundries also offer broad services and components as network stabilizers and control instruments to ensure the growth of their business. The two biggest foundries TSMC and UMC have quite distinct strategies towards the development of such a design ecosystem.

TSMC is organizing the design to manufacture interfaces relying on in-house capabilities and long-term customer cooperation, dubbing this the new integrated foundry model (Yang et. al 2009). Initially the foundry and its customers cooperated only at design tape-out and delivery of product. Today technical complexities require wide-ranging cooperation from the onset of a design project. Despite being a pure-play foundry TSMC has extensive design service capabilities in-house. These operations focus on the development of process design kits as well as physical design services. However, the main focus of TSMC's design service department is the development and maintenance of the company's broad silicon IP and library portfolio. To build up an extensive portfolio of in-house SIP the company invested around US$ 100 million on IP R&D between 2002 and 2007 (LaPedus 2007). Although this level of investment makes TSMC the largest SIP supplier worldwide, the company is neither perceiving itself in competition with the much smaller independent SIP developers, nor moving into a more ASIC-like business model. For TSMC a broad SIP portfolio is a logical advancement of its pure-play foundry business focused on easing IC manufacturing for customers. TSMC is focusing its silicon IP R&D on proprietary physical-level so called hard IP, which is binding its customers to the company as this kind of SIP can not be ported to other foundries' process technologies.[24]

To bolster its in-house capabilities TSMC has developed a broad range of technology and service suppliers. Its IP Alliance aligns SIP from more than 20 independent IP providers with the company's process technologies. This allows TSMC to have a broad offer of various more specialized as well as non-core SIP. To be able to serve its vast numbers of customers and their various design issues TSMC has set up a design center alliance which is comprised of around 28 partners worldwide. Offering qualified IC design services to TSMC's customers these companies are an important interface for the foundry.

On the tool level TSMC's EDA Alliance is an instrument for the development of standardized interfaces between the chip companies and its wafer fabs. TSMC grants members of the EDA Alliance access to its technical insight to validate their tools and methodologies. In this very close cooperation with EDA companies TSMC is able to provide process technology details to its customers for efficient chip design, without having to compromise this information in regards to competitors. TSMC's reference design flows define the validated sequence of design tools recommended for a specific manufacturing process as well as design rules. All tools in these flows must be validated regarding standards established or approved by TSMC. Its newest reference design flow covers not only chip design from system level on, but also has been expanded towards package design. With this, it is integrating vast amounts of electronics system development. Within these reference design flows TSMC's is using increasingly proprietary data formats, that allow for a smoother integration of tools within the flow.

United Microelectronics Corporations (UMC) is less focused on the integration of specific design functions and organizes its design manufacturing interfaces almost entirely through networks of close cooperation. Just as TSMC, UMC is entering the customers' design process well in advance of the finished design to ensure a cooperation. During UMC's shift from IDM towards pure-play foundry the company spun off many design related function into independent companies. Keeping equity stakes in these new companies, such as Mediatek, Faraday or Novatek, UMC was able to build a starting point of its network based organizational interface. Most of the IP, that UMC's customers require for fast design completion, is provided by third-party IP companies that are

[24] However, TSMC's development of hard IP is nothing exceptional in the foundry industry, as most foundries have offered this kind of SIPs for years to attract customers.

partnering with UMC and EDA companies to guarantee process alignment. UMC is also developing IP in-house, however these activities are quite small. UMC's relations to its network partners as well as customers are often stabilized by equity relations. The company holds stakes of sometimes more than 10 percent in companies like Unimicron, Holtek, Faraday, SiS and Novatek that are also part of its design ecosystem. UMC's major customer Xilinx held for many years shares of UMC, which was a strategy to both build up relations that grant earlier access to process technology development as well as guarantee beneficial access to manufacturing capacities. However, Xilinx sold its stakes in UMC by the end of 2008.

3.1.8. The organizational landscape of the electronics industry

The emerging organizational landscape in the electronics industry is characterized by the ongoing vertical specialization, which is paralleled by processes of re-integration, mostly from the manufacturing side. This is only partly translating in dynamics of vertical integration. Network based integration, the outcome of triangular restructuring (Lüthje 2007a), is increasingly the predominant form of industry organization. Production and design are not anymore organized through relatively simple market relations, regarded as the fundamental form of relations in the initial phases of the vertically specialized electronics industry. Now organizational and technical complexities have grown so much that increased levels of control are necessary. Economic limits emerging both from technical dynamics, as well as the financial market driven vertical specialization are triggering shifts in the innovation model, based on the changing place of system knowledge capabilities. However, this new network integration is based on hierarchical networks governed by lead firms occupying positions in the value chain hitherto not generally linked to leading roles. Global Design Networks become the focal point of industry organization.

The knowledge necessary to develop and manufacture one of today's electronic system as well as its major components, the chips, is not anymore residing in one organization. Vertical specialization enables high innovation dynamics through economies of specialization. However, the ability to organize the increasingly complex supply chains of innovation and manufacturing is lowered by the very same process. Triangular restructuring is exploding the simple dualistic relations between the system company and its component suppliers. As knowledge capabilities are shifting, new actors are becoming fundamentally important for the process of product development and manufacturing.

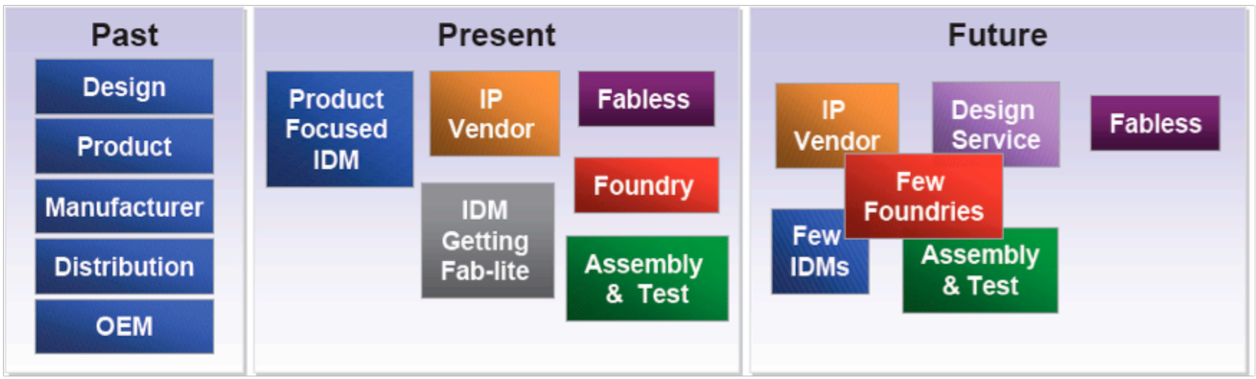
Foundries and EDA companies as suppliers of commodified knowledge and technology are becoming the linking pillar for the new innovation model. Without their investments in and control of processes of standardization the vertically dis-integrated model of innovation and manufacturing would come to a grinding halt. As the big foundries will be among the very few chip companies that will be able to stem the financial burdens of leading edge wafer manufacturing operations, their ability to organize the innovation interface will grow further in the future.

This new innovation model is also changing the idea of a lead firm, as system development cannot be anymore taken as a characteristic of a lead firm. However, the power over GDNs is still based on technological capabilities that allow to set specific standards. Viewed from the perspective of the value chain, foundries, as providers of component manufacturing service providers, are very far away from the system level manufacturing and development. Wintelism has shown, that ownership of system manufacturing is not necessary for standard setting. However, its fundaments were based on companies that were developing major components of a specific system as brand name providers. Contrary to this, foundries are manufacturing service providers that only develop process technology used in their fabs where they fabricate chips for their customers. However, these contract manufacturers with highly developed technological capabilities have become one of the major foci around which the semiconductor industry is revolving. Foundries are developing and controlling the major interfaces required for the industry's organization. Manufacturing has become again central to the organization of the industry and innovation. It is also the basis for control within the GDN of the chip industry.

But one could argue that specific aspects of the Wintelistic mode of innovation have survived and are being pushed to the very extreme. The company ARM is providing IP based microprocessor cores. These cores are used by chip companies such as Qualcomm, Infineon or Samsung to build complex SoC around them. ARM microprocessor cores are known for their power efficiency, making them the prime choice for mobile handsets and all other mobile devices. Within these markets ARM has a dominance only comparable to Intel's in the PC space. However, not only does the company not have any manufacturing operations, but it also does not develop components. Although microprocessor cores are the most important parts of today's complex SoCs they are only on-chip components.

Several years ago Morris Chang, the CEO of TSMC, has summarized the dynamics of vertical specialization and re-integration on the level of the semiconductor industry in a very instructive graphic (Figure 3.5). As Chang held his presentation already some years the future of the graphic is the present time. The past has seen the integrated model of the IDM where the chip company developed and manufactured chips providing them to OEMs. Dynamics of vertical specialization resulted in a highly modular industry organization of the late 1990 and early 2000. The highly modularized industry structure reached its limits both due to economical as well as technological developments. To keep the innovation dynamics high in a modular industry, a higher level of control is increasingly necessary. This control stems from the definition and control of interfaces. As the interfaces to manufacturing became again important, foundries are taking over the role of network organizers. They are the link between the various levels of the horizontal chip industry defining standards for the various interfaces through massive investments in R&D and cooperation. These are not actions of selfless companies but are aimed at securing future business with increasingly dependent customers.

Figure 3.5. Evolution of industry organization in the semiconductor industry



Source: Morris Chang, TSMC presentation 2007

3.1.9. Mediatek – epitome of the dynamics in the electronics industry

Mediatek is a fabless chip design company located in the Hsinchu Science-based Industry Park in Taiwan. The company was established through a spin-off from UMC in 1997. Initially Mediatek focused only on chipsets for optical storage and DVD players, gaining substantial market share in a short time by establishing close customer relations as well as a very competitive price structure. In 2004 the company decided to diversify into the market for mobile handset chipsets. Although the wireless chipset market was controlled by incumbent multinational heavyweights like Texas Instruments, Qualcomm, Freescale or ST Microelectronics, operating with decade long experience in both technology as well as product development, Mediatek was able to achieve rapid success. Within only 5 its innovative business model, combining close customer relations and semiconductor solutions focusing on developing markets, enabled Mediatek to develop years into one of the five leading baseband chipset suppliers worldwide as well as enter the list of the top 25 overall semiconductor suppliers. Mediatek was able to grab more than half of the whole Chinese baseband market only one year after it entered it. Within very short time Mediatek became the market leader among 'white box' and grey market handset OEMs in China (Schneider et al. 2009) and is a major supplier for the biggest Chinese handset OEMs like Huawei, ZTE, Lenovo Mobile, Beijing Tianyu Communication Equipment and Longcheer.

The Chinese mobile handset market was initially a challenge for the incumbent handset OEMs and their chip suppliers with their innovation model directed towards supplying products focusing on technical leadership. The need for fast product cycles in the low-cost segment of the Chinese market both lowered considerably the possible profit margins for incumbent handset companies as well as posed organizational challenges to their development divisions. Local Chinese companies, both big Chinese OEMs like Huawei and ZTE as well as small handset design houses, were eager to enter this highly dynamic market. Although lagging behind in technological knowledge, these new companies had an intimate understanding of the local market. Within the last five years a third category of Chinese handset companies developed very dynamically, based on lax intellectual property rights and providing the so called shanzhai[25], or counterfeit phones.

Although processes of modularization and triangular restructuring have been shifting system knowledge increasingly towards chip companies, the fundamental technological system knowledge and the decisions on the system’s architecture and design are still residing with system companies. Traditional Reference Design Kits (RDK) offered by incumbent companies like Texas Instruments or Infineon are rooted in an innovation model that requires experienced engineers with extensive product development knowledge

[25] Shanzhai stands for "mountain stronghold", referring to bandits withdrawing from governmental control in the mountains. As the shanzhai companies operate mostly outside the legal market only estimations about the size of this market exist. For 2008 experts estimated that shanzhai phones accounted for around 20% to 30% of China's mobile phone market (Barboza 2009). Between 80% to 90% of the chipsets in this market are being provided by Mediatek (Taiwan Economic News 05/15/2009).

on both sides. This innovation model developed through the decade long cooperation between mobile handset and network companies as well as chipset suppliers providing products for markets in Western Europe and North America. With the entry of new local handset companies in the Chinese market, this innovation model became problematic, as the new system companies did not have the necessary knowledge and experience in system development to put the existing RDKs into use.

Mediatek's low-cost mobile handset semiconductor turnkey solutions provided a remedy in this situation, lowering the market entry barriers considerably by offering the lacking system knowledge as a commodified part of its product and service portfolio. The company's turnkey semiconductor solutions allowed all new market entrants from China an easy development process (McGrath 2010). Mediatek's semiconductor turnkey solutions comprise of both technological components as well as organizational structures that allow new handset companies with only low degrees of system knowledge and development experience to develop mobile handsets. The main aspects of the turnkey solutions are the hardware platform, the technological backbone of the future system, essentially comprised of highly commodified semiconductor components with various integration levels, the RDK as an exemplified system integration, extensive software stacks and intensive customer support. The gradual shift of system knowledge between system companies and chip suppliers that already began to show in the processes of triangular restructuring has materialized in full within Mediatek's business model and product offering. However, Mediatek is still firmly rooted in the highly modularized organizational structure of the global electronics industry, showing no signs to move into manufacturing.

Mediatek's hardware platforms, initially focusing on entry level low-cost mobile phones and currently moving also towards low-end smartphones are by no means technically leading edge. They trail mobile handset platforms offered by its incumbent competitors both on the levels of semiconductor[26] and RF technology as well as the complexity of offered functionalities. But Mediatek is able to offer all the necessary functionality for a developing market at price levels at least 30% lower than its

[26] Regarding semiconductor process technology Mediatek is still about one generation behind its incumbent competitors. While Qualcomm, Broadcom, Texas Instruments and Infineon have been already manufacturing wireless chips in 45nm technologies at the end of 2009, Mediatek only started volume production of its chips in the 65nm technology at that time (Digitimes 09/25/2009).

competitors. This offer is combined with the necessary help and infrastructure for the handset OEM to develop the platform into a mobile phone timely and easily.

To be able to develop its integrated hardware platforms Mediatek relies not only on its internal IC development capabilities, but has built up an extensive supplier network. Partner companies from Taiwan and also from China develop auxiliary chips for extended functionality. This allows Mediatek to focus on core functionalities such as baseband processor, RF transceiver, power management and various connectivity functions. The resulting platforms comprising of various components, which are matched for smooth operation of the system, offer an already fully validated hardware base. Software development plays an increasingly important role in the integration of various ICs into one system and software driven IC functionality, as well as in form of easy to use application programming interface. Such programming interfaces allow Mediatek's customers easy customization of the delivered RDK and software stack.

Very deep customer relations are the most important part of Mediatek's organizational innovation, that allow the company to cater for its tier 2 and tier 3 and also very small Chinese handset manufacturers. Furthermore, the company can gather important market knowledge necessary for rapid product adaptations. In 2009 Mediatek had strong relations with more than 250 local handset companies through a very dense network of field application engineers. This allows Mediatek to provide timely technical services and after sales help to its customers. Although Mediatek is providing commodified system knowledge it still needs to help its customers with the application of this knowledge and lead them through the development process resulting in customer relations that are by no means arms length market relations.

Mediatek's turnkey solutions as well as an almost complete mobile phone supply chain in Shenzhen, China have changed the development model of mobile handsets considerably. Before Mediatek development of a new mobile phone cost about RMB 20 million (EUR 2.25 million) and kept around 100 engineers working for 9 months. Now the development costs have been reduced to around RMB 500,000 (EUR 56,200)[27] and require 10 engineers to work for 3 months. These lowered entry barriers have allowed the development of a vivid local handset development and manufacturing industry in China that is providing various and mostly cheap phones for the local market. The innovation

[27] Based on an average exchange rate of CNY 8.87 for an EUR.

model shifted from a focus on technology towards rapid adaptation to new trends through the continuing re-organization of supply chains.

Although not a technology leader Mediatek is able to achieve higher than average margins on a sustained basis. With its turnkey solutions the company is able to keep its average selling price (ASP) on a relative high level, as its customers are paying essentially for complete hardware and software solutions through chip prices. Being mostly smaller white box handset manufacturers Mediatek's customers lack bargaining power that would allow them to push prices down. Furthermore, Mediatek's origin in Taiwan and focus on China has helped the company to keep R&D costs down through the focus on low-cost geographies.

However, while the company was able to grow during the crisis stricken year of 2009 by 20 percent, while the whole semiconductor industry contracted by around 10 percent, the company is facing fundamental problems in recent times. Companies from China, e.g. Spreadtrum, have successfully imitated the business model of highly integrated solutions. This has triggered a fierce price competition that is negatively affecting both the ASP as well as Mediatek's profit margins. In 2010 Mediatek's share in China's 2G handset market declined from 90 percent to 70 percent while Spreadtrum was able to increase its share to around 25 percent. As the Chinese government has started to increase its control over the shanzhai handset industry the growth of the grey-market is projected to have declined to 18.6 percent in 2010 from 43.6 percent in 2009 (McGrath 2010). The increased adoption of 3G based smartphones in its main market China has revealed Mediatek's major challenge. The company's trailing edge technology capabilities can now become a considerable growth barrier as the 2G handset market is growing much slower. The 2G and 3G ecosystems are very different as the former is dominated by the retail sales channel, while the later relies on telecom carriers and their subsidies. This will limit an entrance of white-box as well as grey-market phones into the 3G markets. As Mediatek only started to enter the design networks of first tier handset providers, who dominate the smartphone market, it will be hard for the company to gain extensive market shares.

3.2. The Semiconductor Firm – three case studies in GDN integration and upgrading

3.2.1. The money conscious price specialist IDM

Midtronic is an U.S. IDM developing and manufacturing discrete and power components as well as logic and customer devices. In 1999 the company was spun off from a major U.S. electronic systems company making it one of the first involvements of private equity firms with mature companies from the semiconductor industry. The private equity involvement ended soon, as in 2000 the initial public offering was already completed and the private equity firm lowered its interest to only 17.4 percent by 2007. Compared to worldwide semiconductor companies Midtronic is a niche market player with a very dynamic growth. The company has made some major acquisitions in the last years. Until 2011 the company was able to rise to the 18th rank among the worldwide semiconductor companies. In the highly fragmented analog market the company is also a midfield player. Midtronic employed at the end of 2010 around 14,000 people worldwide, of which app. 11,000 were engaged in manufacturing and around 1,350 were in research and development (Form 10-K, 2011). The company made its name as a specialist in operational cost cutting. Despite its move to higher value add products it is still not perceived in the industry as a technology leader (LaPedus 2007).

Initially Midtronic focused only on analog products such as power ICs with specialty fabs, assembly and test facilities tuned for high-volume, low-integration parts in non-standard processes. This allowed for relatively low capital equipment expenditures and production on fully depreciated manufacturing equipment. Midtronic's high levels of organizational integration are driven both by markets as well as technology requirements. Deep integration is necessary, as only the control over development and manufacturing allows for optimal cost management. The ability to develop and manage a high number of specialty processes is the basis of profitably in the analog market. The numerous specialty processes make a close integration between manufacturing and design essential, as product differentiation is still lying as much in process technology capabilities as in chip design and the perfect alignment of both. This integration allows Midtronic to serve numerous niche markets and to move higher up the value chain by building up system knowledge through the combination and expansion of their overall technological capabilities.

In recognition of the future importance of power management and complex solutions in electronics the company is being reorganized by diversifying its product focus further into power management ICs and the development of capabilities for higher-value complex analog and mixed-signal solutions. The initial step was its move towards digital products through the acquisition of a 8-inch fab specialized for the production of digital wafers in 2006. This was followed by acquisitions that allowed Midtronic to further venture in the growing markets for notebook and PC power management solutions and complementing its higher margin analog products for the digital consumer markets. Midtronic's 2007 acquisition worth US$ 894.1 million was its biggest and most critical for its transformation, enabling the company to enter the markets for ASIC, custom chips and foundry products. Midtronic can now provide integrated solutions to board-level designers until now only concerned with the company's power semiconductors. In 2009 Midtronic acquired a fabless design house in India establishing thereby its first design location in this country. 2011 saw Midtronic acquisition of a Japanese company expanding its business into MCU as well as onto the Japanese market.

Already in the beginning of 2008 Midtronic started to consolidate its operations both due to the financial market crisis, as well as a consequence of its extended acquisitions, that expanded its wafer manufacturing operations with three new wafer fabs. The transfer of process technologies from these fabs to lower-cost locations would have caused high costs and disconcerted customers about product quality and reliability, making it necessary to formulate a consolidation plan that involved all front-end facilities. The consolidation was focused on the migration of manufacturing operations to high-volume fabs with advanced operations, to allow for increased economies of scale, as well as the migration to bigger wafer sizes. Midtronic also announced a reduction of product platforms as well as process flows.

Seven of Midtronic manufacturing facilities are front-end wafer fabs located in Belgium, the Czech Republic, Japan, Malaysia and the U.S. Five of Midtronic's manufacturing facilities are back-end assembly and test sites located in China, Malaysia and Thailand. Midtronic's China facility is operated as a joint venture focused on assembly and test facility. Midtronic is also using third-party contractors for some of its manufacturing, primarily for wafer fabrication and assembly and testing. Midtronic's design centers are located in the U.S., Belgium, Canada, China, Czech Republic, France, Germany, Ireland, Korea, Romania, Slovak Republic, Switzerland and Taiwan.

Midtronic's manufacturing operations have a very distinctive structure with a basic geographical division between front-end and back-end facilities. The former are mostly located in higher cost countries, which is driven both by historical legacies as well as recent acquisitions. The location of wafer manufacturing in high cost areas is also driven by requirements put forward by customers, as well as the specific character of Midtronic's manufacturing requiring high levels of experience from operators to handle the numerous and very specific process technologies. Within the front-end facilities, a further geographic distinction becomes evident, as two of the facilities are located in relatively lower cost locations – the Czech Republic and Malaysia. The wafer fabs in these locations seem to be focusing on the lower end of Midtronic's process technologies. As the lower end wafer manufacturing are operated using highly depreciated equipment, labor costs become important for a profitable manufacturing, making low cost regions that can provide highly experienced personnel important for Midtronic. During the recent restructuring of manufacturing operations most of the manufacturing capabilities from closed down operations were relocated to these two wafer fabs. Although Midtronic is locating its front-end operations increasingly in relatively lower cost locations, the company's location strategy is quite distinctive from big industry players that are moving their wafer manufacturing facilities to Asia since several years.

Upgrading as a continuous process in intra-organizational GDN

The company's main design and manufacturing locations in Central and CEE are located in the Czech Republic and Slovakia. The Czech Republic has a very long tradition in semiconductors that was the basis for a small but thriving industry since 1989. Big multinational IDMs and system companies as well as small local IC design houses have IC development operations in Prague and the eastern part of the country. Midtronic' biggest design and manufacturing operations are located in a small town in east Czechia, where the Czech government established a vacuum tube plant in the 1940s as part of an industrialization plan for the region. The rural character has not changed very much to this date as the town is mostly characterized by touristic infrastructure with the semiconductor manufacturing and design operations being the only local industry. In a move to diversify its manufacturing operations structure as well as tap into low-cost locations Midtronic's parent company started to look for investment possibilities in Central and CEE in 1991, starting a subcontracting relationship with the local factory and eventually forming a joint venture (Linden 1998). Although local manufacturing operations were based on dated technology by international standards, its very low labor costs and highly experienced operators and engineers enabled high quality manufacturing, test and assembly of analog products. In 2003 the manufacturing operations were merged into Midtronic.

In 1994 Midtronic's parent company established a Czech IC design center (RDC) to tap into the already deteriorating local talent pool, initially employing 12 designers. RDC started in line with the company's low-cost approach as an extended workbench focusing on labor intensive, low-tech manufacturing related engineering work. During the last 16 years RDC, now part of the automotive and power group, has evolved from a small low-cost location to a highly integrated development center housing central engineering functions. RDC is employing 165 people (Interviews 2009), which is around 12.5 percent of Midtronic's overall R&D staff in 2009 (Form 10-K, 2010). After 2008/2009 crisis measures that involved 15% redundancies in all of the company's worldwide operations, RDC was the first site to hire engineers at the end of 2009. This was based on both the relative good growth of the segment served by the design center as well as the continuation of cost aware development of Midtronic's business. This development is in line with the post-crisis chip industry, which has been hiring R&D engineers in lower cost locations more dynamically than in high cost locations.

RDC focuses on the development of analog products for the computing, portable and consumer markets – linear regulators, AC/DC power supply and solid state lightning. The product range of RDC is neither leading edge in transistor complexity nor advanced process technologies. But complexity is defined differently in the analog world, as these products require a very high level of precision and accuracy making the experience of an engineer and his knowledge about the characteristics of a specific process technology critical.

RDC's current integrated design operations are comprising all technical functions necessary for new product development, like IC design, layout, application engineering, product engineering and test engineering.

> *„We have all the people speaking the same language, responsible for one project sitting in the same building, which is really a big advantage for everybody."* (General Manager of Design Center – RDC)

RDC's engineers have the same technical proficiency as engineers at other Midtronic sites, providing their technical expertise and driving developments in specific areas. With the long history of the design center the experience levels of particular engineers are very high. They are company leading experts in Bi-polar process technology both in design as well as process technology. Although RDC is adjacent to the wafer manufacturing operations, most of the products that are developed here are manufactured in other Midtronic fabs, in Japan in the U.S. As the products are developed in Midtronic's leading edge process technologies only few of them can be manufactured at the local fab.

Project management for local projects has been located in RDC already several years ago, giving local engineers the ability to develop their management capabilities. Right now the project execution is quite autonomous, relying on other sites only for high management functions. Since 2007 RDC is managed completely by local Czech engineers that have acquired enough management capabilities to entrust them with leading the local operations. Being the center of excellence in finance for Central and CEE and France RDC is also housing some broader management capabilities. However Midtronic's French operations have still the overall lead on these issues. The human resources department at RDC is responsible for all Central and CEE design centers. Marketing and sales operations are not located at RDC, however there were significant developments on this level around 2004. Before this time RDC's design operations were lead by a development center in France.

> *„We worked for them and they highlighted their successes, we were not visible in the company."* (Project Leader – RDC)

After RDC became a separate and independent design center a direct link to central marketing was established making achievements in RDC more visible. This also enabled a better understanding of customer and market requirements as well as a better systems knowledge for engineers at RDC. Midtronic considered moving marketing and sales to RDC but decided to keep it in the headquarters, as the product markets are not in CEE. This global distribution of work has of course its drawbacks that need to be managed. Marketing officers from headquarters are visiting RDC every quarter to enable face-to-face contact with the development teams.

The technical know-how that has been accumulated for years in RDC is used by the sales and marketing department in its product planning process.

> *„Marketing at headquarters uses us as the technical community to judge their ideas."* (General Manager of Design Center – RDC)

During a weekly conference call focusing on possible future products, RDC's design and application engineers are provided with product ideas for feasibility studies. This pre-development process is sometimes reversed as engineers in RDC develop product ideas, based on their acquired market knowledge and overall experience, that need to be considered in their business value by central sales and marketing. Application engineers have the most important role in this process, with their close connection to customers and accumulation of extensive market knowledge.

Besides the integrated new product development capabilities, RDC houses other important development functions. The design system technology group (DST) comprises of the modeling and characterization group and the process design kit development group. After its spin-off Midtronic lacked a modeling and characterization department and appointed RDC as the target location to establish such a team. The main rationale behind this decision has been the low cost of Czech engineers coupled with their technical proficiency and the very low fluctuation, guaranteeing a stringent build up of deep technical expertise. Since its inception the team has grown to 11 engineers, one manager and one technician. Some of the engineers have become distinguished members of the worldwide semiconductor modeling community, lecturing at international conferences. The DST group is providing models which are the most basic link between the process technology in the wafer fab and the building blocks used by IC designers in development centers. With this, it is a critical function in the whole IC development and manufacturing process, enabling the organization of globally distributed work from the technology side and a prime example of manufacturing related R&D work. The modeling and characterization operation in RDC is Midtronic's central modeling group providing models for technologies used at all of the company's major and advanced manufacturing sites and supporting all of Midtronic's numerous technology development groups. The DST group is directly cooperating with the Midtronic Technology Board located in the U.S. The manager of RDC modeling and characterization department is in a close contact with the board and participates in the board's meetings.

Midtronic's second biggest design center in CEE is located in the regional capital city of eastern Czechia. Although the city has no direct history of semiconductor industry, it is home of two of the region's biggest universities which have been educating engineers for the RDC mother-fab and IC design operations for several decades. In 1994 the first local IC design company that developed over time into Midtronic's development center (BDC) originated from the local academic community. In 2009 BDC employed 54 people: test, analog, modeling, digital, analysis and evaluation engineers. Four local group leaders have been assigned to the modeling, ASSP, test and digital ASIC groups.

The BDC has a long history of acquisitions by multinationals. Initially BDC was regarded as a standard low cost ASIC design services location with very limited project responsibilities. However, ownership change brought a new, technically very strong design center manager that helped to develop knowledge and capabilities. Within about two years engineers from BDC were already treated as respected partners and the design team was given own development projects. Project leading functions stayed in headquarters until around 2008 when Midtronic started to reorganize the project management organization after acquisition. Only in April 2009 was the first Czech site manager in BDC assigned, with local group leaders already in place for some time.

The development of project and group leading capabilities required the initiative of BDC's engineers. Although people at the headquarters did not obstruct the development of technical expertise of the engineers, they seemingly were trying to keep management functions in their hands. However, this slow down of management capability build up in BDC, by impeding information flows and obscuring decision making as strategies to stay at the center of power, was perceived by BDC engineers as negative for the overall company development.

Sales and marketing as well as system architects are still located in the U.S. and Belgium, although in mid-2009 one system architect position was established in BDC. Apparently, BDC design engineers are not really interested in more local sales and marketing capabilities as they perceive themselves as engineers and technical experts that do not want to become entangled in marketing details. The center's focus on ASIC and ASSP products already provides a close link to customers regarding technical details. Most of the ICs developed in BDC are supplied to the automotive industry's tier-1 suppliers like Valeo, Bosch and Hela which impedes any direct linkages to the local automotive industry. Most of the company's customer base is located in Europe.

Similar to the RDC the BDC is equipped with all capabilities to conduct a development project from pre-studies and concept phase until sign-off for customer product qualification and mass production. Quality and reliability as well as testing of BDC's designs is located in Belgium while production testing is conducted in Philippines. The center's project groups communicate with sales and marketing, architectural design, assembly, quality and reliability and test located outside of BDC. On the design level the center is quite autonomous. The design center is a leading and supporting site for physical design, consulting other Midtronic design locations as well as providing layout services for internal customers. Physical design engineers in BDC are highly experienced and still relatively cheap, allowing for the offshoring of digital and mixed-signal layout designs from other high-cost locations.

The very localized structure of development teams only evolved during the last two years, driven by local group leaders and engineers that attempted to move capabilities to the city. This localization evolution at the design center was supported by its acquisition through Midtronic. Customer requests were also driving a capability build up that led to the introduction of a system engineer. This position is now an important link between customers and the development team. The previous division of labor in design projects was heavily internationalized – memory coming from the U.S., digital parts from India and BDC designing analog components and performing final integration. Besides problems with time shift and communication within the distributed project groups, severe quality issues arose with the digital blocks being designed in India and integrated in Brno.

> *"There are IP blocks like memory, that can be developed somewhere else, should be. At a certain level this is not so obvious to define the interfaces, it is for sure easier and I think even cheaper at the end to make it at one location."* (Analog Group Leader –BDC)

Midtronic’s design center in Slovakia (BrDC) was established in cooperation with the local Technical University in 2001, initially focusing more on R&D support, performing IC designs more as additional services. Engineers were cooperating with researchers at the Technical University and technology development units of Midtronic on various aspects of process technology development. Only since 2005/06 BrDC has been changing its focus towards IC development as the new product development center was established, starting with shrinks or transfer projects of already developed digital circuits. After some time analog design projects were introduced at the BrDC due to a relocation of design capabilities from RDC. The digital part of the design was phased out and the center focused solely on analog IC design. The products designed in BrDC are quite simple commodity analog products for the automotive market.

Initially the BrDC operations were both small and focused on R&D support making an extensive division of labor neither possible nor desirable. The tasks of IC design and layout lay in the responsibility of one design engineer. Since its focus changed the design center has grown considerable capabilities in application design, product engineering, test, analog IC design, and CAD support as well as project leadership. The center is employing now 25 people. Due to this extension of capabilities the center has all functions required for a full development cycle making it relatively independent from other design centers. Although BrDC is less than 100 kilometers away from Midtronic's fab operations in Slovakia, the R&D and design operations were initially not established as links to the local wafer fab operations. Initial technology development related projects were conducted in cooperation with fabs in Japan, Czech or the U.S. Currently the main wafer fab for products designed in Bratislava is located in Belgium.

Local characteristics – enabling upgrading and driving adjustments

Midtronic is competing with other multinational semiconductor companies on the Czech and Slovakian labor market for the scarce analog IC engineering talent. Small local companies are not competitors as they are not able to pay comparable salaries and offer high technology reputation. Engineering students perceive Midtronic among the top 10 engineering companies allowing the company to be selective in their recruitment process. The company is recruiting only young university graduates with master degrees. Some engineers at the design centers have PhD degrees. The problems in finding experienced analog engineers is visible in the age of the employees, where average age in the BDC is around 32 years, with only one engineers older than 45. A similar age distribution exists in BrDC. Only at RDC does the company employ older engineers due to the operation's history dating back several decades.

To be able to guarantee the necessary number of new engineers the company is utilizing mainly two instruments. First, Midtronic has extended the scope of its recruitment area to Poland, Hungary and Slovakia. A cooperation with a Technical University in southern Poland enables engineering students to write their master thesis at BDC. However, currently still about 90% of engineers originate from Czech Technical Universities. Second, the company has quite elaborate cooperation relations with local universities, focusing on design and test as well as physics for manufacturing and technology development. Both academy relations date back to the days when the Czech wafer fab and development center were established in the 1940s. Together with an multinational EDA provider Midtronic has funded a lab for IC design classes to develop practical skills with EDA equipment. Engineers from both RDC and BDC regularly give lectures on the topics of electronic design and semiconductor technology at local universities, while students write their diploma theses at the centers. To further develop practical skills students can work during summer breaks at the company. Midtronic is also granting scholarships for students committing them to work for a fixed time at the development center in RDC after their graduation.

All Czech and Slovakian operations of Midtronic are characterized by highly stable engineering staff with very low fluctuation rates, contrary to other low-cost locations, e.g. in Asia (Mayer-Ahuja/Feuerstein 2007). Engineers with a tenure between five to nine years make up the biggest group. Contrary to other regions this quite conservative approach is not negatively connoted in the Czech Republic and Slovakia. This stability is regarded as very positive by both local and higher management, guaranteeing reliability and a consistent quality level, while experience levels of engineers are constantly improved without the need for the company to fear talent drain to competitors. Long-term planning of human resource development and a steady upgrading of the development centers' capabilities is enabled, as well as organizational costs reduced.

Salary levels are determined through comparison with annual reports from consulting companies. As no big semiconductor industry exists Midtronic's compares to the IT and related industries, where companies like HP or Sun are pushing the local payment levels. Midtronic is not able to pay these high salaries. Such a differentiation between various multinational companies in low-cost locations has been described already for the electronics industry in China (Lüthje et al. 2011). Multinational companies have different business models and strategies of organizing and regulating their international division of labor. During the last 15 years salary levels have risen considerably at the RDC, but the site manager assesses that they are still two to three times lower than those in the U.S. The entry salary for an inexperienced graduate with a good knowledge of analog circuitry is almost 50 percent more than the average monthly salary in the Czech Republic. This salary level can rise within 10 years of tenure about three times, with the biggest salary increases in the first five years of employment. At BDC the company tries to pay the median salary of the regional IT industry. Midtronic is determined to pay salaries slightly above the median level in Slovakia, but this is always linked to the individual performance of every engineer. Annual salary rises are granted in accordance to their performance and range between 2 percent and 6 percent. The individual performance appraisal is done once a year between the respective employee and his manager.

The individually contracted salary of Midtronic's engineers is a fixed one with only minor variable parts, as no special monthly bonuses exist and project related bonuses linked to project completion have been terminated some time ago. Engineers are eligible for a special cash reward, which is being paid over three consecutive year. This system has developed out of the stock options program, which was not very interesting for Czech engineers, as their salary levels have not allowed to buy too many company stocks. The situation was aggravated by regulatory frictions in the Czech Republic. Although Midtronic's salaries are not in the top echelon of multinational companies in the Czech Republic the company is providing extensive benefits, that make the job offer highly competitive. The engineers at RDC are eligible for up to 75% of their housing costs to be paid by the company for four years, with the company's share annually decreasing, to ease up moving to the countryside where the design center is located. Midtronic is offering help with housing loans for its employees. Private life and pension insurances and other social benefits at the maximum level described by the Czech labor law are part of the benefit package.

RDC's site manager is convinced that experienced engineers require other incentives than money to keep their motivation high, e.g. technically interesting and challenging engineering projects. As the fluctuation rate is very low, this motivation requirement is not so much driven by the need to retain talent but has to be perceived more in the perspective of keeping engineers productive and willing to broaden and deepen their knowledge continuously.

GDN development and upgrading

Functional upgrading is the most important process for the analysis in this study as it is linked to changes of the respective design center's relative positions within GDN through the acquisition of new functions. Midtronic's three development centers in CEE share a considerably high level of capabilities, allowing for locally integrated product development teams. These characteristics go far beyond any complementary international division of labor. The centers occupy central functions in the R&D network of Midtronic. Processes of functional upgrading that led to this status have been facilitated by technological, economic as well as institutional factors.

The development paths of the three centers are very distinct. RDC was established as a low-cost design center with manufacturing related capabilities and developed fully-fledged R&D capabilities over the years. Now it is acting as a center of excellence for many manufacturing related engineering and R&D areas. RDC is focusing on complex standard products with only limited customer relations. The initial local links between manufacturing and design dissolved over time as currently locally designed products are not manufactured in the adjacent fab. The prototypical home-base exploiting engineering center linked to manufacturing operations developed into an integrated global development center (GDC) that does not easily fit into Sachwald's (2008) typology. Although quite detached from its location, as no local markets exist, RDC is building up linkages to the local knowledge community, which it is also helping to develop. The center is providing almost no modularized development tasks for the parent company. With the modeling and characterization unit RDC is possessing characteristics of a home base augmenting R&D center as it is providing fundamental instruments used at Midtronic's R&D operations worldwide. The department's manager is influencing management decisions on technology development. To provide a high level of consistency the department has also major control functions over process changes in the worldwide manufacturing operations.

The BDC was established as a digital design company with close relations to the local academe, working with external organizations and customers from its onset. The center developed into a fully equipped ASIC/ASSP development center, able to provide solutions through direct cooperation with customers. From its onset BDC has been a standard GDC. Working in the highly modularizable field of ASIC design BDC was and is providing specific functions within the IC design process. Besides its highly integrated ASIC design teams, engineers at the center are providing modularized engineering work, i.e. physical design for international design projects, as costs are still very competitive and experience levels high. However, with architectural positions established at the design center and high levels of local integration, BDC has developed beyond a simple GDC.

The BrDC developed out of a R&D related cooperation, acting now as an integrated development center for standard products with no major customer involvement. This marks a very unique development as the center went through all R&D design center roles: initially established as a knowledge augmenting research center, moving through a knowledge exploiting phase of extended workbench engineering work, to develop into a GDC with integrated development capabilities.

The history of upgrading at Midtronic's design centers in CEE has to be seen before the company wide restructuring, driven by internationalization and consolidation. The company's focus on increasingly complex products and solutions parallels the industry wide shifts in the overall innovation model. Midtronic's technological area of analog and mixed-signal products calls for high levels of experience and broad exchange of tacit knowledge. Compared to digital ASIC projects Midtronic's project teams are quite small. This enables the company to source all necessary talent from only one site, which is keeping organizational costs low. The very competitive labor costs in the Czech Republic and Slovakia have been facilitating this process.

The current character of the company's international development operations, at least those in CEE, can be described as a network of highly functionally integrated modules, allowing Midtronic to reap gains from cost advantages and access to talent pools. Complexity of transactions within internationalized development projects is simultaneously lowered, as the number of interfaces are lowered down to a minimum through local integration. By functionally upgrading and integrating design centers in CEE, Midtronic was able to push most of the internationally distributed work out of the direct design process, to interfaces where codifiability is ensured by highly developed standards, e.g. the interface between design/layout and mask or wafer production governed by the quasi-standard GDSII data format. Interfaces for internationally distributed tasks where high levels of standardization and formalization are not possible are supported by personalized bracing points based on joint trainings and close personal contact. Examples are trainings for test specialists from the Philippines at the RDC, providing both a better understanding of technical requirements and procedures as well as the development of basic personal bonds (see Chapter 5.1.), or the regular visits by representatives of central management functions.

From the perspective of work categories the high levels of functional integration of all three design centers is rendering the integrated work as the main category. This promotes steep learning curves for the particular engineers allowing them to develop not only deep but also quite broad skills and knowledge. As all centers also house local management both for the centers as well as for projects, their development has reached important levels. However, as marketing functions are organized centrally and are based on market proximity, it seems that on the management level functional integration has its limits for integrated GDC, as they do not have a local market integration. The existence of architectural and research related positions at RDC and BDC show how the geographical patterns of innovation are changing. The RDC has a focal role in fundamental aspects of technology development, which is mostly facilitated by experience levels as well as cost considerations. The establishment of an architectural position at the BDC shows how customer requests can affect the internationalization of innovation work.

The development centers in CEE started off as low-cost design locations much in the way of extended workbenches. On the management level these centers were highly dependent on their lead centers abroad. This very low position in the company's global design network lowered the visibility of technical achievements considerably. The distribution of project leadership to offshore locations in France or the U.S. was responsible for constant frictions. The development of local management lowered sources of friction within the development process and introduced a management career ladder, extending career possibilities for engineers. By establishing direct links to the central marketing and sales department RDC gained recognition of local results and capabilities and closer market insights, helping to build up local capabilities for product ideas. On the technical level the recent establishment of both an architectural position as well as the addition of application engineers represents major upgrading steps as well as opens up future development possibilities.

Besides the overall semiconductor industry tendency to offshore increasingly more important design tasks and the long ranging history of the development centers, their gradual upgrading can be attributed to highly localized characteristics. The most important facilitator of their upgrading seems to be the very low turnover rate in all of the CEE development centers. These very low turnover rates allow for a long-term build up of technical capabilities that drive both the quality of products and predictability of development cycles, helping to reduce costs.

The upgrading of BDC exemplifies how internationalization strategies vary between companies. While the design center did not change its product and technology focus, the level of integration shifted after the ownership changed. Before Midtronic took over, the level of integration was relatively low at BDC, with highly internationalized project work. As the design center has been operational for many years, low experience levels of engineers can not be used as explanation for this situation. Midtronic's origin in analog IC design favors a more integrated project team structure, both based on technology as well as organizational considerations, that facilitates upgrading as more functions and responsibilities need to be moved to a specific location.

However, this organizational drive was limited by lack of trust both in technical as well as managerial capabilities and well as by a low visibility of achievements. For trust to build up prolonged relations need to have developed as learning processes on both sides take quite a long time. It is important for central management to learn about local technical proficiency and project completion security to be able to move increasingly complex projects to a specific development center. However, if a design center is not visible for central management, as it has only an indirect relation due to its position in the GDN, such learning processes are hindered. This calls for local management to both build up necessary capabilities and try to establish their design center as an independent entity.

3.2.2. Standard based SIPs of exotic origin

Iprov is a Polish provider of semiconductor IP (SIP) and design services. The company was founded in 1991 in southern Poland by two university teachers from the local Technical University as a value-add CAD/EDA system reseller. To strengthen the company's engineering focus the digital SIP design department was founded in 1997, followed by IC design services in 2003. In 1996 first students started to graduate from the newly opened IC design faculty at the local Technical University, enabling the company to recruit enough young engineers for its venture into SIP development. Since 2008 the company has expanded its business into analog SIP development. Iprov employs 34 IC design and design service engineers in its SIP development department, as well as 7 embedded systems engineers in a second design location in a town around 100 km away. Iprov's new analog division is located in the country's capital city and employing 4 analog engineers.

Iprov's business model is focused on commodity SIP products that are either based on quasi-standards, such as market dominating microcontrollers, or on industry wide technology standards like USB. Highly commoditized products offer price as the only competitive factor, however, as engineering labor costs in Poland are slightly below India, the company can still compete on costs. Since its start Iprov has focused very much on the quality of its products. The company founders realized, that within the IC market a company from Poland, as the CEO puts it, is "a priori dubious" through its exotic origin. In the perception of both Iprov's management as well as its engineers the ability to provide high levels of product quality has been confirmed by the repeated cooperation with big Japanese chip companies.

Lack of application knowledge was the driving factor behind the company's initial product focus on IP microprocessor cores. With this the company only provides modules used for systems on a chip (SoC). Many embedded systems were and still are based on simple microcontrollers introduced in the 1980s. The integration of these simple embedded systems onto a single SoC could only be economical if costs were kept as low as possible, e.g. by re-using software extensively, which requires microcontroller IP cores based on known architectures. Iprov's design of IP microprocessor cores is centered on the reproduction of already existent processor designs in IP based circuitry. The company is lowering costs and speeding up the processing power of the cores through incremental innovation. Iprov's initial microprocessor core was released in 1999 and until 2009 was licensed to more than 150 companies, making it the company's best selling product. However, the microcontroller cores business is not anymore regarded as strategic in the company.

Iprov later diversified into the market for interface controller SIP based on industry standards for networks as well as USB. The USB line has become the strategic product line since the decision to move into the development of USB 3.0 controllers in 2008. Although the company has already had a long experience in the USB standard, designing USB 1.0 and USB 2.0 IP cores for almost 8 years, the move towards the USB 3.0 standard was a huge step. The new USB standard required both new technologies as well as new design methodologies and tools, making huge investments as well as the restructuring in design processes and organization of work necessary.

Memory controllers are Iprov's second strategic product line. Although memory controllers need smaller investments than USB, these investments are highly dynamic as product development is being driven by constant changes in industry wide technology standards as well as customer specifications, with technology standards of memory controllers changing up to every two to three months. This makes constant interaction with customers necessary to align with their product and technology roadmaps. As development projects for memory controllers take about six to eight months, constant adaptations during project implementations are necessary.

The trend in the semiconductor industry to offer increasingly integrated solutions is also visible in the IP core industry segment, with an increasing need for sub-chip solutions. To be able to offer more complete products Iprov has set up its multimedia and analog department in 2009. The goal is to offer complete USB solutions with mixed-signal and analog functions.

The development of Iprov's product portfolio as well as engineering capabilities has been constrained both by a permanent lack of talent, especially experienced engineers, as well as the corresponding lack of application knowledge. Iprov's position in various

Global Design Networks is impeding a consistent development of application knowledge. This is a serious problem for the future development of the company's capabilities. Small IP core companies focusing on standards based IPs are facing problems, as they are developing SIP blocks that can be quite easily integrated into the whole SoC based on highly standardized on-chip interfaces, rendering deep knowledge about the system and its future application unnecessary. Furthermore, SIP core companies are separated from the application by at least one organizational boundary, mostly by two as they sell SIP cores through global distributors. Being often quite small, SIP core providers lack the financial resources to build up a group that would be able to focus on creating such knowledge in-house. Iprov is trying to overcome this problem through cooperation projects. Through its cooperation with the SPIRIT consortium Iprov has developed capabilities in the IP-XACT standard for easy SIP integration. But as the company's CEO states "we know about these things more than the market is asking for". At least Iprov's customers are not interested in this technology, which is extensively used at top-tier chip companies.

Although Iprov has also been providing SIP cores to big multinationals, the majority of its customers are small design houses – third-tier IC design houses from Taiwan and China, or small start-up companies from Silicon Valley. These companies generally focus more on cost than on leading-edge technologies. Such cost driven customers impede a technical upgrading of Iprov, as neither opportunities for cooperative technology development emerge, nor are its third-tier customers rewarding higher technology capabilities, e.g. IP-XACT. Iprov's strong US and Asia market focus developed through the distribution cooperation with Distroip, a distribution company without any distribution network in Europe. Additionally, GDNs of European chip companies are quite closed rendering the access of their supply chains problematic. The development of such relations is costly, making investments in various systematic relation building instruments necessary.

Problematic upgrading for a small partner in inter-organizational GDN

As a small SIP core provider Iprov's position and role in various GDNs leads to at least partly mediated forms of cooperation and communication, as many customer contacts are being relayed through an intermediary distribution company. This specific integration into semiconductor GDNs is impeding the development of market and system knowledge within the company, which is perceived by both management and engineers as negative. Information about customer requirements, needs and satisfaction are important both to be able to guarantee consistent quality standards as well as develop future in-house capabilities that will fit the market. Market knowledge is an important competitive advantage based on close customer links and technology cooperation, thorough market analyses as well as participation in various industry trade shows and standardization bodies. System and application knowledge is again important to be able to move up the value chain by processes of functional upgrading. The Silicon Valley is still the focal point of the industry, even for companies from an exotic location such as Poland. Iprov's manager of pre-sales customer services is convinced that an office in Silicon Valley is highly essential. A company's representative in the Valley would allow for fast and personal communication, facilitating customer contacts and cooperation possibilities. However, the company is financially not able to maintain such an office.

Integration into the various GDNs that are important for the future development of a company, is an expensive and protracted process. Engineering capabilities do not suffice as small SIP core companies are increasingly becoming service providers that need to develop various organizational and geographical interfaces to have the necessary capabilities to access GDNs. However, the integration into GDNs is not only based on technical and organizational capabilities but also on trust, ensuring quality standards as well as the easing up of cooperation. Although IP core business is sometimes perceived as a showcase model for market modularization, many of the customer relations are being described by Iprov's employees as trust based. Trust is necessary to lower the need for constant checks on quality, verification as well as design processes. When customers have been satisfied with the products and services of Iprov they are inclined to come back. The cooperation with a reputable distributor as well as a decade long experience in the market enable the build up of trust based relations. The customers' supplier selection is not solely based on time-to-market and price, but is linked, in view of Iprov's employees, to the prestige of the IP supplier. Long-time engineering merits in specific technologies translate into higher levels of trust, as they indicate that the provided IP blocks will be both sufficiently verified as well as easily to integrate by the customer. Building up of trust based relations is linked to high up-front cost on the side of service suppliers. As GDNs are based on long-term supplier relations, the access barriers for new and small companies are high. This is especially true for GDNs of first and second tier semiconductor companies. Although promising steeper learning curves as the focus is tending more towards technology based product differentiation and competition, these GDNs have much higher access barriers.

The majority of Iprov's revenues is generated through sales organized by its distributor Distroip from the U.S. Distroip is providing marketing, sales and front-line support to its development partners focusing U.S. and Asian markets. Iprov's cooperation with Distroip began with the company's venture into SIP development. As the Polish company had neither the financial resources nor the know-how to build up a distribution network, partnering with Distroip provided an easy access to international markets. The division of labor between both companies allowed Iprov to focus on its core interest in engineering work. The distributor charges around 40% of every sold SIP core for its marketing and distribution services.

Until recently Distroip has been distributing Iprov's IP cores under its own brand impeding the development of an own Iprov brand. This aggravated Iprov's problem of poor visibility within GDN adding to the already existing distance to its customers. References by Distroip to their so called development partner Iprov are oftentimes made only through generalization of development locations in low-cost countries. Iprov's manager of pre-sales customer services perceives this as a major problem as it is establishing a perspective on the company's engineering work as being of lower quality or at least simple in technological terms. Although Distroip has a technical background, it is perceived by Iprov engineers as thinking and acting more like a retailer than an engineering company. Most of the communication between Iprov and its customers needs to be relayed through Distroip. As Iprov is cut off from direct customer contact the company is not able to present its full range of technical and customization capabilities.

Iprov cooperation with Distroip lowered the barriers of market entry for the IP provider considerably through the possibility to outsource sales and marketing, simultaneously impeding the development of market knowledge. Iprov's CEO presumes no purpose on the side of their distribution partner but links this problem to opposed priorities. He sees Distroip's priorities in the development of its own brand and not providing extensive information for Iprov. Perceiving themselves as an engineering company, Iprov did not pay too much attention to market information for a long time. Only recently the company realized the importance of such knowledge, starting to ask Distroip for this information and is now obtaining market and customer information in a much more systematic way.

After realizing how important direct customer contacts are Iprov has started to develop its sales and marketing capabilities in a more systematic way by employing a foreign industry veteran as head of marketing and sales in 2009. Iprov's presence on the European market was until recently nearly negligible. The entrance into the European market is an opportunity for its new in-house sales and marketing team. To be able to provide a fast and direct support for the growing number of the company's customers in mainland China, the position of a China country manager has been announced in mid-2010. Establishing such a direct local customer interface is also a way to improve the company's knowledge about future IP requirements in the Chinese market.

Iprov is integrated in the GDN of major FPGA providers as a member of their third party supplier programs. Participation in these design networks is often linked to high upfront costs without a revenue guarantee. One FPGA provider is gathering information about Iprov's roadmaps through Distroip, sometimes suggesting future directions for product development. As the cooperation is relayed through Distroip Iprov is not able to directly participate in discussions concerning these topics, which is regarded as impeding. However, Iprov has build up direct relations with a smaller FPGA provider's European operations cooperating on specific customer projects.

Iprov is providing design services to various companies. Msystems is their oldest customer with extensive cooperation linkages since 2001. The first design service project had the character of a design capability test. This was followed by sub-contracting parts of customer projects, to lower overall engineering costs and allow Msystems to focus on higher value-add activities. Iprov is still providing this kind of design services, that focus on the customization of already existing Msystems products. Such design services are not technically demanding and do not drive the development of Iprov's design capabilities. However, as the trust of Msystems towards Iprov's design capabilities has grown the design of whole modules is being sourced out to the Polish company, which are later integrated by Msystems.

The cooperation with Msystems triggered dynamics on the organizational and management level of Iprov. Before cooperating with Iprov, Msystems required the company to systemize its quality management. Iprov established a quality management system by developing its previous design procedures into an integrated development process that complies with international standards. The newly responsible manager for quality management oversaw the reorganization of work organization, customer relations as well as pre- and post sales support. This pushed the company towards a more systematic organizational structure, moving to product lines as well as a clearer definition of responsibilities within the design process as more stringent interfaces with the customers became necessary.

Providing design services can develop into a fallacy for SIP companies. Design services can serve as a very good source for information about what customers are doing, where the overall market is heading as well as what application will be interesting in the future, bolstering the company’s aim to develop market knowledge. However, as design service projects are often focused on the integration or modification of already existing SIPs from other SIP companies, the limits to derive information for own future IP projects are very tight, as venturing into SIP markets connected with former design service projects could result in IP theft charges.

In the beginning of 2010 Iprov announced a cooperation with a German foundry focused on analog and mixed-signal wafer manufacturing services. The cooperation has resulted in the development of physical IP libraries of Iprov SIP cores, that allow the foundry’s customers to easily integrate these cores into their IC designs. Just like leading digital as well as analog and mixed-signal foundries worldwide, the foundry is raising its control over the highly modularized supply chain through the organization of an ecosystem, to enable the provision of integrated and verified product solutions. Such cooperation allow for alignments early in the process of design and technology development. Iprov is among around 10 other IP providers that cooperate with the foundry on the development of IP cores. Through this cooperation Iprov has moved closer towards manufacturing offering the company the possibility to develop relevant knowledge in physical design. Until now Iprov has no layout capabilities as SIP core development does not necessarily require know-how in physical design. Iprov will be able to develop fully integrated design services, ranging from specs through synthesis to physical design and layout, at least regarding analog and mixed-signal projects.

Since several years Iprov is participating in the USB Implementers Forum, a non-profit corporation founded by companies that developed the USB standard. This involvement secures early access to new USB specifications as well as possibilities to voice the company’s opinions during the process of standard definition. However, the company only had a passive member status which is prohibiting an active influence on the development of the standard. Active participation in standard definition bodies is putting a much higher demand on the company's engineering resources, requiring a sufficiently big and experienced R&D department capable of contributing to the development process.

The local labor market as barrier for upgrading

The Polish semiconductor industry was highly neglected during the socialist era, even in comparison to other countries in CEE, leaving neither experienced engineers nor local companies in the field of IC design. Iprov is the only local company active in IC related design and development in Poland. With only four universities in Poland offering a curriculum focused on hardware development and chip design the labor market for IC design engineers is very tight. As there is still almost no semiconductor industry in Poland, Iprov is only able to recruit fresh graduates and needs to invest heavily in their training. This lack of engineering talent is seen as the biggest restriction to the development of technical capabilities of Iprov.

The labor market situation has become even worse since multinational companies have set up R&D centers in Poland. As all of the multinational companies focus on software development in their Polish operations, the labor market for IC design specialist has not been positively influenced by their presence. Local engineering companies are in a disadvantageous competitive position both due to their lower wage levels as well as limited career opportunities. Iprov experienced this surge in labor competition three years ago when Mentor Graphics took over R&D operations in a nearby city. The EDA company was looking mainly for software engineers who had experience in testing and using EDA tools, offering up to 75% higher wages than Iprov. The company was not able match these wage rises and some engineers moved to Mentor. However, wages increased substantially and all of the first generation engineers stayed at Iprov. Iprov is paying graduates and young engineers initial wages that are comparable to the regional average wage. However, as the initial wage is linked to grades and capabilities it can be up to 75 percent higher. These wages are around the median wage levels for the IT sector. Experienced engineers can earn up to 50 percent more than the median wage in the IT sector. Engineers in the analog subsidiary in Warsaw earn even higher salaries, both due to their specialization as well as different local wage levels.

Iprov has a very low fluctuation rate, which is driven by both biographical and cultural factors as well as labor market dynamics. Engineers are working mostly since the start of their career at the company, with tenures up to 11 years. After working for a long time as IC designer the specialization level of these engineers is quite high, without any possible other employer in sight, as IC design is only a niche activity in Poland.

Most of the engineers are former students of Iprov's CEO, who is still a lecturer at the local Technical University. The cooperation with the University is very close, with students being able to complete mandatory internships at the design center. Students with a higher interest in IC design are offered internships up to four months. The company also offers students the possibility to work on their diploma thesis at the company, both offering professional help as well as hoping to find future recruiting candidates. Iprov is trying to recruit engineering graduates also from other universities. In addition to both company founders, only the leader of the new analog department is a PhD. However, the company is employing three PhD candidates. Three more engineers have voiced interest in PhD research. The company has a positive attitude towards PhD ambitions of employees, paying for tuition for PhD studies as well as working towards an arrangement between working and research hours. Besides helping their employees expanding their specialization, the company is also hoping for a possibility to expand its R&D activities through PhD projects that are aligned with its strategic technology development plans.

GDN position and upgrading

As a small provider of commodity SIP, Iprov's position is at the lower end of the value chain with a role as a highly dependent company struggling for upgrading. Iprov is a prime example of how the history of a company's integration into GDN combined with general characteristics of GDN and the business model as well as local factors define the very specific development path that sets certain limits to upgrading processes on firm level. Iprov's Polish origin exacerbates the problem adding uncertainty on the customers' side as the country is not known in the semiconductor industry as a design location.

The silicon IP market is highly competitive with low profit margins. Big EDA companies and foundries are offering IP cores as add-ons for their tools or wafer manufacturing sales, keeping prices under constant pressure. The myriad of small IP companies from Europe, Asia and the U.S. are an additional competitive threat. Most of the SIP sourced by chip companies are standard based cores that allow to focus their valuable in-house capabilities on higher value-add parts of the development project. Companies like Iprov are caught up in price competition that is impeding the development of technical capabilities necessary for substantial upgrading processes.

SIP providers are highly dependent companies within semiconductor GDNs, with the only exception of companies that have highly proprietary products, such as ARM or MIPS, that are leading edge and allow both for high profit margins as well as standard setting. This dependence is visible in the developing service character of SIP companies, that are increasingly required to offer fully developed customization possibilities for their customers. For companies such as Iprov that offer commodity SIP the difference towards design services is gradually dissolved. Combined with the very low and dependent position within GDN this process is impeding the upgrading of the company in two fundamental ways. IC design services require a different organization of work and drain resources from strategic development projects aimed at moving towards proprietary IP that would allow to command higher profit margins. Additionally, SIP design and design services are mostly exclusionary business models as problems of IP theft have to be observed.

The way how Iprov entered SIP business and various GDN set the company on a very specific development path which structured the development of the company fundamentally. Limited by local labor markets the company entered the SIP market as highly depended on both standards as well as its distribution partner. The dependency on its distribution partner restricted the innovation and upgrading possibilities of Iprov essentially. As SIP development is highly service oriented direct contact with the customer ensures the ability to offer customization services that allow for higher margins. This possibility is partly lost when customer relations are relayed through a distributor, making even simple communication too complex for fast reactions.

Specific path dependent cognitive barriers on the side of Iprov also influenced upgrading of the company. As the company's management and engineers perceived themselves only as technical experts, they did not recognize the importance of market knowledge for a long time. With this development of projects sometimes tended to miss market requirements. A representative example is the development of IP-XACT capabilities in the company. This project was driven solely by the technical interest of the engineers and founders of the company, who highly valued the technical possibilities of the technology. However, Iprov's customer base is not interested in this technology which is used only at major chip companies. Developing technical capabilities is not the sole factor for upgrading processes. The capabilities of a company always need to be in accordance either with its target markets or strategic decisions based on market knowledge.

Iprov's integration into semiconductor GDNs through a distribution company can be perceived as a generalizable example for many small companies in the semiconductor industry. Allowing for a fast market entry through the outsourcing of marketing and sales activities to a distributor, the SIP company set on a path that emerged as at least partially impeding upgrading processes, as mediated forms of communication and cooperation with customers prevail. Although Iprov's customer relations are often long-term and trust based, the communication is mediated through their distributing partner. Being removed from direct customer contact not only lowers brand recognition, as distributors often market products from small suppliers under their own brands. Even more important, the absence of direct customer relationships impedes the development of market knowledge. Market knowledge is the paramount capability for companies like Iprov that cannot create a market through leading-edge innovative products, but as they provide commodified products have to respond to a highly competitive market. Market knowledge allows for a more efficient use of the company's technical capabilities and resources, as development projects can be aligned to future customer needs and foreseeable market demand can be served faster, allowing for a better competitive position. Market knowledge therefore is highly important to be able to frame a development strategy that would allow the build up of capabilities, both technical as well as organizational, for future demand. Small companies that neither have the necessary financial nor research resources necessary for radical innovations need to find other ways to be able to shift beyond incremental innovation. The model of architectural innovation is such a possibility where limited technical and financial capabilities can be used for the development of products and services that do not only compete on price. One of the fundamental prerequisites for architectural innovation is market knowledge. The case of Iprov shows how the development of this important resource can be impeded by the position and relations within GDN.

Only since Iprov understood the importance of the fusion of engineering capabilities with market knowledge the way to extensive changes of the company's strategy were possible. This change in the company's self-perception resulted in processes of functional upgrading. Through the installation of an own marketing and sales department and the subsequent China customer support the company integrated these very important functions. Although the distribution cooperation with Distroip still exists Iprov is now moving towards a different network position, where it integrates marketing and sales data into its development process in a strategic and systematic way.

With its newest employments Iprov is clearly responding to the problems created by the specific integration into GDNs through its distribution partner. The very nature of the employment strategy, recruiting industry veterans from abroad, points to one of the major limits in the company's development and upgrading strategy. The lack of experienced talent both technical as well as managerial is impeding any upgrading strategy. As a company founded by engineers originating from the university Iprov is perceived by its owners and employees as an engineering company focused purely on technical solutions putting almost any marketing considerations aside. However, lack of management talent is nothing specific for Poland or CEE but is a known problem for almost all developing markets. The lack of almost any engineering talent is quite specific for the situation of hardware development in Poland. This lack coupled with absence of any experienced hardware engineer translated and still translates into a design work force with almost no application knowledge, making architectural innovations impossible. Iprov's initial business focus on microcontroller IP cores was driven by this lack of engineering capabilities as only products based on the transfer of already developed trailing edge products into IP cores could be developed. Standards' based products are quite similar as industry standards such as USB provide very stable development guidelines and framework. Iprov's mediated form of integration into GDN impeded learning processes focused on application knowledge as the company's engineers could neither learn about the final systems nor about their usage. Iprov's attempts to move increasingly towards applications have only begun and are characterized by very incremental successes. This underscores how both financial and, maybe even more importantly, managerial resources are of prime importance to be able to drive upgrading strategies.

The limitations of the local labor market are aggravated by the lack of any semiconductor industry agglomeration in the country. For the near future there seems to be no second source for engineering talent in sight. Multinational companies that opened design centers in Poland until now only use the capabilities and the experience of engineers from Iprov. As they focus on software development for chips or chip design, these companies need engineers with experience in chip and hardware design but do not develop these hardware development capabilities further.

Analyzing Iprov from the perspective of work categories (Gereffi 2005, Huws/Ramioul 2006) it becomes apparent how GDN position and upgrading path affect the level of work. Although the company's engineers perform various functions and are quite experienced in developing SIP, their work can not be categorized as integrated. The design projects executed by Iprov are either highly driven by externally set narrow limits, such as in design services, or customer driven SIP development. In the case of processor SIP development, despite quite specific work requirements, the projects are still based on the idea of a complementary division of labor and a highly modularized development process. With this auxiliary work, or modularized work is the predominant work category at Iprov. However, this is not surprising for a SIP company focused on standard based products competing through price. The company's move towards solutions, with the establishment of its analog design center, and the integration of marketing capabilities point towards the possibility of developing integrated positions.

Iprov upgrading processes are mostly focused on process and product upgrading resulting in better production methods as well as more sophisticated products. The most prominent driver of process upgrading at Iprov was the integration of the company into Msystems's GDN. IC design services as well as IP development require stringent quality management that meets international standards. Within an IP market increasingly focused on customization and services certified compliance with international quality standards becomes an important asset. Although Msystems is using Iprov design services still often in a highly complementary division of labor, the initial requirements drove Iprov to systematize its development process fundamentally. The implementation of a standardized quality management system forced Iprov to analyze and reflect its own development process in full. A more systematic organization of the hitherto evolved structures involved not only clearly defined interfaces between the company and its customers in pre-sales and post-sales activities but also facilitated changes in the organization of work. Parallel to the increasing shift towards the customization of IP development the implementation of a quality management system fueled the organization of work around product lines, requiring engineers increasingly to specialize within these clearly defined areas, allowing for a more efficient build up of expertise.

Most of the company's upgrading was driven by its diversification strategy that aims at a more efficient utilization of its engineering talent as well as the development of access to new and dynamic markets. The venture into USB 3.0 was enabled by participating in the development forum, which is a major part of the USB GDN setting future standards. Although Iprov is not able to actively influence the standard setting process as it lacks both financial as well as R&D resources, the company benefitted from the early access to information about the future standards. This product upgrading resulted in process upgrading as SIP development methodology and organizational structures were adjusted to the new product line and its differing technical and organizational requirements.

One of Iprov's focus in its diversification strategy is to further develop its design services. However, providing design services can develop into a fallacy for SIP companies. Design services can serve as a very good source for information about what customers are doing, where the overall market is heading as well as what application will be interesting in the future, bolstering the company's aim to develop market knowledge. However, as design service projects are often focused on the integration or modification of already existing SIPs from other IP companies, the limits to derive information for own future SIP projects are very tight, as venturing into IP markets connected with former design service projects could result in IP theft charges.

The shift towards a service and customization oriented IP provision is further advancing the need for longer termed and trust based relations with customers. Iprov's case offers valuable insight for discussions on complexity and codifiability of transactions. The SIP model is following the logic of modularity based on highly standardized interfaces. However, the need for reviewing quality measures, verification procedures as well as the whole design process is driven by the high levels of complexity of the development and integration process itself. To lower the number of necessary checks of suppliers, customers tend to prefer long-term relations even for standard based IP cores. Trust based relations, including complex learning processes, are required to safeguard certain levels of quality, that go beyond conforming to stable interface designs. Such relationships also involve higher levels of control to both align the companies' development processes as well as product roadmaps. The increasing service character of IP development calls for a further broadening of customer cooperation that goes beyond a market coordinated arm's length relations, requiring high investments in capabilities beyond technical dimensions as organizational and geographic interfaces need to be developed and maintained. Although long term relations characterize the way Iprov is mostly integrated into various GDNs, the fact that the company is offering standard based products with a focus on price makes it vulnerable to customer changing their suppliers as high levels of competition prevail in this market. The specific hierarchies and power relations within GDN distribute risks and costs of such long-term and trust based relations unevenly between the cooperating firms

Although companies like ARM or Wipro, focusing both on architectural as well as highly integrated work, are in the markets for IP cores as well as design services generally companies in this market are providing auxiliary work. Iprov is a prime example of such auxiliary work as the company only recently started to build up capabilities for physical design through the cooperation with the German foundry. Until then the company had capabilities that allowed only for a quite limited development process, positioning it at the lower end of skill levels within the international semiconductor industry. On the level of management work Iprov had until recently also only limited capabilities as marketing and sales were almost completely outsourced.

3.2.3. The slashed IDM

Leadtech is a German IDM developing and manufacturing semiconductors and system solutions focused on automotive, industry application as well as for chip cards and security solutions. Leadtech is one of the leading companies on these markets. The company has had a eventful history since it was spun off through a successful initial public offering from its parent company, a major German engineering conglomerate and electronic system supplier, in 1999. The company employs around 26,500 people as of September 30, 2010. Around 5,700 employees are working in its worldwide R&D operations with 50 percent employed in German R&D centers (Company Annual Report). The company has R&D centers in Austria, China, Germany, India, Italy, Romania, Singapore, Sweden, U.K. and the U.S. Leadtech's manufacturing operations are in Austria, China, Germany, Hungary, Indonesia, Malaysia.

Initially Leadtech was a traditional IDM with a very broad product portfolio, ranging from high-volume memory chips, to communication solutions wireless and wireline consumer and infrastructure markets, to automotive ICs and highly-specialized power semiconductors used in industry applications. The company employed in its peek times over 36,000 people worldwide. Driven by pressure from financial markets and in line with the general development in the semiconductor industry of further vertical specialization and triangular restructuring Leadtech increasingly narrowed its product portfolio while initially moving towards a fab-light strategy. This has translated in an inconsistent ongoing process of restructuring.

The company's first and most major restructuring move was the spin off its memory chip business in 2006. However, after the spin off Leadtech was unable to divest substantial parts of its ownership in the new memory chip company, while the new organizational boundaries were impeding technological cooperation and knowledge exchange. The financial crisis of 2008/09 aggravated the new company's problems driven by the memory chip highly volatile business cycles and the company had to file for insolvency protection in the beginning of 2009. As the main shareholder Leadtech incurred severe financial repercussions from this insolvency.

In its ongoing restructuring Leadtech put the biggest focus on the wireless business, as the company had fundamental merits in this technology segment. Leadtech was already one of the leading companies in the wireless market, especially in the segment for highly integrated solutions for ultra-low cost mobile phones. However, these single-chip platforms were not essential profit margin generators. Despite its leadership in the development and integration of RF, power and baseband functionalities the company lacked development capabilities for application processors and extensive connectivity functions such as Bluetooth or GPS. This impeded Leadtech to fully enter the very dynamic market for smartphone chip platforms that guarantee high profit margins. Smartphone chip solutions call for increasingly huge investments in platform design that have to be offset by high sales, which poses a risk for a technological latecomer with extended financial issues such as Leadtech.

To be able to establish a competitive position in the wireless market Leadtech strengthened its wireless business through several acquisitions in 2007. The biggest acquisition, a €330 million take over of an entire mobility products group including around 700 employees, was mainly driven by the possibility to expand its customer base. This investment seemed necessary, as Leadtech has fallen victim to processes of vertical specialization and triangular restructuring that resulted in the loss of its largest wireless customer. However, these acquisitions did not advance Leadtech's technological capabilities for smartphone chip solutions substantially. The required investments that would enable the development of technological capabilities for the smartphone chip platforms were still substantial. Additionally, the financial market crisis of 2008 did not provide a favorable setting to venture into such huge and risky investments. Only three years after initiating its strategy to develop into a wireless powerhouse Leadtech ended this venture completely. In 2010 the company announced the sell off of its entire wireless division to a major IDM.

Already in 2009 Leadtech sold its wireline division. With these two disinvestments Leadtech almost completely moved out of the communication and consumer markets focusing now on three business lines that provide chip solutions for the automotive, industrial as well as security. This resulted in a loss of relevance in the overall semiconductor market as the company has abandoned the business lines that were its major revenue sources. However, from a profit margins perspective the company will be able to rise and stabilize its margins considerably in the future. The dynamic development in the markets for automotive as well as renewable energies and smart grids will give Leadtech steady possibilities for growth of its revenues as a specialist chip supplier.

Abandoning communication and consumer products, almost completely based on leading edge digitally process technologies, marked a fundamental shift in Leadtech's business model and manufacturing focus. Previously the company pursued an increasingly fab-light strategy coupled with strategic technology development partnerships to guarantee manufacturing and process development capacities. For the most important CMOS digital process technology Leadtech was planning a considerable extension of wafer manufacturing outsourcing of up to 50 percent, while developing its multi-sourcing strategy that would limit dependence from suppliers. The development into a fab-light chip company, that would have maybe resulted in an almost fabless business model, seemed already predetermined.

Leadtech's analog and power manufacturing activities were using outsourcing of wafer manufacturing only as a possibility to increase flexibility of production. This results in outsourcing ratios for analog and power products that are far below 10 percent for wafer manufacturing and below 15 percent for assembly and test. The strategic business refocus substantially lowered the overall outsourcing ratio establishing Leadtech again as an IDM with extensive manufacturing capabilities focused on analog and mixed-signal chips. The reinvigorated importance of manufacturing is also evident in the strategic investments the company is undertaking. In 2011 Leadtech announced the acquisition of the remaining fabs of its former spin-off company in Eastern Germany in 2011. Leadtech is planning to set up volume production of 300mm wafers for power semiconductors in the former memory chip fab. Moving to 300mm wafers for power semiconductors will require substantial investments and enable the company to catch up with analog industry leaders such as Texas Instruments, that already have announced 300mm analog wafer production.

Differentiated upgrading in a developed location

The company's only development center in CEE is located in Bucharest, Romania. The country has a long history in the electronics and semiconductor industry, with own IC development and wafer manufacturing operations developed already during its socialist era. This has left behind capabilities mostly on the educational and research level, such as the National Institute for R&D in Microtechnologies IMT in Bucharest, which is a internationally renowned research organization. The IMT developed in the beginning of the 1990s partly out of the remnants of the R&D operations of the local semiconductor IDM Microelectronica. Already at the end of the 1990s, after the political situation started to stabilize in Romania, the first multinational IC development companies located their operations in Bucharest. The numerous well educated semiconductor engineers coupled with very low labor costs and cultural and geographical proximity provided an interesting offer for companies that were willing to take a risk. Initially the companies were mostly small start-ups and specialist IC design houses with highly cost-driven business models, mainly in markets for analog and RF products. Many of these operations have changed ownership several times during the last ten years. Today Romania and especially Bucharest is a well established specialist location for IC design, hosting several design centers of big multinational semiconductor companies.

Leadtech started its IC development operations in Bucharest in 2005 to tap into the talent pool of experienced and still cheap IC engineers. As Bucharest has been developed by multinational companies since around 2000 as a location for IC design, Leadtech was able to hire engineers with several years of experience both in IC design as well as in international development projects. The Bucharest development center (BuDC) was lead by the company's Austrian development operation, which also provided most of the initial training. The Austrian development operations were initially leading BuDC in all technical and managerial aspects. This situation has changed over the last years. However, although managerial positions have been increasingly staffed with local management talent, the design center manager is still an expatriate from Austria. Since 2008 local department managers exist while local team leader were in place almost from the beginning.

In 2010 BuDC employed around 200 people, giving it the status of a medium sized development center in the intra-organizational GDN of Leadtech. This can result in future problems for the design center, as it neither has the size to be indispensible in the short run, nor the high specialization and technological capabilities of a small research oriented center. However, 2010 saw also further investments in the location, both by expansion of its premises by around 20 percent as well as the installation of new machines. As Leadtech is strengthening its position in the automotive market these investments seem to indicate further confidence in this the design center.

BuDC is focusing on automotive applications and chip cards. The automotive department of BuDC is cooperating with development centers in Germany, Austria and Italy. Initially a RF wireless department was located in Bucharest, contributing substantial work for the company's smartphone solutions. The 2008 financial crisis triggered another round of restructuring that resulted in the concentration of RF design capabilities at the company's headquarters in Germany. To keep the engineering talent, the Romanian engineers were offered jobs in other departments of BuDC. This high level of commitment to a relative job security was perceived a positive by the employees of BuDC.

Within its five years of existence BuDC was able to develop already substantial technical expertise that translates into at least partial independence from other development locations. After the initial phase that lasted to around 2009 during which the employees and processes were set up, the development center is now regarded as a fully-fledged location important for overall business and performing central projects for major customers. BuDC was already able to develop into a competence center for one specific product group. Within another product line the center is able to initiate new projects taking overall responsibility for their execution. In the new field of mixed-signal chips for power BuDC was also able to develop unique knowledge and gained technological responsibility.

In its initial phase BuDC served mostly as a support for German, Austrian and Italian development centers, along the line of a complementary division of labor. However, Leadtech is trying to minimize the number of such multi-site projects as the higher number of international interfaces is limiting efficiency and speed of project completion translating into higher development costs. Projects for the automotive markets allow for single site projects as their size is small, mostly not exceeding 10 to 12 people. The integrated project character eases up the build up of experience based knowledge which is much more important in the field of analog chips. However, multi-site projects still occur and BuDC can sometimes take the leading position in such projects if the main IP is located in Bucharest.

As Leadtech has no local manufacturing operations in Bucharest the integrated development projects still have international interfaces. Especially the test department needs such interfaces as it is working closely with manufacturing sites in Asia. Although test engineers are working with highly standardized technical interfaces the development of personal bonds is still very important to develop a mutual understanding and a communication level that allows to work efficiently over the distance of several thousand kilometers.

> *"This is the thing that we are also doing with the fabs, most of the test engineers, went to the fabs in Asia, to meet the guys there. Because, you go there and you work during the day. In the evening maybe you go for a beer, there is a different relation created. And this is quite important because you communicate with the person outside the office and that's nice because you can ask them about their culture, see how they are thinking, their way of being. [...] It is easier to spend some time on one day to make a pseudo-training, a little training, to discuss certain specification, which you find recurring."* (Test Engineer – BuDC)

Such international interfaces result in higher costs on the company level as the efficiency levels are lowered, especially during the initial phase, as well as travel costs are constantly incurred. This situation also affects the engineering labor process and drives skill shifts on the level of engineers. Although the cooperation is organized through standardized and formalized processes and communication channels, it requires informal stabilization initiatives by the particular engineers (see: Chapter 5.3).

The BuDC is working over the complete value chain, from concept to product ramp-up: engineers for analog and digital design, analog IC layout, analog and mixed signal behavioral modeling, design flow support, test as well as product support are in place and allow for locally integrated development teams. The competence level of these engineers is regarded as almost as high as in other locations. However, this has to be put into perspective as engineers in other locations have experience levels that sometimes exceed 25 years. Almost all of these functions were in place in Bucharest from the beginning. Even the highly important function of concept engineers was initiated quite early in BuDC. After the center existed for around one year some of the very experienced engineers were give the opportunity to assume responsibility for concept design. The concept engineer is an architectural position with lead and control functions during the design process, reviewing the compliance of the design to the initial concept.

> "*But after two years being technical leader I decided to move to concept engineering due to the fact that is more challenging. The responsibilities are on another level. Working with the customers, working directly with application engineering, defining the products at the end. As technical leader, as analog designer the responsibilities were to implement the data sheet, I had to do the chip. But now I have to define the data sheet working with application engineering, discussing with the customer, and then defining the chip, architecture the chip, the blocks and so on. I find this more attractive from a technical and challenging point of view.*" (Concept Engineer – BuDC)

The concept engineer is focused more on the chip itself contrary to the application engineer whose focus in on the whole environment, the PCB and the system. This is of course setting limits to architectural decisions that the concept engineer can make. However, the architecture of a chip within a give system is still the result of a architectural choice made by the respective engineer driven mostly by economical and technical consideration.

Application engineering is not located at BuDC as all products developed at the center are focused on customers outside of Romania. Several engineers at the BuDC approached the company's management to move into this position. Leadtech refused based on the non existent local market. Since several years Romania is developing into an internationally renowned automotive location, with various multinational OEM setting up their manufacturing operations in the country. After successfully manufacturing cars for several years in Romania Renault established a local R&D center. This development center is the company's biggest outside of France, establishing Romania as an important R&D location in the automotive industry. Although this can result in possibilities for local cooperation for BuDC they are quite limited as the interface for chip companies in the automotive sector are mostly tier-1 system suppliers.

The technology and methodology and behavioral modeling department in Bucharest is involved in the technology development processes of the company, focusing on the services for design flows and further development of automation. As the German headquarters are both taking the lead and are the location of technology development and technology modeling there is a clear complementary division of labor, where BuDC is responsible for the less complex parts of technology development. However, within the field of behavioral modeling the BuDC department was already able to develop substantial capabilities and IP. Behavioral modeling is gaining importance as customers are increasing requesting the ability to model their future device in software before going into production, to speed up system development. The increasing technological complexity, driving system level design on the chip level, as well as dynamics of vertical specialization and triangular restructuring that increasingly shift system development capabilities towards chip suppliers require the build up of behavioral modeling capabilities on the supplier level. It will be interesting to see how these structural dynamics will influence the importance of the behavioral modeling capabilities existent at BuDC and affect its role in the technology development of Leadtech's GDN.

The position of program managers is at the intersection of business line management and pure development. Since some years program managers at BuDC are locals, regularly recruited from the center as this secures both the required knowledge about the company's processes as well as the industry. Together with marketing, which is not located in BuDC, program managers are responsible for a specific project from idea until production ramp-up. They manage the cooperation between marketing and sales departments, application, concept, design engineers, technology and package departments as well as quality control during test and product qualification. Before taking the responsibility of project execution, i.e. the implementation of the product's specifications, they are involved in the initial phases of a project in the definition of the technical specifications in cooperation with the customer.

Although BuDC was almost from the beginning locally highly integrated with a complete development cycle, the complexity of the located development projects was lagging behind. Derivative projects were the main focus of the development center. This involved mostly shifting an existing project towards another process technology as well as fixing bugs in existing products. This situation, where on the one hand technical capabilities exists but are only used for technically not very complex and sophisticated tasks, is changing. The learning phase was important for both sides – engineers as well as the company. The engineers had to get accustomed to the company specific development processes and technologies, while the company's management had to learn about the new capabilities at the BuDC as well as build up enough trust to locate increasingly complex projects in Bucharest.

> *"But after 4 years we started to do our chips, to define our competences. Completely new projects."* (Concept Engineer – BuDC)

The complexity of the projects is now comparable to other Leadtech development centers. And as there are already two center of excellence at the BuDC initiation and responsibilities of projects are also located in Bucharest. Projects in a completely new technology as well as innovative and risky projects are still mostly located at development centers in Austria and Germany. Although most of the engineers described a steady and positive development of the complexity of projects located in Bucharest, a minority voiced its opposition to this view. These engineers still perceive BuDC as located on a lower position within Leadtech GDN, with both technical and organizational limits that are linked to such an unprivileged location. However, a definite upgrading both on the capability as well as complexity level is not denied by these engineers.

Drying-out labor market as future threat for upgrading

Similarly to the Czech Republic Romania's long history of semiconductor industry made it interesting for multinational companies. Although international companies started their investments later than in the Czech Republic, Romania was integrated quite successfully into the GDN of the semiconductor industry. However, both lacking a dynamic local market for semiconductors, local electronic system companies as well as a population of engineering talent that is comparable to that in China or India, the country can only exist as a small and quite specialized engineering location. The size of the Romanian labor market for IC design engineers small. Although the country was able to provide relatively many highly experienced analog engineers in the past, the numbers have to be put into perspective. The design center general manager estimates that the whole Romanian labor market can currently provide around 700 to 1000 engineers focused on microelectronics, out of which around 300 to 400 could be classified as analog experts. Additionally, the labor market is increasingly drying-out. This development is already limiting a dynamic expansion of design capacities in Romania, putting the location into an unfavorable position in the international competition with Asian locations. Development centers in Asia are still mainly specializing in digital IC and software development. The very high fluctuation rates in Asia impede the development of extensive experience required for leading edge analog IC development. However, as chip companies are gradually able to tackle these problems in Asia, IC design engineers are building up experience in analog design. With the massive numbers of engineering graduates Asia can become a heavyweight also in the analog field.

The general manager of BuDC describes the most fundamental problem for the future of the Romania semiconductor industry as an institutional one. Governmental agencies are not interested enough in microelectronics, focusing the overall very small R&D

contribution of the country on other fields. As software development centers are offering quicker ramp up and bigger employment numbers, they fit better with the dynamics of political cycles. Since several years Romanian technical universities have shifted their educational focus away from analog semiconductors and related field of engineering. As big multinational software and IT companies have invested in Romania heavily and are also offering jobs that are more attractive based on higher salaries, increasingly more students focus on software development. This shifted focus resulting in lower graduate numbers as well as inferior engineering training reduces the attractiveness of the location for analog chip design.

The post 2008 crisis European labor market for engineering talent is yet another threat for Romania as an IC design location. As German and Austrian economies gain momentum facilitated by dynamic growth in Asian markets, IC companies lack engineering talent to be able to cater for all their new development projects. This has lead to a further internationalization of the engineering labor markets within Europe. Experienced Romanian IC engineers are migrating to development locations in central Europe where they are offered far higher wages. The BuDC has lost at least ten of its engineers to companies in Germany. As only the most experienced engineers are being offered positions in central Europe, the brain drain is weakening the ability for upgrading for the whole Romanian semiconductor industry.

To be able to secure enough engineering talent in the future the manager of BuDC is already developing strategies for a regionalization of the labor market. This involves the initiation of a cooperation with a technical university in Moldavia, a country on the north-eastern border of Romania. As the wage levels and living standards are far below those in Romania this would allow for the stabilization of development costs at the BuDC.

As the local labor market is drying out and universities increasingly shift their curricula away from the analog field the company needs to invest substantially in the development of its engineers. The company has already developed extensive cooperation relations with universities from Bucharest and Iasi. Engineers from BuDC regularly hold lectures that are focused on power semiconductor topics important for engineers working at the BuDC. The company is also driving changes in the curriculum of the master degree program at the Technical University in Bucharest. The most important part of these cooperation are the internship programs, with around 30 students in the whole development center.

> *"Then we have some summer internships, some students from the 3 or 4 years or 2 year they come to work for us for 3 months. And this also gives us the possibility of selection. We evaluate them over the summer, if there are some that we really like, we can make them an offer to work part time. Of course when they finish their studies they can come and work full time. Then they are already integrated, know the projects, the team. This is then very smooth."* (Program Manager – BuDC)

The workforce at the BuDC is being described as quite stable with fluctuation rates around 8% per year. As the manager of BuDC was managing design centers in Asia before he took over his position in Romania he perceives such a fluctuation as quite low, however compared to other locations in CEE it is considerably higher. This is the downside of a small but relatively well developed local labor market, where many IC design companies exists and also compete for talent. During the crisis of 2008 Leadtech was the only chip company in Romania that did not lay off engineering staff allowing the company to build up trust on the side of its engineers. This strategy was however more informed by the fact, that the company wanted to be able to ramp-up quickly after the crisis. Nonetheless it is interesting to see how employees in peripheral locations are granted with similar job security as employees in central locations of the company. However, the specifics of the local labor were certainly an important factor in this strategy. The very competitive and limited labor market penalizes companies for low job security, as the ability to recruit experienced personnel is highly restricted.

Salary levels at BuDC are quite high in comparison with the average wage levels in Romania. The BuDC HR management is using independent benchmark analyses of the local labor market to establish appropriate wage levels. However, a big diversity in the internal wage levels for comparable positions is reported, which is especially true for engineers working at BuDC from its beginning. This is linked to the negotiation capabilities of the respective engineer. The average net wage level at the BuDC for an engineer with an experience of three years is about three to four times of the Romanian average wage. Department managers are earning up to twice as much as engineers, approaching slowly net wage levels of Germany and Austria. However, overall costs for the company are still up to three times lower per employee than in locations in Germany. The manager of BuDC perceives Leadtech as one of the best paying technology companies in Romania. From his perspective this is necessary to tie the engineers to the company for a long time.

Engineers have quite a different view on the wage levels offered by Leadtech at its Romanian development center, as the cost of living in Bucharest is often comparable to other metropolitan areas in western Europe.

> *"Comparing with salary from Romania, four times bigger, should be very big number, but the live is not so nice, due to the fact that we have half of salary from Germany or Austria, but the prices are the same. The prices sometimes are bigger or the same, maybe only the rent is smaller, its half, here you can rent for 300-400 Euro a flat, in Munich maybe 800 or 1000. But maybe this is the biggest difference in prices. For clothes, eating, buying a car everything is the same. And then the life is not so easy."* (Concept Engineer – BuDC)

The wage situation is driving engineers to search for jobs at other IC design companies that offer higher salaries pay than Leadtech. This has led to fluctuation during the initial phase of the development center. However, as is also being reported by some engineers, pay levels are not the most important factor. The overall working place, the ability to develop engineering capabilities, stress and complexity of projects are important factors as well. As the complexity of projects has constantly developed during the last five years, many engineers are trading lower wages in for technically more interesting work.

GDN position and upgrading

The BuDC is an interesting example of a differentiated upgrading process driven by local and technical characteristics. The existence of a developed labor market and the relatively small size of development projects for the automotive market allowed for functional upgrading processes already quite early in the history of the development center. The long history of the Romanian semiconductor industry was fundamental for an engineering work force with a solid technical knowledge and experience. Despite the decline of the Romanian semiconductor industry after 1989 the local universities persisted and provided the necessary institutional framework for training and research. The specific integration of Romania in the GDN of the semiconductor industry facilitated a further development of the work force and the local labor markets since the late 1990s. The existent engineering talent pool made Romania an attractive location, however combined with low political stability and lacking industrial policies the location of big design centers was impeded, as the overall risk was too high. However, for small IC design companies with lower investment volumes and a lower risk aversion the possibility to employ well trained and often already experienced IC design engineers in a low-cost country was very attractive. This drove the first investment wave, with small international IC design companies setting up shop in Bucharest in the late 1990s. Although many of these initial design centers ceased to exist, either as they went out of business or were integrated in bigger local design location, they helped to develop the local semiconductor ecosystem as well as established a local labor market.

One of the fundamental differences between Leadtech and the other two case studies is the relative high fluctuation rate. Compared to Asian or U.S. design centers the fluctuation rate at BuDC seems negligible. However, compared to the other case studies it stands out as a important difference. Engineers at Leadtech work in an environment where a relatively well functioning labor market is available, while in Poland the labor market for hardware engineers is non existent and IC design engineers at BDC and RDC would need to be willing to move several hundred kilometers to the country's capital to access an existent engineering labor market. Combined with the gradual drying out of the labor market due to shifts in the academic curricula this specific market situation of an employee market is amplified and drives the relative dynamic upgrading at BuDC. The necessary retention of engineering talent required BuDC management, as well as central Leadtech management, to locate increasingly complex and innovative development projects at the design center to provide for the intrinsic technical interest of engineers. The extension of career ladders towards local management capabilities was a consequential process as gradually higher complexity of projects as well as technical capabilities required local oversight for effective management. However, the labor market situation is obviously not translating into generous wages for engineers.

Especially crucial in this process was the establishment of the position of concept engineer, with its important architectural responsibilities. Architectural work is one of the most central tasks in development, integrating both technical as well as economic and administrative considerations. The location of architectural decisions in peripheral locations such as the BuDC is an important fact for discussions regarding the continuous development of the international division of labor, as it points to an international division of labor that is driven by dynamics of local integration, resulting in at least partial reversal of localization dynamics facilitated by the technical as well as organizational modularization.

Similarly, the development of local capabilities on the management level was quite fast. With its responsibilities for the alignment and organization of all necessary activities for a development project, of which some are located in the headquarters, program management was the next big step in the integration of functions at the BuDC. However, the development center is still managed by an expat. As local management talent is still developing, this situation may change in the future. On the level of capabilities the BuDC has seen a quite fast functional integration. This process of local integration at Leadtech was driven by the relatively well developed local labor market, that initially reduced the need to develop these capabilities by the company over a long time.

Architectural and integrated work categories dominate on the level of design work at BuDC. Here processes of functional upgrading have pushed the technical as well as organizational development formally quite far. However, despite the introduction of these high and relative central technical functions at the BuDC the technical complexity of the particular design projects was relative low. Derivative IC design is technically challenging as various process technology related contingencies have to be observed. But compared with innovative projects that develop completely new products the technical requirements are obviously lower. Processes of product upgrading that lead to the location of complex and new projects at BuDC are necessary to exploit the developed technical functions in their full dimension.

For more research related work, such as at the technology and methodology department, auxiliary work based on a complementary international division of labor is prevailing. As Leadtech has both highly experienced research personnel at its HQ as well as the necessary geographic proximity to its manufacturing operations, it would seem futile to try a more locally integrated division of labor. However, as the example of behavioral modeling shows, also research related work can have the prospect to be more of an integrated kind at BuDC.

The dynamics on the level of research related work seem to be important empirical evidence that a complementary division of labor is not driven by logics of centrality and peripherality and is not the end of a process but marks its beginning. The theoretical discussion of the developing international division of labor has lagged behind the empirical evidence, seemingly fighting somewhat a defense battle against the ongoing relocation of more functions. During the first waves of offshoring when increasingly complex manufacturing functions were located in low-cost countries, authors argued that innovation work is much more geographically sticky that manufacturing work impeding an easy internationalization. As the internationalization of innovation work is unfolding since several years, again a theoretical partition within innovation work is established based on central and peripheral functions. Design related functions are perceived as prone to offshore dynamics while more research related functions are again defined as geographically sticky. Although it is yet too early to predict how innovation work will be organized when fully internationalized, it seems quite clear, that an international division of labor based on logics of centrality and peripherality of locations and functions can only be an insufficient theoretical crutch for its analysis.

In the beginning of BuDC multi-site projects were dominating. A practice that was abandoned due to positive effects of locally integrated development projects, that allow for the reduction of costs and the increase of quality and development of speed. However, these multi-site projects were a driver of technical upgrading, as they allowed for a fast development of capabilities on the organizational level.

On the level of project complexity – which is linked to product upgrading – BuDC only recently was able to move towards higher levels as increasingly non-derivative projects are being located at the development center. This development can be linked with learning processes involving the build up of trust focused on local capabilities on the side of headquarter management. Innovative, non-derivative projects involve higher risk on the level of project completion and lost market opportunity. Locating such project in a development center which has only been active for some time is therefore not a viable option. Only after the development center has shown the ability to complete projects on time without major slippages and to work effortlessly within the structures of the company, location of more complex projects can be considered. This shows how technical capabilities and economic considerations are not the only factors in the evolving international division of labor. Upgrading processes, especially those within intra-organizational GDN, are governed by long-term relations that require trust as a basic stabilizing factor to be effective.

As the labor markets for engineers in CEE are increasingly regionalized it will be interesting to see whether the stability of the workforce will be sustained over a longer term. The skill shortage in Germany and Austria after the 2008 crisis has already put the Romanian workforce stability to a test. As this was only a quite limited spike in competition for talent this has not translated into wage pressures in Romania. However, as the skill shortage is ongoing the countries of Western Europe this could result in a cost explosion for the local development centers with negative impacts on their future upgrading. However, such cost developments can also have a positive effect on upgrading forcing the company to locate increasingly more complex and important projects at the location, to make use of its relatively expensive engineering experts. As the automotive IC product development is highly dependent on experience, this seems to be a more realistic scenario for the mid-term development.

The fast integration of highly integrated development projects and a development center with a complete development value chain has to be seen before the background of the quite developed labor market in Romania. Although Leadtech was the first big multinational chip company that invested in Romania, engineers could react to an unchallenging work and non-complex projects by changing their employer. To be able to retain and recruit enough good engineering talent multinational companies such as Leadtech need to offer both interesting development projects as well as career options that go beyond simple engineering positions also towards managerial careers. In case a multinational keeps a development center in a peripheral locations constantly also in a peripheral status, granting only low-complexity projects and no career options, over time it will become the training center for the local labor market. After having worked for some time at such a center, IC engineers will pursue a career in other companies with more interesting job offers.

This translates for the company into investment requirements in HR development and in the extension of local capabilities through the creation of excellence centers to be able to keep the stability of the workforce over a long time. In this way relatively developed low-cost labor markets providing already experienced engineering talent can be a driver of quite dynamic upgrading processes.

With its focus on low-complexity projects and an often times extended work bench style of work during the learning phase the BuDC was initially a home-base augmenting development center, although it neither had a local market nor manufacturing operations in its vicinity. However, it allowed Leadtech to tap into an already developed talent pool for analog engineers. This specific labor market situation was also the driver to develop BuDC quite rapidly into a global development center with integrated development capabilities.

3.3. Triangular restructuring and local integration on industry and firm level

The ongoing internationalization, the triangular restructuring of the electronics industry, as well as semiconductor technology dynamics fundamentally impact the development of the international division of labor of the semiconductor industry resulting in specific locational strategies on firm level. The organizational shifts analyzed on the sectoral level currently lead to a network like structure based on long-term relations that enable the required control levels to be able to organize IC production efficiently and profitably. Simultaneously the focus of the semiconductor industry is moving away from the previously dominant IDM model and towards further vertical specialization, with foundries gaining in importance as focal points of global design and production networks. As foundries have started to play a central role in technology development their position will become even more essential in the future. However, this industry organization dynamic is until now mostly limited to the development and production of digital ICs. The analog IC market is still dominated by highly integrated IDM companies, as the organizational integration between wafer manufacturing and IC design is a major differentiating factor and fundamental for competitiveness. Although specialized analog foundries and analog IP provider already exist, it is arguable whether developments of triangular restructuring will have similar effects in analog chip production, as the economics of analog chip production as well as its technological issues are peculiar. However, there are at least two developments that will drive dynamics of change in the analog space. First, as analog functions are increasingly integrated with digital logic circuitry restructuring pressure can build up over time. Second, and even more important is the growth of markets for analog and mixed-signal chips. Electric cars, power management for mobile devices and the future smart grid, integrating renewable energy production with a modern power grid infrastructure and management as well as power usage, are already driving the demand for analog and mixed-signal chips. As the competition will rise and lead to price and margin deterioration, pressure towards structural changes are raising.

The shifts on sectoral level have also taken effect on the international division of labor on firm level. Although my case studies have dealt mostly with analog IC design the extrapolation of fundamental insights from my analysis seems possible, as problems that emerge and trouble internationally distributed work are comparable. The most fundamental insight of this study is, that not only are the sectoral structures of industry organization shifting fundamentally, but also the firm level international division of labor is becoming much more fluid resulting in new patterns. The offshoring of central manufacturing capabilities superseding complementary divisions of labor has been researched and analyzed both for OEM as well as EMS/ODM companies and their suppliers (Lüthje et al. 2013). For innovation work however, the idea of a complementary division of labor seems to have prevailed in elaborate concepts of central and peripheral engineering positions. The idea that architectural engineers are located in central R&D department, mostly in the home countries of the chip companies, or at least in development centers that are located in the central industrialized countries, is such an elaborate concept of complementary division of labor. This idea is linked to the notion, that central decision, such as the fundamental architecture of a future product, need to be located in central locations, both driven by local engineering capabilities as well as specific power structures within the organization.

The empirical evidence from the presented case studies suggests an international division of labor that has moved beyond basic central and periphery dichotomies superseding simple complementary divisions of labor. The location of architectural engineering positions in CEE design centers of Midtronic and Leadtech refutes claims of simple international division of labor fundamentally. Here central technical decisions are not located at the companies' central locations but have been moved to design centers that are peripheral in at least two dimensions. First, these design centers are in new locations that do neither have a long history as locations of the international semiconductor industry nor an elaborated local ecosystem based on both industry potentials as well as research capabilities linked to local universities or research institutes. Second, design locations in CEE do not have an intimate market link to their target markets, proving as global development center product development and design for international markets. The local markets in CEE are by far too small to drive locational dynamics. Midtronic's and Leadtech's research oriented departments at RDC and BuDC are further indicators for how the concept of a complementary division of labor is at most a transitional category, that only focuses on the first phases of internationalization, when organizations have to cope with contingencies and lack of experience.

From the presented case studies it seems that a different international division of labor in the organization of innovation work is emerging, driven by the process and dynamics of local integration. The requirements for local integration are driving a much more focused and effective international division of labor that allows to reduce the necessary international interfaces to a minimum while simultaneously upgrading local capabilities and thereby the ability to retain engineering talent. The division of labor is developing towards a division between control activities and implementation activities. In contrast to a complementary division of labor, implementation activities are not focused on the final implementation of existent product specifications. Locally integrated implementation activities comprise of all development activities required to develop a product from the first concept to final tape-out, integrating also managerial activities where necessary. Centrally organized control activities are then comprised mostly of management capabilities that are required for the definition and implementation of general business strategies, while on the product level local initiatives need to be managed and aligned. The local integration of these control activities also allows for more effective communication processes, while keeping functions that are better organized in a decentralized manner out of the streamlined headquarters.

The patterns of local integration are only now emerging as they are the result of the ongoing development of the international division of labor. Processes of labor market development as well as shortages of engineering talent are driven by the integration of new locations into the GDN of the semiconductor industry. However, the effects of these processes only show in later phases of internationalization, when the international division of labor starts to mature. This is why the analysis of the semiconductor industry with its decades of internationalization is able to provide such insights. However, evidence from discussion with experts from other industries such as software development, point to a similar tendency of local integration to be able to cope both with problems of international interfaces as well as local labor market dynamics and knowledge management issues.

It is still not possible to estimate the final results of the dynamics of local integration on the international division of labor. However, there are two major issues that will emerge due to the increased fluidity of the new locational dynamics. First, a higher level of competition between the particular design centers regarding both product lines as well as spheres of competence will ensue, as the local integration will most possibly lead to concentration dynamics. Although concentration dynamics will be both limited by the existence of engineering talent as well as the development of wages, the managerial experiences made in the first phases of internationalization should not be neglected. Initially internationalization of innovation work along complementary divisions of labor has promised enormous cost cutting possibilities. However, during the implementation of such projects the incurred costs have oftentimes proved the initial cost estimations wrong, as transaction costs and friction were immense. In case these experiences are used for future internationalization decisions, or at least minimize the hope for easy cost cutting through an increase in levels of micro-modularization, concentration dynamics should prevail in the organization of innovation work.

This leads to the second issue that is a very probable result of the ongoing triangular restructuring and local integration dynamics. Hitherto central innovation locations and the engineers employed in the particular design centers are increasingly endangered by the growing maturity of formerly peripheral locations. As the international division of labor becomes gradually more fluid their central position based on technical expertise as well as history will be put into question. Local integration is further accelerating the development of experience as well as necessary system level knowledge in the particular and previously peripheral design centers, as engineers not only work on integrated development projects but also are assigned to complex technical problems. Although wage levels are very dynamic in some new innovation locations such as China or India, the cost advantages still prevail, especially as Asian countries have extreme high numbers of engineering graduates. With the market shift towards Asia, the importance of Asian locations in technology development will grow even more, undermining the position of currently central development location even further.

The international division of labor is in constant development and it is already now visible that the former central periphery divide is neither theoretically supportable nor empirically viable. The fundamental shift in the international division of labor, or a more mature phase of its development, is formulating fundamental questions towards the formerly central locations. How the results will eventually affect particular locations is not yet evident. However, what is already apparent is its dissolving into a complex system of various locations that will be under a more severe competition than ever before.

4. Knowledge, control and internationalization in the chip design labor process

The establishment of development processes across spatial and organizational distances has effects on industry organization and shifting geographies of innovation. Moreover, internationalization fundamentally impacts the work of engineers that are located in the particular design centers scattered worldwide. Moving the focus of analysis towards the level of work allows to capture the intricate processes through which dynamics of globalization and vertical specialization are transformed into the everyday life of local employees. The international division of labor presented in the previous chapter needs to be revisited on the shop-floor of particular design centers, to describe how work is organized, what contradictions are inscribed in it and what dynamics are fueled by the integration of work into internationally organized processes.

First however, we need to take a step back and try to understand how work is organized in capitalist production in general. Critical writers on the capitalist labor process underline the fundamental contradiction between workers and management based on the specifics of the capitalist relations of production. This contradiction makes certain arrangements in the labor process necessary to be able to ensure a sufficiently profitable production. Control is one of the most important issues in the capitalist labor process and highly intertwined with dynamics of skill. However, as the definition of such arrangements is by itself a complex social process there is no simple deduction of forms of labor process organization from structural characteristics (Selwyn 2012). How work is organized is dependent on the industry, market dynamics, technical requirement of the production and workers' resistance, or in a broader sense the social relations of production. For internationalized production differences in local characteristics such as labor market are important drivers of variety.

Design engineers are prototypical knowledge workers as their main work task is focused on the analysis, creation and revision of systems, be it electrical, mechanical or architectural. Using their engineering knowledge they manipulate signs on paper, in CAD and EDA computer tools or on blackboards, with the aim of developing and designing artifacts that will materialize later on in the process of production. Or, as many engineers put it – they solve technical problems. The central role of knowledge in the engineering labor process requires a detailed analysis of the peculiarities of knowledge, its characteristics as well as its dynamics. The organization of the engineering labor process has also to focus on the organization of knowledge, its flows as well as the assertion of control over it. Knowledge management is therefore not only an instrument to establish structures that allow for knowledge sharing to enable higher innovation dynamics. Knowledge management has to be analyzed also as an instrument of control, that allows management to try reduce the dependence on the individual worker.

Control, skills and knowledge are thus the major themes of the following chapter to be able to develop a model for analyzing engineering work in GDN of the semiconductor industry. First, insights from the labor process debate will be reappraised to enable a general understanding of the contradictions and dynamics within the capitalist labor process. Accounts from labor process based analyses of specific engineering processes will be presented as informative examples. Then, the concept of tacit knowledge will allow to understand what frictions knowledge is subject to within the engineering labor process, as management needs to walk the fine line between control and autonomy to enable innovative engineering work while managing the knowledge resources and flows. Finally, an analytical model based on the notion of managerial strategies as well as the central relevance of knowledge management will be developed.

4.1. Labor process – perspectives on work, control and skills

The publication of Braverman's book *Labour and Monopoly Capitalism* in 1974 sparked extensive debates around workplace control and labor agency that were subsumed under the term labor process debate leading to the later formulation of a more concise theoretical body (Rowlinson/Hassard 2000; Thompson/Smith 2000; Thompson 2009). Based on Marx' work on the specific nature of labor, Braverman (1974) analyzes the dynamics of work organizations and their effects on labor during Fordism, with its domination of large firms based on an industry organization characterized by high levels of vertical integration. Shifting his view away from the capitalist mode of distribution towards capitalist production as the key determinant of work organization, he seeks to analyze the labor process and what he perceived as degradation of work.

For the labor process debate the idea of indeterminacy of labor power within the capitalist production is fundamental. Labor power, what the employer hires and worker exchanges, has to be transformed within the process of production into effort or labor that will result in a finished good or service. Although the employment contract defines the level of wages, the definition of work effort remains loose, resulting in the incomplete nature of labor contracts (Rowlinson/Hassard 2000). This indeterminacy of labor power is the conceptual key allowing to understand the workplace antagonism between employer and worker (Smith 2006). Putting it in a highly simplified way, both workers and employers want to increase their relative advantage in this situation of indeterminacy, by either lowering or rising the work effort provided in the labor process.

The indeterminacy of labor power is what Braverman (1974) identifies as the main factor driving the establishment of control systems that allow management to extract a level of work effort necessary for a profitable production. Braverman links his control thesis with a historical outline on the development of scientific management and its effects on the growing division of labor. Scientific management, or Taylorism, sought to organize production work through an increasing separation of conception from execution, dividing work into increasingly simple and repetitive operations. Such a highly segmented labor process leads to a deskilling of workers and drives the degradation of work, while lowering the dependency on individual workers, as they become increasingly interchangeable. The control in the labor process is seemingly passed from worker to management, whose task is now to organize the labor process precisely step by step for the workers.

Although Braverman develops his main arguments through the analysis of production work, he extends it towards white collar or office work (Braverman 1974). Beginning with clerical work he showed how tendencies of scientific management, separation of conception and execution and control were introduced in the administrative and also engineering labor process. For Braverman the dynamics of increasing levels of control and the narrowing of the scope of work are also present in the everyday working life of the white collar workers. This industrialization thesis of white collar work has been extended by scholars in the context of informatization (Schmiede 1996) and internationalization (Boes 2004; Chang et al. 1999; Kämpf 2008).

Braverman's analysis sparked a debate in which many authors sought to challenge or amend his vision of an almost completely deskilled production work, that suffered from two major drawbacks. First, artisan work and its unity of conception and execution as the only point of departure in the analysis of deskilling were conceptualized in a very idealized way by Braverman. In place of developing a systematic definition of skills and their development Braverman argued almost entirely historically. The focus on artisan work eliminated non-artisan work from his analysis. However, it can be convincingly argued that artisan and artisan-like work constituted only a minor part of work as such.

Second, and most importantly, Braverman's deskilling thesis lacked in general almost any worker agency, leaving labor only the role of an object smoothly malleable by capital to its interests. The second wave of labor process debate focused on the resistance of workers on the shop floor and how these processes transform both control systems as well as the deskilling tendency (Edwards 1979; Friedman 1977; Penn 1982). Investigations of management control and the attempts by capital to maximize worker productivity now moved into the center of labor process analysis, with researchers arguing that the labor process is far more intricate and interdependent than Braverman has postulated.

4.1.1. Responsible autonomy and direct control

Friedman (1977) analyzes the systems of control that capital requires to maximize worker productivity and how they develop in regard to both economic dynamics as well as worker resistance. He disputes the viability of scientific management as a system to ensure productivity due to the constrains Taylorism is imposing on worker creativity. The development of managerial strategies and how they affect the organization of the labor process are in the focus of Friedman's analysis. The concept of managerial strategies allows him to develop a less deterministic framework of control structures as they can vary within comparable economic environments with regard to technical characteristics of a labor process as well as encountered resistance from workers. Friedman (1977, 1990) understands managerial strategies more as management's practices to assert control over the labor process than as control systems stringently subsuming the labor process under one central control logic.

Labor power as variable capital can be interpreted either positively with its creative potential and adaptability or negatively as an independent and often hostile will. These both aspects relate to the two forms of control that Friedman (1977) identifies – direct control and responsible autonomy. Based on the idea of labor as a creative potential, responsible autonomy allows for some degree of freedom in the labor process, with less instruction and supervision, while authority is maintained by linking workers with company aims. This produces a situation where a sense of responsibility is invoked on the side of the employees bolstered by a specific commitment to the company's goals. With this relatively open labor process, management can access tacit knowledge and experience developed by workers in their every day work by harnessing it rather than by separating it from the workers. Such an organization of the labor process does not lead to a degradation of work, as it is fundamentally based on the assumption that the development and maintenance of workers' experience and broad skills are necessary for profitable production. This managerial strategy is bolstered by internal labor markets that offer further incentives for staff to work hard in order to progress internally within the firm.

Friedman links strategies of responsible autonomy with high levels of job security that allow the development of trust and identification on the side of employees. This seems to be still important in the current situation of highly flexible and globalized labor markets for engineers. Especially engineering labor processes requiring high levels of experience are characterized by continuity (Brown and Linden 2010). However, the perspective of job security is sometimes reversed, becoming a driver of labor process organization rather than its outcome. When employers need to secure engineering talent under the pressure of high fluctuation rates, job security for the individual engineers is not anymore defined by employment at one particular company. With engineers changing their jobs quickly firms need to organize the labor process based on responsible autonomy in such a way that the control over knowledge allows for project completion. This can result in higher levels of control in design centers that are located in dynamic local markets such as U.S. or India, where job changes occur constantly and are both a possibility to drive individual careers as well as a form of engineering resistance.

Direct control on the other hand focuses on the negative interpretation of labor power, trying to gain control over the labor process through an extension and increase of mechanisms of control and coercion. Time-clocks, direct supervision and assembly lines are only some of the instruments used by management for direct control of production work. Within the engineering labor process, characterized by high levels of autonomy, the granularity of milestones and deadlines in project work organization are analyzed as instruments of direct control (Barrett 2004; Upadhya 2009). The separation of conception and execution is, in line with Braverman's (1974) characterization of scientific management, fundamental for direct control. Knowledge management is probably the most important instrument of direct control in knowledge intensive labor processes as it is both imposing strict guidelines structuring the engineers' work as well as trying to access tacit knowledge produced during product development. This aims at lowering the dependency of employers on particular engineers and their individually bounded knowledge through objectification. However, knowledge management is a more ambiguous instrument of control, that can be used in line with strategies that tend towards responsible autonomy. Knowledge management can also offer less regulated social space for engineers to develop new ideas and share knowledge (McKinlay 2004).

With knowledge management the ambiguous and often dialectical character of managerial control becomes apparent (Barrett 2004). Responsible autonomy with its high levels of freedom and discretion is structuring the overall engineering labor process, allowing to access specific forms of knowledge necessary to develop solutions for complex technical problems in a contingent environment. The required creativity can only be facilitated by certain levels of autonomy within engineering work. The very process of accessing knowledge through knowledge management systems can lead to direct control imposing processes of knowledge objectification in a very clear form, while structuring the work organization of engineers through formalized and standardized procedures.

As managerial strategies are never able to define one best way, Friedman (1977, 1990) defines both strategies as opposite ends of a continuum that gives management a horizon of possible practices. Both have inherent limits and inflexibilities which arise from the need for control as such in the capitalist production. Direct control strategies in their most radical design reduce workers to machines that are only executing highly specified work orders. This strategy limits the possibilities to quickly react to contingencies in the production process, as any change requires complex and time-consuming planning, communication and implementation of new detailed work tasks. High degrees of responsible autonomy have their inflexibilities as management cannot easily replace workers' skills or impose direct control with new machinery, without eroding the main ideas upon which responsible autonomy is founded.

Whether responsible autonomy or direct control are used as managerial strategies to govern the labor process is the outcome of a complex social process. The ability of workers to form resistance is an important factor, with responsible autonomy positively integrating workers and lowering drivers of resistance (Friedman 1977). However, the engineering labor process, although characterized by high levels of responsible autonomy, is often not integrating engineers on the level of interest representation. Individualized contract negotiations imposed by the employees impede the development of common interest representation. The self-image of engineers as professional experts, individually able to define and assert their interest, as well as their relatively high social status and remuneration levels are not facilitating the organization of unions in engineering companies. However, this does not translate into an absence of resistance in the engineering labor process. Although not in the form of a strike or other forms of collective action, engineers still practice both open and covert resistance. With such often very situational and focused actions engineers can change work organization in their favor.

Shifting away from the shop floor to his initial question about the varieties in the spatial organization of production and work Friedman (1977) describes a system of hierarchical divisions of control. Central and peripheral workers are located both across spatial inter-organizational divisions of labor as well as in supplier relations. In his basic spatial model central workers are generally organized through a responsible autonomy strategy, as the firm needs to access their creativity required for high value added tasks. The history of resistance in these central location has driven the establishment of this labor process. In contrast, peripheral workers focused on simple and routine tasks are largely organized through managerial strategies aimed at direct control. However interesting this nucleus of a spatial analysis of control systems is, its fundamental structure is rooted in the spatial division of labor of the 1970s, where more complex international divisions of labor were only beginning to develop. These ideas can easily be linked to the New International Division of Labor (Fröbel et al. 1977) with its concept of a complementary division of labor and simple relations and hierarchies between center and periphery. The development of the last two decades has made such simple analyses unrealistic both regarding production as well as development work (see: Chapter 2 and 3). Although the position within a global network of production and development, the centrality or peripherality of a design center, can have influence on the labor process, local characteristics as well as technological dynamics play also major roles in determining how work is being organized. This can lead, especially in the organization of professional work, to quite surprising results, where the labor process in peripheral locations can be characterized by relatively higher levels of autonomy than in centrally located design centers.

4.1.2. Structural forms of control

Edwards (1979) reiterated and expanded the idea of different control systems that may be adopted by a given firm. Although his account on control systems is established in a historical analysis, where simple, technical and bureaucratic control are replacing each other successively in the history of capitalist development, it is much more helpful to see it as an elaboration on the variety of control structures. These three control systems represent an increasing shift towards structural forms of control, that are embedded in the physical and social fabric of the workplace. However, as critical revisions have shown (Kunda 1994; Upadhya 2009), more systemic control systems do not replace simple control but lower its significance for labor process organization, while simultaneously providing a control framework in which such personal based control is put to use where necessary.

Bureaucratic control guarantees loyalty of workers through intricate mechanism that help to further disguise control systems by integrating them into the social fabric of the labor process. Control is being institutionalized through formalizing and codifying it in rules and regulations. The procedures and functions of management are translated into objective routines and management processes that govern now the entire labor process, consisting of assignment, evaluation/appraisal and discipline. This hierarchical, command based system with its impersonal rules is penetrating the entire labor process. Highly stratified work, numerous job titles, and almost automatic rules for appointment and promotion structure the longer-term aspects of organizational life. Bureaucratic control corresponds with the growth of internal labor markets and offers workers a higher mobility within the firm, while rising job security and establishing a system of rewards for positive behavior. Simultaneously, the impersonal rules and objective routines of bureaucratic control grant more rights to workers. A general consent among workers is generated and aligns them increasingly with the interests of the company. The identification of a general trend, where control is shifting gradually away from coercion and moving towards consent and integration, is backed by Burawoy's analysis (1979).

Beirne et al. (1998) show how bureaucratic control has been extended within the labor process of software development engineers. Software development has seen the development from an almost esoteric, highly individualized practice towards software engineering, moving to the ranks of applied sciences. This lead to fundamental changes in the labor process organization of software development. Formal design methodologies were developed and defined increasingly strict procedures, protocols, tool and techniques, documentation requirements as well as the points when customer have to be integrated in the development process. Rules for quality management have been established over time, that further extend the control by formalized rules and routines.

IC development, with its tradition in hardware engineering, was from its onset not as unregulated and individualized as software development. The necessary interface to expensive manufacturing operations as well as the rapidly rising complexity of devices made an organizational regulation and group working necessary almost from the onset. However, similar to software developers IC designers were working in a very fluid labor process where design methodologies where often governed more by engineers and their technical requirements than by management's drive to assert their control. Just as with software development design methodologies provide extensive formal rules and procedures that govern the IC development process. The increasingly complex chips and design innovations such as SoC require a much more controlled engineering labor process as both control over cost and quality need to be achieved. However, the complexity of the entire process also sets the limit for too high levels of standardization and formalization, put forward by ideas of SoC design factories. Direct communication between engineers is very often much more efficient in solving contingencies than highly standardized processes.

4.1.3. Consent and commitment

The control debates of the first and second wave labor process debate point to the fact that labor remains a creative force that capital needs to take into account and not only try to objectify. Or put in another way, especially the second wave labor process debates show that capital is not only focused on strategies that try to rise the levels of direct control as this can affect productivity negatively, through too much deskilling and alienating the individual worker.

A very specific perspective was introduced by Burawoy's (1979) accounts of factory work, based on his long ethnographic studies. He was able to show how despite systems of direct control factory production involves high levels of tacit knowledge, countering Braverman's simple degradation of work thesis. However, his main argument was that rather than acting as passive objects of production, workers not only control their machines by themselves but also reproduce the control structures through their own strategies that allow them to cope with the labor process. Workers are active in the labor process by 'making out' (Burawoy 1979), or in other words, by adaptation to work through 'games'. These are informal rules and practices geared at making work more interesting as well as establishing relatively free space and time within the labor process. Burawoy argues (1981) that by playing these 'games' workers reproduce the control system governing the capitalist labor process and while trying to carve out some autonomy within the labor process, they simultaneously are not able to question the overarching rules of it. Management knows about these 'games' but tolerates them as these practices allow to maintain required productivity levels. With this the manufacturing of consent is directly connected to the workplace and the specific labor process organization. However, as Thompson (1983) argues, within manufacturing such situations are highly dependent on the existing power relations. The engineering labor process seems to be fundamentally different in this point, as the very characteristic of engineering work requires specific levels of freedom to enable innovation and learning. As engineers are focused on developing 'the new', they need space for reflection and extensive processes of knowledge gaining. However, this does not rule out the use of the self for control measures, but pushes it to other levels. In engineering work strategies of searching for and finding workarounds often emerge, that point to similar playful and creative manipulation of the technical as well as social fabric of the labor process, to be able to achieve required work results.

The relative freedom that is being constituted in this way within the labor process is driving a second process of inclusion of the self into control. Involving workers in making choices though the specific organization of activities, is manufacturing consent through integration. Participating in practices that reproduce the capitalist labor process is determining an increase in self-control. This can take the form of unregulated and informal practices. However, much more important for current engineering work are processes of negotiability, where engineers are integrated into the definition of organizational and technical details of their very own work. Here the manufacturing of consent is much more clear-cut as schedules and ownerships defined in the process of limited negotiability become direct measures of work effort and drivers of self-control.

The growth of forms of control that integrate the subject is evident as employers try to cope with changes in industry organization as well as market shifts driving the rise of innovation dynamics and network based work organization. To be able to meet with these new demands, management tries to access and put to use the tacit knowledge and skills of employees by opening up control towards subjective capabilities of particular workers (Thompson et al. 2001). From a more immanent perspective one can argue that structural control systems such as bureaucratic control undermined themselves by the treatment of individual employees as anonymous cogs within the machine and not as knowledgeable and responsive agents. This leads to disenchantment and depersonalization on the side of employees that can be encountered by engaging the personal subjective nature of the employee. However, such control forms based on the workers' subjectivity have to be analyzed as developments of the capitalistic imperative to assert control over the labor process.

Based on a detailed ethnographic study Kunda (1992) develops a very informative analysis of control systems of engineering work that are centered on both control and commitment taking subjective capabilities within the labor process as their starting point. Rooting his argument not only in the labor process debate but also drawing heavily on organizational theory, his notion of normative control develops a specific perspective on control that is quite useful in the discussion of engineering work.

Normative control is based on the manufacturing of a strong corporate culture creating a self-motivating and committed workforce. Direct coercion and formalized routines are superimposed and partly replaced by shared corporate beliefs, norms and values with which employees are indoctrinated (Sturdy et al. 2010). The focus of normative control is the group that is sharing specific values and norms, elevating the reference framework towards the whole organization while, at least partially, dissolving subgroups as most important reference points. Functional and hierarchical barriers, both for communication and internal mobility as well as importance of status, supervision and formal control are cut back. The manufactured culture allows to integrate the selves of employees as key mechanisms of control, as they align with the interests of the company. Hierarchical structures of bureaucratic control based supervision are dissolved by strengthening of the member roles through gatherings such as project team meetings (Kunda 1992). The face-to-face control in such gatherings are extending the direct control of supervisor to practically every member of the organization individually as well as through group pressure. Normative control is based on the decentralization and deepening of control as the following of the specific modes of behavior and mindset are controlled by everybody in the organization. The essence of bureaucratic control – formalization, codification and the implementation of rules and regulations – is not changed in principle. Normative control does not rule out other control forms but rather provides for an underlying framework on top of which other control strategies are also pursued by management.

Commitment is a fundamental driver and basis of normative control as it allows for a strong identification with company goals. Kunda (1994) shows how commitment is manufactured through training workshops and management presentations. His view of commitment is solely focused on commitment on the most extensive level, the organizational ideology or culture, as this is seen as the fundamental integrating mechanism. However, commitment and integration should be analyzed on less abstract levels where the organization of work is coming into perspective. Commitment on the more practical levels such as the definition of project schedules and product specification is produced through a system of negotiability. Engineers are integrated in the process of defining major parts of their future work content and time horizon through a process of limited negotiations, where customer requirements and managerial aims of profitability set the borders.

Upadhya (2009) shows how engineering work focused on customer interaction is controlled by a company culture that is centered both around global standards as well as customer centricity. Here a specific contradiction inherent in the model of normative control becomes visible. Global standards for software engineering work, originating at least on a symbolic level from Silicon Valley, highlight high levels of autonomy and freedom. The customer centricity on the other hand establishes a level of direct control as the client is always present and watching. A similar perspective is possible on team work, yet another management technique that can be subsumed under the notion of normative control. Team based organization of work aims at delegating at least parts of decision making on the shop-floor and facilitate cooperation and knowledge sharing driving new skill requirements for engineers. In a highly competitive and time restrained environment team based work is resulting in control through peer pressure. These tensions in the system of normative control point to its specific control structure as at particular points the high levels of autonomy require to be bolstered by control. As normative control does not replace other control systems it offers an additional layer of control developing the mutual dependence of control systems further. Sturdy et al.'s (2010) analysis show how the ideological framework integrating employees in a labor process characterized by high levels of autonomy needs to be bolstered by strategies of control, based on technical, bureaucratic and direct personal control.

The notions of bureaucratic and normative control are specific control systems whose practices need to be located within Friedman's continuum between direct control and responsible autonomy. These control systems shift control towards a more systemic level by establishing complex technical, bureaucratic and cultural frameworks within which specific managerial practices determine what level of autonomy is granted by management. Just as Friedman (1977, 1990) developed his model as a continuum allowing to understand various managerial strategies, bureaucratic and normative control are situational systems that develop through the requirements formulated by the specifics of particular labor processes as well as worker resistance. Although normative control tends to favor managerial strategies associated more with responsible autonomy, it also drives direct control measures, e.g. within project teams.

What is evident from the discussion of labor process theory is that there is no imperative to constantly increase control while deskilling workers in capitalist production. Additionally, as we will see in the case studies, dynamics of internalization cannot be simply analyzed as drivers of industrialization of engineering work. When the international division of labor is maturing, industrialization of engineering work is not allowing to realize the highest possible profits, as it limits processes of upgrading. However, the inherent logic of capital accumulation drives constant changes in the organization of production. Changes in competition as well as technological dynamics drive the need to lower costs of labor which can be achieved through various strategies. The increasing need to access tacit knowledge and experience often results not in conventional deskilling or upskilling but in a broadening of the palette of skills that are required. This qualitative intensification is especially evident in the labor process of engineers in GDN. Here the intensification can be characterized as a shift of skills where new forms of knowledge become increasingly important.

On its focal level of control the labor process debate has produced very important insights regarding the development of systems and practices over time and their constant change both due to external dynamics in societal normative structures as well as due to the emergence and prevalence of specific labor processes, i.e. knowledge work. Most importantly the idea of a single overarching control system has been increasingly refused in favor of notions of more intricate layers of control (Barrett 2004). The idea of a worker who is actively participating in the reproduction of control, while management is increasingly putting his self to use, is highly important. Both Burawoy (1979) as well as Kunda (1994) show how manufacturing consent and commitment is tightly integrated in the labor process. However, for our analysis also more clear-cut dynamics such as high levels of negotiability within the labor process are important. The notion of negotiability is not only describing how engineers are integrated into the planning and definition of their own goals and schedules, while rising their levels of commitment and ownership. The process of negotiability is also concerned with problems of knowledge creation and access. As knowledge is one of the most central parts of the engineering labor process we will now turn to its peculiarities.

4.2. Knowledge and experience

Knowledge can be broadly distinguished into two categories – objective and subjective knowledge. The category of objective knowledge comprises forms of knowledge that are characterized by formalized and verbalizable statements and are the base of instrumental-rational actions. Subjective knowledge spans many knowledge forms such as experienced based knowledge, process knowledge or organizational knowledge. The main characteristic of these knowledge forms is that they are at least partially bound to persons and resist a full objectification.

Objective knowledge is mostly abstract descriptive knowledge allowing for spreading through text and with this it is not bound to individual subjects aiming at context-independent use. Objective knowledge can be taught and learned through textbooks relating to abstract models resulting in formal qualifications. A subcategory of objective knowledge is technical knowledge, focused on the field of technology and engineering. Technical knowledge is based often on the utilization of technologies and engineering solutions and problems occurring in this process. Its creation is pointing to a more experience based process, where the transformation into objective knowledge is central. A major aim of the transformation is to make it available for learning. Subjective knowledge, or experienced based knowledge, is a form of knowledge that shows quite contrary characteristics. Most importantly it is not available in textbook form. Experience based knowledge is linked to the person that gained this knowledge. There are methods for sharing this knowledge, e.g. the master apprentice relationship, verbalization through story-telling, or the verbalization through case study data bases as used in many knowledge management strategies (Schilcher 2006). But the specific character of experience based knowledge limits the possibilities of transforming it into objective and therefore easily communicable forms of knowledge.

The practice in which experiences are obtained is not aimed at a systematic generation and verification of knowledge, such as with scientific or objective knowledge (Böhle et al. 2002). The situational and ad hoc manner of gaining experience is forming a skill set allowing for flexible and fast reactions to various situations e.g. new situations or situations characterized by high contingencies. The development of experience based knowledge is a process of routine building, destructing and re-building. From this perspective experience based knowledge can be perceived as an independent form of knowledge which is necessary to complement objective knowledge in its practical applications (Böhle et al. 2002). With this no clear-cut separation between objective knowledge and experience based knowledge exists as experience based knowledge is oftentimes based on objective knowledge forms which are being put into context within specific situations.

Experience based knowledge in the hands, or better: minds, of the workers was perceived by scientific management as obstructive for an efficient organization of the production process. Objectifying the labor process and its organization by removing the subject through control methods based on instrumental rationality and automation as well as reducing the role of the subject's sensory perceptions through measurement devices was one of the main aims of scientific management's direct control (Braverman 1974). Only recently scholars of organization and work sociology started to argue in favor of experience based knowledge as either an essential factor enabling workers to cope with technically highly complex systems (Böhle 1994; Böhle/Milkau 1988, Böhle/Rose 1992) or as a source for innovations (Nonaka/Takeuchi 1995).

However, the social and organizational patterns in which works takes place were mostly neglected despite their fundamental importance for the creation and utilization of experience based knowledge. With the advent of project based work and the decentralization of organizational tasks the social and organizational dimensions of experience based knowledge gained importance (Porschen 2002). The dynamics in the international division of labor, especially with regard to international development projects, have further increased the organizational and social complexity of work. The social and organizational structures and dynamics of the workplace have to be included in a broader concept of experience based knowledge, as they can be used both as sources for knowledge distribution and workers' resistance as well as barriers of knowledge sharing. Flexible work settings require social and organizational knowledge or organizational feeling (Boreham 2002), that grows out of the awareness of the interdependency of different parts of the organization. This organizational feeling involves not only knowledge of the formal organizational level but encompasses also the informal networks and social structures that develop in an organization. Knowledge about how one has to work with colleagues and how various workers perform their work tasks is particularly important in development work (Kunda 1992). Process coordination is increasingly assigned to the employees. Engineers must be aware and take into account how their individual decisions and ways of problem solving will influence or even constrain the work of the following engineers. These problems are amplified in internationalized labor processes. Standardized procedures defined by management are only establishing the framework in which the particular employees need to actively develop relations with their colleagues in other locations. The establishment of informal relations is an essential part of this process to enable processes of knowledge sharing that go beyond the formal requirements. This can also involve informal processes that run in parallel to formal ones and allow for their frictionless operation. Initiatives to develop these relations can only emerge in a labor process that allows for autonomy, enabling engineers to invest time and resources nor directly linked to project work.

Increasingly the engineer's self is being accessed as an important resource in the labor process. The engineer needs to take an active role in the development of the informal structures and procedures that allow him to both carry out his assigned tasks as well as to cope with contingencies driven by the growing complexities of the labor process of a knowledge worker. The engineer is engaged in these activities with his subjective capabilities as communication skills and management capabilities need to be accessed to organize his own work environment. Understanding one's own needs, the requirements of the formal process as well as the capabilities and limits of the cooperating partner and the ability to devise an informal process that will accommodate all of these factors calls for more than mere technical proficiency. To know who is doing what, how and on what expert level can be very helpful in such situations. To cope with design problems and contingencies engineers often arrange informal groups combining specialists of different fields that can work out a solution (Porsche 2002). The ability to constitute such informal groups is based on the information and experience about the variety of specialists within the organization. The establishment of such knowledge is driven by knowledge management systems, especially of instruments that facilitate direct personal knowledge sharing. However, the most important part of such ad-hoc groups and informal knowledge sharing channels are sufficient levels of personal contact. Here we see how the organization of the labor process based on managerial strategies leaning towards responsible autonomy drive the need to integrate the worker's self increasingly into the conduction of work related tasks.

Experience based knowledge is very important in the labor process organized along the lines of responsible autonomy, especially when abstract and complex data and information need to be processed and produced and contingencies emerge on a regular basis. Knowledge workers, such as IC engineers, are relying heavily in the everyday work on their experience knowledge as well as on the experience they can tap through personal informal and formal networks. For the employer experience based knowledge is becoming of central focus, especially as innovation processes are increasingly tightly organized, and its needs to be both accessed as well as controlled. However, the process of objectifying experience based knowledge is limited through inherent dynamics of this knowledge form, summed up by the notion of tacit knowledge.

4.2.1. The tacit dimension of knowledge

Michael Polanyi (1966) summed up his concept of tacit knowledge with a famous aphorism: „we know more than we can tell“ (Polanyi 1966: 14). In his view knowledge consists of knowing two types of elements, integrated into one entity by an implicit link, where the first one can be expressed in words, the second not. Tacit knowledge refers to the process of knowing, as the creation of the implicit knowledge link. This formation, or integration, is the main driver in the creation of knowledge. Humans posses the ability to see details in terms of the whole, the ability for interpretation. For Polanyi this process of integration is occurring in the formation of both theoretical and practical, or objective and subjective knowledge.

The body is in Polanyi's view the fundamental instrument in the production process of every theoretical and practical knowledge (Polanyi 1966). His view of the knowledge process based on all sensory abilities of a human is paralleled in Böhle's (2004) model of experience based knowledge, where both perspectives conceptualize this process as an open and iterative one, with the subjective elements of sense and perception playing a fundamental role. Böhle et al. (2002) emphasize that knowledge generation is not only an intellectual process but involves subjective sensations and sentience. The explorative and associative character is fundamental to the creation of both knowledge as well as the very skills necessary for this process. The access to such knowledge forms is not possible by formalized, planned and highly regulated closed processes of question and answer. Here open processes that integrate and give the ability to influence the dialogue become fundamental.

Tacit knowledge is not another form of knowledge opposed to explicit knowledge, but the concept is referring to a dimension of knowledge that is characteristic for every form of knowledge (Schilcher 2006). In this perspective even highly abstract scientific knowledge contains a non explicable residual. Understanding tacit knowledge as an inherent dimension of the knowledge process and therefore of every knowledge form sheds a different light on processes of objectifying knowledge within an organization. The process of knowledge transformation is far more problematic than just to extract knowledge from employees, as the tacit dimension is never fully verbalizable and can be therefore not formalized completely.

The transformation of subjective knowledge into objective knowledge, changing it from the implicit to the explicit form based on explication and formalization has to be placed in the context of the labor process. Taylor's scientific management approach can be interpreted on the background of knowledge theory (Malsch 1987). In this view the experience based knowledge of workers is transformed into planning knowledge of the management. With this knowledge transformation within the capitalist labor process is not a process that can be described by knowledge theory in its full. Control, power and resistance aspects discussed by labor process theory are essential and fundamental dynamics of this knowledge transformation. However, as tacit knowledge is a dynamic process of producing and reproducing knowledge, the process of transformation, as a means of codifying tacit knowledge and thereby in some way petrifying it, is limited.

Explication and formalization need means of expression, that allow the individual subject to verbalize forms and dimensions of knowledge that are not easily communicable. Communication based on known symbols becomes a vital part of the transformation process. Especially in connection with engineers highly specific symbols emerge and the need for a common language grows. Engineering science and engineering traditions in the specific specializations provide formalized sets of symbols that generate a base for communication. This base is a starting point, however the fact that experience based knowledge and tacit knowledge both are not easily articulated, requires the establishment of other means of communication. Proximity, as face-to-face interaction, generates the broadest basis for communication. The situation of a personal discussion over a matter allows to answer questions, quite contrary to the process of writing down specific bits of knowledge in a concise way. The explication can be augmented by stories regarding applications of the specific knowledge under consideration. Examples and references to former ways of handling similar situations expand the formal articulation of specific bits of experience based knowledge. Such a dialogical interaction allows to transport and share experience based knowledge with its multifaceted character.

The process of explication and formalization, as a means of building systems of expert knowledge, can never render a full copy of the experience based knowledge. As such knowledge is generated through practical experiences and used in work in a situational manner, it is not possible to generalize it without either loosing too much information or having to consider almost every situation in which this knowledge could be applied. Such a full coverage would render neither transformation nor learning practicable. If the means of expression and proximity are given and lead to elaborate knowledge sharing systems, transformation of knowledge is still a fragile process. These expert knowledge systems are only accessible for experts, as the technical language that constitutes them must be actively translated into meaningful decisions (Malsch 1987; Schilcher 2006). This calls for an intelligent user being able to handle the process of translating generalized objective knowledge into specific and situational work practices. This ability is again a form of experience based knowledge as an ability to contextualize information and knowledge.

Malsch (1987) examines the process of knowledge transformation in the context of informatization of work. In line with Braverman (1974) many authors (see for example: Kraft 1979; Schmiede 1996; Weizenbaum 1978) argued over the years that the process of informatization is only aiming at the enforcement of instrumental reason as way of rationalization, forcing an industrialization of engineering work. In this perspective informatization has only one direction, which is the degradation of work through observation, externalization and formalization of workers' knowledge summed up as knowledge expropriation. Malsch opposes this view and argues that informatization develops in a dialectic way in which experience based knowledge is both destroyed and restored, conceptualizing the process of transformation of experience based knowledge into planning knowledge as a circular flow (Malsch 1987). During knowledge extraction and objectification knowledge, both explicit and implicit, is collected and transformed into formalized planning knowledge. Knowledge return translates this objectified knowledge into applied knowledge confronting the worker in form of machines, organization and planning.

This process in the context of informatization inherently involves two points at which the degradation of work is experiencing major frictions. Informatization is changing knowledge extraction fundamentally as it requires a different mode of knowledge extraction. While tayloristic knowledge objectification was based on observation by others, informatization makes a self-monitoring of workers necessary. This leads to the development of information skills on the side of the workers, underpinned with requirements towards the expansion of reflection and communication skills. Knowledge return is confronting the worker with changes in the labor process. These changes may constrain the worker's autonomy and the qualifications and skills required for the job. Simultaneously, these changes produce situations that are the basis for the development of new experience based knowledge, which can be located at a higher abstraction level.

Regarding labor process dynamics driven by informatization Malsch (1987) concludes that consistent negative effects for the power relations in the firm and for the individual qualification demands cannot be assumed. Describing the frictions and contradictions in the process of knowledge transformation he rightly opposes degradation of work theses that argue in a too mechanic and deterministic fashion. But his positive view on the changes in the labor process assumes that both the described skill shifts as well as the new more abstract experienced based knowledge are perceived as positive by workers. Technical experts such as engineers with their intrinsic interest in technical solutions can have fundamental objections against the shift from technical to organizational tasks. Within the engineering labor process questions of motivation and resistance arise, as engineers are not content with constant reporting and delivering data for knowledge management systems. The point of knowledge return in Malsch's model is also underexposing possibilities of resistance from workers. The implementation of specific procedures and requirements is not to be confused with their application in the everyday work. Especially knowledge workers have often enough autonomy to decide how they obtain and access the knowledge they need to perform their assigned tasks. Furthermore, Malsch is not taking into account that the process of objectification is dissolving personally bound knowledge. The mere fact of explication is lowering the workers' position within the company's power relations, as their expertise knowledge can now be used by others rendering themselves at least partly exchangeable.

Sabine Pfeiffer (2004) formulates a fundamental critique of Malsch's knowledge transformation circular flow, where the question of a principle ability to transform experience based knowledge comes again into focus. The base for Malsch argumentation is the assumption that experience based knowledge is fully transformable into planning knowledge. Pfeiffer (2004) insists that experienced based knowledge has to be viewed in a more differentiated way. There is experience based knowledge that can be explicated, formalized and thereby transformed into planning knowledge. But there also exists experience based knowledge resistive to this transformation. Pfeiffer's (2004) argumentation is convincing both based on theoretical considerations in line with Polanyi (1966) as well as empirical evidence. The non-explicability of specific knowledge parts limits the industrialization of engineering knowledge. However, the specific transformative resistance of certain parts of experience based knowledge does not translate into an impossibility to harness this knowledge through unique labor process organization and managerial strategies. Devising managerial strategies based on dialogue and iteration, open processes of integration and control allow to access such resistive knowledge forms. Albeit being managerial instruments of control, iterative negotiations of both schedule and technical details are structurally comparable to the process in which experience based knowledge is established and applied. In such an open process Malsch's knowledge transformation of experience based knowledge is not only based on the formalization of it into machines, organization and planning. The resistive parts of experience based knowledge are put to use by management for the organization's goals, while not being expropriated from the individual worker. This implies that the degradation of work is not a straight forward process in knowledge work. However, this points also to specific control mechanisms that while affirming experience based knowledge simultaneously try to assert control over them as well as the entire labor process.

Both notions of tacit and experience based knowledge and their increasing importance in the labor process, point to the focus that is put on the integration of the worker's self into the labor process. The individual worker needs capabilities that enable him to generate knowledge out of formal information and data and apply it to contingent situations. Formal procedures and processes that organize work are only defining the direction and the required speed of this process. However, experience that lies in the worker's self is what enables him to generate, apply and share knowledge that is essential for the production or development process. A broader understanding of experience based knowledge and how the social and organizational fabric of the firm is fundamental for knowledge generation. This indicates also how the development of experience can be limited, when viewed from the perspective of the development of the intricate structures of the international division of labor. Highly segmented and detailed work packages received by engineers in peripheral design centers limit their ability to develop experience linked to contextualization of their work within the entire development project. The fear of loosing their jobs to these new colleagues can put engineers in central design centers off from sharing necessary knowledge. To both assert control over the labor process and the knowledge used and produced within as well as facilitate the required knowledge sharing across the various boundaries management is setting up elaborate system of knowledge control.

4.3. Knowledge management as control

Knowledge management is the purposeful organization of the knowledge sharing within a firm regulated by management for the advancement of the company. The administrative processes of knowledge management aim both at explicit and implicit knowledge produced in the everyday engineering work. The base for knowledge management strategies was laid out in Nonaka's and Takeuchi's (1995) seminal work on the knowledge creating company that provided the initial ideas and framework for the analysis and deployment of knowledge creation and management within particular firms. Their aim was to better understand how knowledge, both explicit and implicit[28], can be harnessed for the competitive advantage of the company.

Knowledge is the work effort that the employer wants to access and maximize through the specific organization of the labor process of engineers. It is not easily measurable, neither in a quantitative nor qualitative way, and needs some degrees of autonomy to develop. Thus, the control in the labor process necessary to extract the work effort cannot be overtly direct. Knowledge management is a fundamental part of organizing as well as controlling the labor process, focusing on two objectives. First, to rise efficiency, knowledge management establishes organizational structures and processes that allow for knowledge sharing between particular employees. This drives steeper learning curves and can raise innovation dynamics. Second, to lower the dependency on particular employees their knowledge is appropriated, codified and

[28] Nonaka's and Takeuchi's (1995) distinction between explicit and implicit knowledge is the difference between objective knowledge and subjective, or experience based knowledge defined above.

collected in specific repositories as well as used for a constant process of reflexivity (McKinlay 2000).

Engineers as knowledge workers exhibit distinct features that are common for creative work, most importantly a high commitment to the work itself coupled with a strong identification with the content of their everyday work (Huws 2010). Work content becomes then a very important aspect of the labor process. Elements of really free labor combine with notions of pride as engineers can develop new ideas to resolve specific technical problems and challenges. This self-actualization is extended as learning is fundamental for the development of future individual capabilities. If the work content of an engineering labor process can provide for these aspects, monetary reward is only but one part that facilitates high commitment of knowledge workers. Knowledge management that focuses solely on rigid documentation and standardization processes can have adverse effects on the work content, lowering the identification with the work itself. Engineers negatively perceive administrative tasks such as reporting, which form the base for knowledge management systems.

The distinct characteristics of creative work also form the central line of conflict between the individual and the group as well as organization – the main levels that knowledge management aims to link and to control. Knowledge and ideas are the main assets of the knowledge worker, constitutional for his labor power sold on the labor market. Parting with this central moment of power cannot be done freely as it can lead to a diminished position on the labor market. However, as engineering work is team based sharing knowledge is highly important both to rise the quality of the results of the particular project as well as to learn from team members for future tasks. The level of competition on the labor market as well as the precariousness of the current position can influence the willingness of knowledge sharing between project members. In addition, in global development networks considerations regarding the international division of labor and its dynamics come into focus, as sharing knowledge with a co-worker in another location can rise replaceability. Knowledge sharing within a company is also a necessary process to be able to both realize projects as well as integrate complex knowledge pools between workgroups. However, within the company questions about autonomy and control as well as deskilling and interchangeability come into focus as engineers cede their individual knowledge to the organizational level.

There is a mutual dependence of knowledge and work organization as the process of appropriation of knowledge needs to be integrated into the labor process and the character of required knowledge is dependent on the way the labor process is organized (Krings et al. 2006). Taylorism, analyzed from the perspective of knowledge management, assumed an endless possibility to extract subjective knowledge, or the routine in the labor process and transform it into codified knowledge in the hands of management (McKinlay 2004). The idea was to secure full access to subjective knowledge to be able to organize the labor process meticulously as means of establishing further control. Modern knowledge management does not aim at full separation of subjective knowledge from the particular worker, but accepts its existence outside of the direct control of management. However, organizing knowledge sharing through knowledge management systems aims at lowering the dependence on a particular employee, sharing the most basal similarity with Taylorism.

This changed perception towards subjective knowledge accepting it as a positive and dynamic resource facilitates different managerial strategies. Knowledge management aims to organize the flows and storage of various forms of knowledge by control strategies that account for the specific degree of autonomy that subjective knowledge requires to both be developed as well as shared. The specific control strategies towards knowledge management are also shaped by labor resistance and local characteristics such as labor market dynamics. As product development projects produce massive amounts of data, information and subjective knowledge, management needs to set up appropriate processes allowing for a way to obtain, organize and share these various knowledge forms within and across the various functions of the company. Retaining, organizing and sharing knowledge is a fundamental prerequisite for knowledge based production processes to be profitable. This control requirement from the perspective of management, facilitated by the need to retain the most valuable parts of the process besides the finished product, collide with the interests of the knowledge workers.

The aim of managing subjective knowledge requires it to be made explicit. While Nonaka and Takeuchi (1995) base their ideas of knowledge management on Polanyi’s (1966) concept of implicit knowledge they do not consider the inherent limits in the process of explication. To take control and impose authority over the labor process of knowledge workers managerial strategies are not only limited by the specific characteristic of experience based knowledge but also by the labor process itself. Production work and its tacit dimension already posed limits to the appropriation of knowledge through various forms of resistance both individual as well as organized. These limits are increased fundamentally for knowledge work where the target of knowledge management is the source of productivity, i.e. work effort. If knowledge management takes a too harsh objective to gain control over the tacit knowledge of engineers, their very interest in the work based on high commitment and creativity can be lost. Confining the labor process of engineers too much by highly intrusive processes of knowledge management can result in a grinding halt of production as well as reduce the possibility to access these knowledge resources to nil. Subjective knowledge is tacit knowledge through the very process of explication that requires cooperation from the respective worker (Huws 2010; McKinlay 2000). This resource cannot be extracted by management but must be freely given by the employee. A certain gap between knowledge and power exists that must be bridged by management to be able to access and retain both the knowledge as well as the sources of the ever renewing knowledge in the heads and practices of the particular engineer.

Resistance towards knowledge management is linked to dynamics negatively influencing qualification as well as work content. An important aspect on this level is time required to both transform and feed knowledge into a respective system as well as make use of the system. As project work is characterized by increasingly tight schedules, working with knowledge management systems, i.e. documenting and reporting, is raising the intensification of work even more (Hill 2000). Additionally, time dedicated to knowledge creation is decreased by knowledge management systems as they at least partly provide the necessary knowledge (Taskin/Van Bunnen 2010). These deskilling tendencies of knowledge management can impact the quality of knowledge that is introduced to the database, as limiting the amount and quality of provided data and knowledge can be one form of resistance.

Problems also arise in the process of retrieving data from knowledge management databases (McInerne/LeFevre 2000) as well as from highly standardized documents such as technical specifications. The process of transforming data and information provided by knowledge management systems in an explicit form into a meaningful work procedure requires experience that the engineer must possess and be willing to apply. This knowledge application can also be limited by knowledge hierarchies within the international division of labor. Highly hierarchically organized global development networks impede the development of required context knowledge at peripheral design centers increasing the need for detailed work instructions provided by central locations.

Management can use various knowledge management strategies and instruments that can be placed on a continuum between highly routinized top-down approaches and more subtle communication based forms (McKinley 2000, 2004; Thompson/Walsham 2004). Top down approaches aimed at collecting and archiving explicit knowledge are often designed as flagship projects of top management as they result in measurable amount of knowledge in databases through straight forward processes. These can include the collection of slides, documents and templates into digital databases that are accessible from every point of the organization. For highly technical labor processes such databases are important, as they can provide at least examples of solutions for similar problems. However, as the data can be inappropriate and lack necessary qualitative dimensions the general effect of such knowledge management tools is disputable. Simple codification is seen by practitioners often as a wrong way of knowledge sharing as the necessary communicative interaction is being left out. However, such simple systems of codifying explicit knowledge can be more helpful if they are organized in a decentralized way resulting in personal knowledge databases.

Extensive debriefing during and after development projects through the instrument of lessons learned is used to access and gather more implicit forms of knowledge. This is mostly done within project teams to enable knowledge sharing and learning, focused on the handling of technical as well as organizational contingencies. This routinized process at each phase of a development project is time consuming and often results in a ritualized affirmation of organizational routines rather than a fundamental rethinking of them, thereby falling short of one of the most important ideas of knowledge management (McInerne/LeFevre 2000). However, these process can help to keep project member informed and give a quite good overview of possible solutions for technical problems, especially where experience based ways of coping are important.

Both, extensive debriefing as well as data bases storing objective and objectified knowledge are the most visible instruments of managerial control strategies. They point to the mutual dependence of control systems, where high levels of autonomy need to be bolstered by strategies of control. The control of project work is mostly focused on the result and not the person as such. Utilizing milestones leaves enough room for the engineer to be able to come up with ideas if a reasonable timeframe is granted. Debriefing and data bases refocus control on the person by offering a possibility to assess and quantify a particular work effort. The very process of debriefing and feeding data in the data bases is often characterized by direct control, expressed in high levels of standardization and formalization. The specific work of a chip design engineer – developing the circuitry – is mostly structured by technical limits of process technologies and tools at hand, while organizational limits are quite loose. Producing documentation is quite different as the standardization is very high both due to narrow technical as well as organizational limits. Filling out templates with required information that will be uploaded to a database is neither a creative nor an interesting work task.

More open mechanisms of knowledge sharing are based on a continual inter-subjective communication between individuals and focus on the deliberate sharing of knowledge between particular employees. However, these open mechanisms are also an essential part of the engineering labor process using instruments that tend towards managerial strategies of responsible autonomy. One of the main sources for knowledge in an organization is the knowledge about the existence and specific location of experts. Mentor relationships during the initial integration of engineering graduates and new engineers into the company as well as with high level company wide experts, provide an important way to share knowledge. Establishing such direct and personal bonds allows for the development of trust, which is an important factor in the process of knowledge sharing. Experience based knowledge both on the technical as well as organizational level can be shared easier based on a long-term relations. The mentor can also act as a gate keeper for the whole organization routing questions towards the most appropriate expert.

Communities of practices aim at the development of personal bonds or at least direct informal contacts across the whole organization between experts from the same area of expertise. Establishing specific issue-focused fora to organize and structure communication between particular experts in a more formal way is the aim of communities of practice from a control perspective. Within these fora the communication is being structured mostly in a way resembling academic knowledge sharing with lectures, presentations and discussions. Forms of story telling that allow for the transportation of dense implicit knowledge based on experience are also facilitated within communities of practice, as they establish informal personal networks with high levels of trust. For the company it is important to enable such communities of practice by carving out time in which the respective engineers can devote their concentration on preparing and attending such fora. However, these processes are always limited by the overarching profit interest of the company.

Process based knowledge management is the way how management can both access subjective knowledge as well as assert control over the labor process, while keeping direct forms of control low. Negotiability, of technical and organizational aspects of a development project, is the main instrument for such a process based knowledge management. Here the direction of knowledge sharing is not as much between employees but focused rather towards management. The aim of negotiability is not to separate this knowledge from the particular employee but to harness it for the organization's aims. Integrating engineers into the process of defining their schedules as well as at least some corners of technical details allows to access both their technical experience as well as knowledge about possible contingencies in the project execution. Simultaneously, such an integration enables the identification of the particular engineer with the organization as well as strengthens commitment towards the observation of the project's schedule.

Knowledge management is one of many instruments used by management to assert control over the labor process. Just as with other control tools managerial strategies are not homogenous but are characterized by layers of control where the simultaneity of various control and autonomy strategies allows for flexibility and mutual enforcement. The development of the international division of labor is an important factor in the dynamics of knowledge management as the ability of knowledge explication and knowledge application by design engineers is closely linked with the position of the particular development center in the global design network. The ability to work on complex projects is not only facilitated by the technical capabilities of the local engineering teams, but is also linked to their knowledge about and experience with the overall system and organizational context.

4.4. Strategies of control – analytical model and guiding questions

To be able to analyze the organization of engineering work within Global Design Networks (GDN) of the semiconductor industry and to integrate the discussed issues of control and knowledge management, Friedman's (1990) framework based on managerial strategies focused on maintaining authority over labor is useful. Friedman's initial model (1977) of managerial strategies was criticized regarding the simple dichotomy as well as the level of rationality in the choice of a specific managerial strategy (Nichols 1980;

Littler 1982; Thompson 1983) leading him to counter the critique with a more elaborate framework.

Friedman (1977, 1990) argues convincingly that managerial control strategies are the primary dynamic influencing the organization of work. The notion of managerial strategies is helpful to describe how the labor process is organized as the specific actions of management as well as the particular organization of work cannot be simply deduced from structural characteristics. In this view management is an agent that reacts to changes on the levels of markets, technologies as well as resistance from workers. However these reactions are not derived from a coherent and conscious set of policies, that dictate every step. Furthermore, both consistency and rationality of managerial actions are not given within the managerial strategies framework. Management is muddling through, taking initiatives that might be abandoned before the consequences are implemented in full. This often displayed inconsistency is rooted at least partially in organizational complexity where different levels and factions of management can pursue different interests and strategies. However, although management is seen as not always following a coherent and rational plan from strategic analysis and choice to implementation, its actions are guided by a specific process of reflection. Past choices and outcomes both positive and limiting come together in an iterative process where specific paths of management strategies evolve through the development of greater awareness. The success of these developments is still not guaranteed especially as management has to react to an evolving environment both within the firm as well as on the markets and in the supply chains.

The environment in which managerial strategies evolve is first and foremost the firm with its peculiar production that is driving a specific labor process. That is not to say that a specific production is linked to only one specific managerial strategy. The production process is integrated in a wider environment of specific market conditions that form the competitive landscape for the firm, the technological accomplishments and requirements that set the possibilities and limits as well as the outcomes of worker struggles. As globalization has developed and the semiconductor industry is fully internationalized further factors that facilitate shifts in managerial strategies have to be taken into account. The position of a company in the GDN is affecting its business model which sets certain limits to managerial strategies. However, as we will see in the following case studies on chip companies in CEE, the importance of the position within the value chain can be outweighed by local characteristics. The ability to secure enough engineering talent as well as the reluctance or inability of engineers to change workplaces are decisive factors for the definition of managerial strategies in this region. Institutional conditions such as IP protection are framing these dynamics, as they allow for a development of trust necessary for higher levels of autonomy.

Barrett (2004) already noted that management strategies change over time as a consequence to industry and economy wide developments as well as labor's resistance. This accurate observation on the historical dynamics of management strategies has to be extended by the notion of space. Friedman formulated in his book *Industry and Labour* a simple model of spatial differentiation in work organization where workers in peripheral regions are organized through differently governed labor processes than centrally located workers. However, in the current situation a simple deduction of managerial strategies from particular geographic locations is not possible. Especially with the highly specific labor process of engineers the relationships become much more complex. There are intricate links between local characteristics and the character of work outsourced or offshored to design centers in peripheral and developing countries in CEE and Asia. Local characteristics describe the possibilities and limits of design work that can be located in particular countries as well as the possibilities for upgrading processes. With this local characteristics influence both the specific position of a design center within intra- and inter-organizational GDN as well as the managerial strategies of choice. As we will see the organization of the labor process of chip design engineers in CEE resembles in many ways the labor process of engineers in central countries. However, local characteristics make interesting modulations of various aspects of the labor process necessary, ranging from control and recruitment to remuneration.

Friedman's (1977) dichotomy of managerial strategies between direct control and responsible autonomy is not describing opposing types but defining a continuum of possible ways how to maintain authority over workers. The choices in which work is organized are articulations of these strategies. However, managerial strategies are not exclusive. They are articulated through the ongoing process of managerial trial and error, where a one best way is not existing, forming complex systems. Following Storey (1985) Barrett (2001, 2004) regards these managerial strategies to evolve into systems where layers of control exist that consist of various strategies used separately and simultaneously to control the labor process (see also: Upadhya 2009). Within the engineering labor process these layers of autonomy and control form a dialectical relationship where management needs to balance responsible autonomy and direct control in such a way that both creativity has enough space for development and profitability can be achieved as development projects are successfully completed.

The system of layered managerial strategies and its differentiation between direct control and responsible autonomy can be linked to particular managerial activities in various dimensions of the labor process. The entire organization of work and production can be analyzed through four major parts that define specific categories of activities allowing to determine the specific forms of control in place: task organization, control structure, lateral relations and labor market relations. Every category of activity incorporates specific aspects of activities of the management, which guide the focus of empirical research. The particular character of the strategic dimensions of managerial activities informs about the orientation of the managerial strategies. Taken together this multi-level perspective allows to gauge the strategic orientation of management in every one of the four categories of activity. Friedman (1990) developed this model of activities to enable a systematic analysis of the labor process and the particular management strategies used on various levels (see: Table 4.1).

Table 4.1. Managerial strategies and activities

Categories of activities	Task organization	Control structure	Lateral relations	Labor market relations
Aspects of activities	Work Organization Scheduling Tools	Procedures (instruction and direction) Monitoring Evaluation and rewards	Structuring of communication Cross-functional Cross-location Customer relations	Recruitment Training Promotion
Strategic dimensions	Task complexity Task variety Task originality	Detail and formality Monitoring – people or work Evaluation through rewards or punishment	Degree of communication Forms of communication – hierarchical, technical, personal Cooperative or competitive	Dependency on staff Local market characteristics Employment protection
	Knowledge Management (Aspects of activities: Documentation; Prioritization) (Strategic dimensions: Procedures; Form; Content)			

Developed based on Friedman (1990) and Barrett (2004) and own research

4.4.1. Task organization

Task organization relates to the very organization of work by management based on division of labor. This includes work requests, formal organization of workers, scheduling structures as well as the tools in use. Work requests focuses on how specific tasks are defined and distributed among employees. Work requests can be formulated highly hierarchical in the form of clearly defined mostly small work packages that are handed down to a particular engineer who will be in charge to implement the particular technical specifications. More autonomous forms of work requests integrate the engineer in both the definition of the technical specifications, or even in the definition of the architecture of a particular chip, which is then being partitioned in subprojects that the engineer is taking responsibility for. Work requests can be also characterized by an intimate customer involvement which is both rising the complexity of required communication as well as possibilities of managerial interference. The way how work request are defined as well as their character can be interpreted using the strategic dimensions of task complexity, variety and originality. Managerial strategies tending towards direct control involve recurring and routinized tasks that do not call for high levels of creativity. Responsible autonomy on the other hand implicates technical independence and problem solving of the particular engineer with high levels of originality.

The organization of work requests is often linked to the way how scheduling of work tasks is organized. Partitioning a big design project can result, similarly to work requests, in hierarchically governed top down schedule settings. However, as scheduling of complex projects and tasks requires experience and is an error prone process more autonomous techniques are often used by management. Besides lowering possible glitches in planning, a dialogical definition of project schedules has the advantage of higher commitment on the side of engineers by moving more into the direction of responsible autonomy. Scheduling includes also questions about the length of specific tasks which, linked directly to task complexity and creativity.

The organization structure has consequences on both the size and variety of tasks engineers will receive affecting their skill requirements. As project organization prevails in today's chip design work questions regarding organization structures need to shift more towards the composition of project teams as well as the ability of engineers to change the functions they carry out in between different projects. The specific characteristics of the technology in use and the products under development have a decisive effect on both the size and complexity of tasks as they determine certain organizational and economic limits of organization. However, it is apparent that engineering work located near technology research is characterized by higher levels of task variety and originality than normal development work without being organized fundamentally different.

The use of specific tools and machines is linked to the level of detail described by the design methodology as a way to transform technical specifications into finished chip designs is influencing the complexity of knowledge required by the engineer. Here the complexity and the dynamics of technology in semiconductors do not allow for easy conclusions as highly automated design steps still can require complex knowledge.

4.4.2. Control structure

Control structure describes the activities that govern the instructions for procedures, the monitoring of their adherence as well as general aspects of work and the evaluation and reward of people. The term control structure points to the direct involvement of management in the labor process, opposed to the general control or the imperative of control. These activities are most directly related to Friedman's managerial strategy continuum of responsible autonomy and direct control. In task organization, technologies can sometimes dilute the options of managerial control strategies, as they pose limits through complexity and necessary specific organization structures. In contrast activities relating to the control structure are both strategy driven as well as quite visible for workers. This high level of visibility can be the source for open conflict between managers and engineers.

Friedman (1990) differentiates the category of control structure into the dimensions of degree of detail, monitoring and evaluation, with each being a continuum of possibilities. For engineering work the degree of detail is often not very relevant, as a precise description of the assigned work would require something very close to the finished project, or sub-project. However, there are still differences in degree of detail, especially from the perspective of the international division of labor.[29] Evaluation and monitoring engineering work seems also very problem laden. Evaluating engineering work, or the complex results such as sub-functionalities of an IC can be tedious tasks that

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[29] Although this is not part of this study there is cursory evidence on problems with detailed work instructions for offshored work. Engineers from central design centers sometimes complain about the amount of detail they have to provide in iterative communication processes with engineers in peripheral design centers. As long as this is necessary efficiency gains through such an international division of labor are seen as minuscule.

are not realizable by management, as again a complete evaluation of all design choices an engineer made would render a re-design necessary. The complexity of the work result therefore is obstructing any too detailed evaluation. Evaluation in such a labor process is focused more on the adherence of the design to the technical specifications determined by the initial data sheet, as well as the standards set by the design methodology. Design reviews are a possibility to delegate the evaluation process to team members or engineering experts while keeping the required quality standards in place. This points to a shift of managerial control responsibilities to workers.

Quality management can be an aspect of a direct control strategy in evaluation through rising levels of standardization and rationalization (Upadhya 2009). Quality management adds to the design methodologies already in place or restructures them in a more standard way. Especially for companies working in a more service oriented market quality management is a requirement to bind customers. However, the effect of quality management on engineering work is not unambiguous. As the introduction of quality management measures can result in upgrading the complexity of development projects can rise affecting engineering work positively.

Similar to detail and evaluation, monitoring of engineering work is limited by the very specific character of the labor process. Monitoring can concentrate either on people or on work tasks – either on the work process or on its results. The process of analyzing and thinking cannot be monitored in a quantified way regarding time and effort. To come up with the solution for a technical problem engineers often require idle time, that from a point of direct control could call for sanctions as it is, superficially considered, unproductive. One possibility to obtain a certain ability of monitoring is to gather data on the progress of the engineering work through dialog and weekly reports obtained from every engineer. However, such a monitoring of people is still error prone as it is based on the cooperation from the engineers' side, leaving room for resistance. Monitoring of development work is therefore more focused on monitoring work tasks and results than people. Milestones are the prevalent instrument of control in such a complex labor process. Each engineer is responsible to deliver specific results on time that was defined beforehand. Verbal clearances, design reviews of work and other evaluation procedures can be required.

The number of milestones within a specific design project can be an indicator of a strategy that is shifting from responsible autonomy towards higher degrees of direct control. A finely grained milestone structure is regarded by engineers often as confining both their creative capabilities as well as scheduling autonomy. Milestones are connected with scheduling in task organization as a small number of milestones give engineers more discretion and autonomy over their development work. In a situation characterized by a highly volatile workforce a system of finely grained milestones can play also the role of a tool for knowledge management, as it provides management with many points at which engineers need to deliver completed tasks and documentation that can be put to use in case the respective engineer leaves the company and abandons his part of the project.

The already mentioned dimension of evaluation is also important in relation to reward or punishment structures. Bonuses and penalties linked to specific work results such as timely project completion or level of re-use can be focused on individual engineers or whole project teams. Such control systems are dependent on the local institutional and cultural framework as well as the situation on the labor market. A high competition for talent on the local labor market can drive high bonus systems to draw the best talent to the company. However, local labor laws can obstruct too big imbalances between bonus and regular pay.

Control structure with its both direct as well as indirect measures is driven by many factors. The business model of the company can be a decisive factor. Upadhya (2009) describes how Indian software service companies control the labor process of their software engineers. High levels of direct and indirect control are necessary as Indian software service companies base their business model on cost advantages. Cost competition coupled with service work translate into the need to structure the labor process in a very explicit way. However, hardware development, with its much longer project duration puts severe limits to high levels of control. In contrast to the very short project durations described by Upadhya (2009) slippages in product development work can be much better absorbed by both the respective engineer as well as the whole team.

4.4.3. Lateral relations

With the lateral relations category Friedman (1990) introduced a highly interesting perspective on the shaping of the labor process by managerial strategies. The focus here are the communication processes that are encouraged, hindered and organized within a firm and within particular project teams and how such communication is structured by management strategies. This involves both communication between engineers of similar status and different status, cross-functional and cross-location communication as well as customer related communication. By controlling communication between various groups of the company management is able to create hierarchies used for managerial control strategies.

As engineering work is mostly organized in project teams the individuation of work is neither a problem for the particular engineer nor an aim of management as cooperative work based on dialogical communication is offering both productivity gains as well as quality assurance. This does translate into much higher levels of structuring of communication compared to highly Taylorized labor processes characterized by individuation. The desired everyday free communication between team members as well as engineers of the same specialization are often augmented by several levels of organized and structured group communication. Regular team, expert/specialist, design center or customer meetings impose open but often highly standardized ways of communication. However, as free as such communication may be within a company, the need to gain authority over labor is the guiding principle of management structuring communication among engineers. For engineers these high levels of communication translate into requirements of skill development, as presentations and group discussions need to be prepared and conducted. The requirement for such structured communications also raise work intensification as tight schedules often do not allow for constant interruptions.

Internationalized company structures integrate the major problems and possibilities for organizing and structuring the communication between engineers. Here the strategic dimensions of degree, form and character of communication come into full play: How is communication organized between employees from various locations – only through technical means or are personal relations fostered? What is the intensity of this communication and who is initiating them? Are these communication processes framed by a competitive or cooperative perspective from employees?

Communication with customers is an area where, despite all open communication structures, hierarchical forms of communications can present. When communication with a customer is always relayed through a dedicated engineer, i.e. project leader, arguments of efficiency are only one explanation. As this communication often focuses on business aspects leaving technical discussions aside, the need for a more controlled communication structure is evident. Customer communication regarding purely technical aspects has to be analyzed as a practice of direct control, as explicit and detailed work requirements are formulated and change requests have direct implication on engineering work. The ability to both conduct such communication as well as react to its outcomes is very important in the skill requirements of todays engineers.

4.4.4. Labor market relations

Managerial activities concerning labor market relations focus on recruitment, training and promotion of engineers. Recruitment and training are used as instruments to address aspects of the indeterminacy of labor (Hastings 2011). The ability to secure talent that will fit into the specific labor process both regarding technical skills as well as the personality of the prospective new worker is an important aspect of management strategies. The specific groups that management is aiming for are of importance both for recruitment as well as training activities. Their characteristics together with the particular labor process organization determine how long it takes until a new employee is able to perform his tasks. The levels of required experience based knowledge and autonomous work are linked to both the adjustment to the new job as well as specific training systems.

The strategic dimension comes into play in the labor market category in relation to the dependency of the firm on the particular employee. Labor process related factors such as skill and knowledge requirements that are structured by the specific task organization are important. The more a labor process is focused on responsible autonomy the higher this dependency is, as factors such as high levels of experience based knowledge are important and individual workers are not easily exchangeable. Besides these purely labor process driven factors dependency on staff is also highly dependent on local characteristics. Local labor markets, educational systems as well as labor laws structure the possibilities of a firm to recruit, employ and lay-off staff. Constrained labor markets require companies to develop complex systems of recruitment that can extend over the labor markets towards education systems to be able to secure enough talent. However, there is no simple link between a labor market situation and a specific organization of work, as various other related factors affect managerial strategies. A highly constrained local labor market that offers engineers many job opportunities rises their initial negotiating power. However, as such a situation often translates into high fluctuation rates that are endangering timely project completion high levels of control in the labor process are necessary to retain both knowledge as well as allow for easy hand-off. Labor markets that are constrained from both sides, and these constrains are supported by specific structural as well as cultural traits that do not facilitate rapid job change, give the firm enough security over its workforce that more autonomous work organization is possible. However, management needs to invest heavily in recruitment and training policies.

Training is linked to the major two phases of an engineering career. Recruiting fresh graduates enables companies to keep their labor costs low, however it requires big investment in their initial training. The two main directions of this training are the build up of actual design knowledge and experience based on the formal knowledge from university. This is mostly organized through on-the-job training where increasingly complex tasks are assigned to the young engineer. Firm-specific knowledge about design methodologies, organizational structures as well as all relevant processes are also mostly presented through informal training. This training is also required for already experienced engineers joining a company. Formal training focusing on specific technical, organizational and managerial skills is also necessary for engineers. These kind of training is connected to control. Engineers can voice interest in specific topics and issues that will help them to develop their capabilities further and pursue their desired career on the technical or managerial ladder. However, management is deciding whether it will grant such training opportunities based on financial deliberations as well as strategic decisions concerning the future development of the respective design center.

The development of two career ladders both a technical and a managerial at a particular design center are an indicator for the importance of the specific location. The expansion of career opportunities for engineers is further developing the internal labor market raising the potential of job security for engineers. Friedman (1977) links the development of internal labor markets and high levels of job security with the managerial strategy of responsible autonomy, as trust relationships between workers and management can develop. However, other factors can affect job security especially during times of crisis. Here the origins of a company and the associated cultural traits, in the sense of varieties of capitalism discussion, become important and sometimes can overrule local managerial strategies. The orientation on mid-term development drives companies to retain engineering talent even in times of crisis to be able to ramp up product development during economical upturn.

4.4.5. Knowledge management

For my analysis of the labor process of chip design in GDN I add a lateral dimension to Friedman's (1990) model to be able to grasp the specific dynamics of a knowledge intensive labor process in a complex international division of labor. Knowledge management is important to be able to grasp both specific forms of control as well as skill shifts inherent in the internationalized engineering labor process. Knowledge management encompasses all activities that aim at the organization of knowledge sharing on all levels of the company. Managerial activities that lead to knowledge management systems based on various forms of documentation and knowledge retention are important. In the tight project schedules the priority that specific knowledge sharing processes are given is significant. Procedures, forms and content of knowledge management systems are of interest. Are there clearly formalized procedures in place that govern knowledge sharing and are they followed? Is knowledge management organized mostly through global databanks or group and communities of practice? Is knowledge sharing only focused on project related issues or does it include also broader technical questions driven by engineers' interests? Control systems leaning towards responsible autonomy would be characterized by lax procedures, or low adherence to procedures, while putting a focus on less automated systems of knowledge sharing. To develop a feeling of responsibility and foster the individual ability to solve problems knowledge sharing that goes beyond project-related issues is important.

Simultaneously, knowledge management is a lateral dimension affecting on all four categories of managerial activities. Knowledge management systems need to be integrated into task organization to impose specific duties into the work of engineers. The originality and complexity of tasks required by top-down knowledge management systems are mostly narrow. Although engineers notice the positive effects of knowledge sharing some specific instruments such as software based systems can have inherent limits. Personal contact with an expert is seen by engineers as the best way to organize knowledge facilitating cooperative lateral relations. In companies with an international scope these lateral relations between experts of specific technical focus need to be organized and integrated into the labor process. The establishment of communities of practice is a fundamental instrument of knowledge management establishing yet another highly structured level of communication.

However, knowledge management is not only based on the activities of the company but is also a process advanced by engineers as they gather experience both on the technical as well as organizational level. Knowing who to ask about specific issues is a major capability that is developed through tenure in a company. Such necessary knowledge management capabilities of the respective engineers are not only based on organizational knowledge but also on good communication skills, marking skill shifts in the engineering labor process. Organizational knowledge is also in the focus of more institutionalized attempts to formalize knowledge on specific expertise of engineers in lists, or company yellow pages.

Knowledge management is aimed at separating the knowledge from its carrier thereby reducing dependency on the individual engineer. This is especially important when a company has to cope with high fluctuation. However, this separation of knowledge from the engineer is not resulting in a degradation of work directly. The separation of knowledge is not solely aimed at the Taylorization of the engineering process, as knowledge is the most important tool engineers use in their work. Specific chip design methodologies, such as the system on chip designs, were aimed at a modularization of engineering work with high levels of separation between conception and implementation. These ideas to taylorize chip design development are limited by the inherent characteristics of the chip design labor process driven by specific aspects of the international division of labor. Providing peripheral engineers only with simple parts of development projects will eventually result, in case an absorptive labor market exists, in high rates of fluctuation, impeding knowledge management. This is one of the major drivers of upgrading processes of technical and managerial capabilities located at specific design centers.

4.4.6. Lateral dynamics

The categories of strategy, technical and time autonomy (Barrett 2001, 2004) can be used to group dynamics from several categories of activities. Managerial strategies are based on layers of control that do not operate in a discrete way over the four categories of activities. Rather managerial strategies have lateral affects within the labor process. Technical and strategy autonomy are crossing both task organization as well as control structure and lateral relations. The ability to define how to tackle a predefined problem relatively autonomously, i.e. technical autonomy, needs a specific organizational framework. With technical autonomy the engineer has some degree of control and discretion over the development process, at least over the parts he is responsible for. Design methodologies and quality management limit tool choices as well as the way the result has to conform to technical requirements. However, with a high level of technical autonomy an engineer still needs to develop the idea on how to resolve the problem on his own. The implementation of this idea, especially the specific sequencing of the various necessary steps, are in his discretion.

Technical autonomy is linked to the ability to monitor the labor process by management. The higher the level of technical autonomy, the lower the detail of control. The monitoring of work, especially through the evaluation of goals that were predefined becomes more important. The characteristics of the process leading to the definition of project goals and schedules are important to understand how autonomy is being injected into the labor process. Technical autonomy affects lateral relations as it is based on the flow of knowledge within and between various hierarchies and functions of the respective firm. This knowledge flow has to be organized by management mostly through various communicative elements, such as team meetings, as well as more hierarchical machine based mechanisms such as knowledge data bases.

With regards to time milestones are the most important control instrument. Milestones are based on a specific way of task organization and scheduling and in respect to their granularity can have effect especially on the task variety of a particular engineer. The way milestones are defined is linked to the way how communication is structured in the specific firm as well as how organization structures have been set up. Milestones can be analyzed as practices of direct control, as they define precisely the deliverables and the dates these are due. A dialogical definition of milestones based on the experience of engineers tilts this practice more into the direction of responsible autonomy. But in light with Burawoy's (1979) insights we have to be aware that such a integration of workers into managerial tasks despite rising the level of autonomy is integrating them further and providing the basis for the reproduction of control structures. Within the system of milestones engineers can act relatively autonomously and manage their time and tasks on their own. This is rising the subjective levels of work, especially skills like time management as well as experience.

4.4.7. Guiding questions

The analytical model of managerial strategies of control can be linked to the major questions and theses of this study:

1) *How is engineering work organized in design centers in CEE?*

- Major differences between the organization of work in design centers in CEE and developed markets are not apparent, as the previously peripheral design centers have matured over the years.
- On the levels of task complexity and diversity engineering work in CEE is comparable to other developed regions. Task originality is sometimes lagging behind as processes of product upgrading are only starting.
- Negotiability of both organizational and technical aspects of work organization is a fundamental managerial strategy.
- Lateral relations have a phased character when it comes to international communication. The integrated character of the design centers allows engineers to concentrate on local communication during the implementation of designs.
- International communication and international interfaces are important, for some engineering functions on a daily basis. Here subjective capabilities to stabilize these interfaces are central.

2) *What general control systems are applied through managerial strategies and how does this relate to the industrialization of engineering work?*

- The fundamental control system is based on responsible autonomy, with major characteristics of normative control. Commitment is produced through elaborate institutionalized processes of communication.
- The entire control system is arranged in layers, where strategies of relative autonomy and direct control are deployed to stabilized the international labor process.
- International dynamics include customer involvement that can add a layer of direct control.
- Dynamics of industrialization of engineering work are not widespread. While standardization and formalization of international interfaces is enforced

simultaneously these interfaces require stabilization through autonomous activities.

- The high levels of local integration of development work are limiting dynamics of industrialization of engineering work additionally.
- The high levels of negotiability that are a fundamental characteristics of the engineering labor process in CEE facilitate skill shifts.

3) *How is knowledge managed in design centers in CEE and are dynamics of standardization and control visible?*

- Complex knowledge management systems exist in most design centers in CEE to enable knowledge sharing within the centers as well as between various locations.
- Formal standardized procedures are in place that govern data input as well as the usage of these knowledge management systems.
- Both engineers as well as management regard global knowledge repositories as problematic and are to some degree opposing their utilization.
- Local knowledge sharing and personal knowledge databases are regarded as most important and most effective tools for managing knowledge pools.
- Global knowledge sharing processes and tools are used as starting points to develop personal knowledge sharing networks.

4) *How is workers' resistance shaping of the engineering labor process in CEE?*

- Engineers in CEE are not exerting resistance in an organized way through labor unions as unionization is very low, or non existent.
- Individualized resistance from engineers is existent especially when organizational control is becoming too high. Engineers try to negotiate with management to reach mutual beneficent changes.

- Covert resistance is used on a daily basis, e.g. by using knowledge sharing tools in a not intended fashion. This form of resistance points to autonomy within standardized and formalized parts of the labor process.

5) *What role does the labor market play in the development of the local labor process organization?*

   - The high levels of technical proficiency and experience of local engineers allowed to build up relatively big design centers with high levels of capabilities fast.
   - The low fluctuation rates facilitate the development of a labor process organization based on relative autonomy as knowledge retention systems are not necessary. Simultaneously, the growing levels of experience are increasingly put into use making a more autonomous organization necessary to enable creativity and motivation.
   - The high levels of local integration of development work are limiting dynamics of industrialization of engineering work additionally.

6) *How are the processes of upgrading linked to labor process organization and the evolution of control systems?*

   - Upgrading is the concept that helps to understand how dynamics on the sectoral and local level are connected. Functional and product upgrading are the most important types of upgrading for the development of the labor process organization.
   - While functional upgrading establishes the role of an technical expert through rising the level of independence, product upgrading acknowledges this role through the appropriate development project. Only through this double movement is the establishment of a effective labor process possible.
   - Upgrading is linked to shifts in the position within global networks of production and design. There is no direct connection between the organization of the engineering labor process and the position within such networks.

However, shifts in network positions through upgrading facilitate changes in the labor process organization through processes of standardization.

5. The labor process in chip design – three case studies

5.1. Midtronic – a multinational's integrated operations in CEE

5.1.1. IC development – work in locally integrated project teams

During the last 15 years the development capabilities in Midtronic's CEE development centers have been upgraded significantly comprising now all technical and most managerial functions required for product development. This enables the formation of locally fully integrated product development project teams. The centers are lacking only high-level management capabilities, especially sales and marketing. Engineers are able to work both on complex projects with local ownership as well as to organize their work in locally integrated projects keeping issues related to distributed work to a minimum. This high level of local integration allows to shift the need of international cooperation out of the design process towards the initial and final stages of a development project, facilitating also a more focused control of the labor process.

Project leader – caught up between managerial and technical sides

In all three design centers Midtronic has eventually upgraded the capabilities of project management by establishing local project leaders. Local project leading positions have both eased up communication within development teams as well as opened up a second career path for Czech engineers. Initially project leading responsibilities for the BDC were located solely in Belgium, increasing the complexity of the communication within the single project development teams. Simple engineering inquires required high coordination as well as good English skills as the project leader was mostly a Belgian. Supervision of distant projects made weekly written reports to the project leader obligatory to communicate the project status as well as progress of work. Regular visits of the Belgian project leaders to BDC were necessary. Today such communication is much easier as it can be accomplished by simply walking to another room. This allows for a much more flexible control structure based more on personal communication and assessment than on complex and standardized procedures. The establishment of local project and group leaders simplified communication within particular development teams considerably. Project leaders now monitor the engineers' work on a day to day basis and forward these information verbally to the group leader, who again is reporting to his superior in Belgium or the U.S. on a weekly basis.

The position of project leader implies a shift from technical to more administrative work for the respective engineer. With the responsibility for a project composed of five to ten engineers the project leader is focused on managing mostly organizational issues, drawing him away from the technical side of engineering work. The involvement of a project leader in at least two development projects in parallel further complicates the ability to focus on technical work. His main task is to develop a working schedule for his team, assign tasks, monitor and control the compliance to the schedule and deal with issues both within the design team as well as with other parts of the organization involved in the development project. Project leaders particularly work on the interfaces with manufacturing and test operations to ensure a smooth delivery of tape-out data to manufacturing operations and first evaluation samples to the designers. They are the international interface of the development project, aggregating and organizing communication flows between the various functional parts of the project. This shift in work towards administrative and communicative tasks is perceived by most engineers as negative, as their main interests lay in the technical part of their work. However, project leaders are not completely derived from engineering tasks. Their technical focus shifts towards the more abstract level of development planning. It is their task to translate the technical sketch developed by the system architect into a detailed plan in close cooperation with the customer. As this work requires close cooperation and constant communication with the customer's engineers the project leader is often traveling to the customer's development centers.

Organizational aspects of project work, personified by the position of the project engineer, are not something many engineers at the BDC aspire to.

> "*That's the most difficult part, most disliked part*" (Analog Design Engineer 2 – BDC)

However, some engineers admit that shifting towards the managerial focus is the only way to move on in their career and leading projects is the first step required. The managerial career track is offering higher gains in both responsibility as well as financial rewards.

Although the project leader is responsible for the control of the whole project the position is characterized by supervisory tasks and is heavily dependent on decisions made by management. In the pre-phase of projects project leaders are assigned as technical expert but not given any information about the specifics of the business contract arranged with the customer. Their only, albeit highly complex task is to assess the technical feasibility of the planned project within the given limits. Although they can voice issues regarding the projects, it seems that their ability to enforce a change are impeded not only by their institutionally low leverage. The management side is composed of former engineers who are perceived as being convinced that they can assess the technical aspects of the project at least as good as the particular project leader, making it hard for the engineer to argue for his opinion. The ability to convince a management board is not only based on good engineering knowledge, but also calls for rhetoric skills, enabling to devise a business relevant reasoning on short notice. Such skills need to develop over years, requiring steep learning curves for new project leaders.

The group leader, as the superior of the project leader, is responsible for the workloads of the specific engineers. This organizational structure can interfere with the interests and goals of different projects and their leaders. The project leaders are responsible for the projects' execution but lack power to influence all factors that are impacting the projects' progress. Some engineers describe this as a situation of powerlessness, rendering their work sometimes frustrating.

IC development – engineers and their tasks

Architectural decisions are referred to as most important from both the technical as well as business perspective. Thus system architects become strategic assets mostly located in the headquarters, or design operations in high-cost locations. System architects need to integrate both technical as well as business aspects into their decisions. The choice of a specific chip architecture is a highly cooperative process where engineers from the Midtronic's Czech design centers can also voice their opinions. From an engineering perspective it is very important that architectural decisions are based foremost on technical considerations, pushing business aspects to the background, as otherwise issues can be missed both on the technical as well as organizational level. This makes a co-location of architectural capabilities with IC design engineers desirable. However, as the managerial perspective is often circumventing purely technical considerations such a co-location is only possible after a design location has developed positively. The position of a system architect was established at the BDC only after several years and apparently on customer request.

Based on the parameters defined in the project's data sheet IC designers are developing the schematics for the circuitry that will be manufactured in silicon. As the IC designers at Midtronic are developing mostly analog products they do not make use of

HDL[30], but work with software that uses graphic representations of the silicon structures, called electronic schematics. The design of an analog IC is described by the involved engineers frequently as a highly creative and manual act. The degree of automation is quite low in analog IC design and design engineers are using EDA tools mainly as schematic editors and simulation environments. As IC design engineers at Midtronic's design centers work mostly only on one project at the time, they need to wait for the first shipped chips to come back from manufacturing to be evaluated after design tape-out. During this time they prepare evaluation boards, work on minor projects or study. The IC designers are evaluating the chips they have designed, which is not only required by the company's development process but is also connected to the curiosity of the respective engineer. The intrinsic interest of the engineers in their work as such, their inclination towards technical problems and solutions is here the integrating mechanism facilitating the perception of work in a very positive way as a playful activity:

> "*I am playing with the chip, because I want to know, I want to see it personally.*"
> (Chip Design Engineer 1 – RDC)

From a purely technical perspective IC design engineers are the major focal point of a product development project, as they need to integrate and in some way guide the work of both layout and test engineers. This cross-functional cooperation is facilitated by locally integrated development teams. In this respect IC design engineers shift between positions as they also take over control tasks towards their engineering colleagues. The international division of labor within the respective development project is pushed out to the initial and final project phases. Only during project set-up and design tape-out and manufacturing is a deep and broad involvement of internationally distributed intra-organizational functions necessary.

Design engineers at BrDC focus on quite simple and small products. However, as Midtronic is manufacturing products with around 50 different process technologies design engineers have to master most of the technologies in their respective product ranges. Even the design of derivative products is affected by the high number of process technologies as process technology shifts drive the complexity of engineering work, without adding considerable design complexity. Such reasoning brought forward by some engineers has

[30] Hardware Definition Languages such as Verilog and VHDL allow IC designers to define an IC through syntax based code looking quite similarly to software code. However, contrary to software code HDL code is describing material structures of the IC, i.e. the concrete transistors and gates that make up the chip.

to be understood in the context of processes of upgrading and hierarchies of technical expertise as well as power as strategies to legitimize one's own technical proficiency and expertise. The complexity of designing derivative product using a big number of complex process technologies is without question a sophisticated engineering task. However, it does not involve the development of specific circuitry that will perform the required function, but only the transformation of already existent circuitry onto a different process technology.

Layout engineers or physical designers are taking the electronic schematics from the IC designers and are transforming them into an actual physical arrangement of the various functional components and the connecting wires.[31] Almost the whole layout work has to be done manually with the help of layout tools that deliver graphical representations of the silicon structures. Only for minor parts of the chip layout automation tools are used. There is no single best way to design and layout a chip and technical trade-offs need to be taken into account as well as preferences of IC designers. The basic trade-off in layout is between the robustness of the layout and the die area, i.e. between how perfectly parameters are met and the production costs of the individual chip dependent on its size. Layout engineers and IC design engineers need to closely cooperate and communicate, in the development process. This is ensured at Midtronic by geographic proximity. The connection between layout and design at RDC is described as very close, with the IC designers communicating every day or two with the layout engineers about the development of the layout.

Test engineering focuses on the development of automated tests used in mass-production that are to ensure a constant high quality level of shipped products. The work of test engineers includes both hardware as well as software development. Based on the test plan, developed during the project's initial phase, test engineers are developing the interface between the automated tester and the chip. At RDC local test engineers are responsible for the layout and debugging of these test boards, while the manufacturing is taken over by a small local contract manufacturer. Test engineers are also responsible for the development of the test program that will run on the tester. Some perceive test engineering for analog chip as not offering as many opportunities to gain high levels of technological knowledge as IC design. However, the work of test engineers is characterized by a high diversity.

[31] These physical representation will then be extracted into a file format for mask production which is used in wafer manufacturing.

"*On one activity I spend no more than one week. This activity will only repeat in another project. That means after 2 months or 7 months, it depends. The variety of activities I have to do is tremendous.*" (Leader of Test Group – RDC)

Similar to layout design it is useful to locate test engineers in close proximity to other development engineers. Both application and design engineers need feedback from the test department as soon as possible. Off-site test departments prolong the time until application and design engineers receive the necessary data to jointly test and analyze results. Especially during new product development testing is highly important and eased by close proximity. Midtronic's U.S. locations are lacking on-site test department and are only relying on test and measurement data from offshore manufacturing. This results both in delays as well as in problems with the data itself. This specific international division of labor is linked to high labor costs of U.S. engineers. While the highly integrated project development teams at the RDC development center are enabled by relatively low labor cost, making the co-location of the various functions economically feasible.

The upgrading of the technical and management capabilities in Midtronic's CEE development centers have enabled locally integrated development teams that show distinct forms of modular IC development. The levels of integration of local development capabilities vary between the respective regions, with CEE development centers apparently comprising increasingly broader technical capabilities while centers in the U.S. and other high wage regions lack specific technical capabilities such as test engineers. This integration of lower level technical tasks opens up possibilities to further upgrading and provides steep learning curves for local engineers. However, higher management functions are still concentrated in these high wage locations, keeping final decisions out of the range of CEE design centers.

The locally differentiated levels of integration seem to fall in line with cost considerations as well as historically developed local capabilities, pointing however to a clear preference for higher integration levels when economically and technically feasible. This hints to the fact that modularization has severe limits and attempts of micro-modularization, or the partitioning of the labor process into increasingly small and internationally distributed functional modules integrated through sophisticated interfaces based on leading edge CAD and EDA tools and management processes, are in the long run neither organizationally practicable nor economically supportable. The level of technological maturity seems to be only of minor importance, refuting claims that only leading edge technologies with their quite unstable processes, interfaces and tools need high levels of integration. Midtronic is best known for its cost specialization based on mature process technologies even in relation to its competitors. Such mature and stable technologies as well as development processes optimized already over several product generations would be the prime example for these maturity arguments for a micro-modularized international division of labor aimed at cost advance optimization. Instead, Midtronic is committed to increasingly upgrade its low-cost development centers as relatively autonomous entities. Simultaneously, the company is also further developing its design centers in the higher wage regions. However, an important driver of the high integration levels is the size of the respective projects. Midtronic's project teams are composed of only up to 20 engineers enabling locally integrated teams. Huge digital IC projects can comprise up to several hundred engineers limiting the ability of companies to source all engineers from only one design center.

Although this locally integrated development team approach is trying to keep international linkages to a minimum, specific operational parts of the whole production cycle are located in various global regions, making the development of interfaces necessary. One of such major interfaces is the local project leader, a position where the international character of the labor process is becoming visible. This specific international character is driving the need for extending and shifting the skill sets of the respective engineers. Besides obvious language skills the project leader needs to manage internal suppliers and customers within a global design network. Communication capabilities enabling the smooth cooperation with distant partners, based both on a thorough understanding of and experience with technical and organizational processes as well as an increased empathy for the communication partner as a basis to aggregate and interpret various information become key for such a position. Such capabilities need to be developed over time as they are mostly based on experience requiring long-term practical learning and wide ranging cooperation horizons.

It seems that such a skill shift is not only perceived as a positive extension of the individual capabilities of respective engineers. For many engineers this equals with a shift away from their primal interest of work. However, as project leaders need to be recruited from the more experienced talent pool of the respective design center, this task seems often almost imposed on engineers who would be happy to focus on the technical side. Project based organization of development work is the main driver of the fundamental need for project leaders. With the integration of design centers into intra/inter-organizational GDN the required capabilities of project leaders expand dramatically. The administrative and organizational tasks now need to be mastered on a much wider scale integrating different cultures, communication levels and technical proficiencies over big distances. High levels of local capability integration help to lower the requirements towards project leaders to a minimum.

5.1.2. IC development – project flow and communication in the development cycle

As the design centers are characterized by locally integrated IC development projects levels of internationality and external involvement in cooperation and communication vary greatly between the three main stages of a project: definition, implementation and closure. Functions necessary for the start and complete a development project such as marketing and sales as well as manufacturing are not located locally, expanding the necessary international cooperation and communication during the first and third project phase. During the project execution phase, i.e. the development and design of the specific circuitry, the international cooperation is reduced to a minimum.

RDC – IC development with limited customer contact

In the initial stage of a project located at RDC the product that will be developed is defined through a data sheet, a task mostly done by the application engineer in the U.S. headquarters in cooperation with marketing and sales. However, application engineers at RDC and local field application engineers in Asia are sometimes also responsible. Apparently, most of the initial product ideas come from the marketing and sales department and their application engineers, based on either future market needs or on specific customer requests. After the initial product idea in form of the data sheet a more precise study is performed – the product feasibility analysis (PFA), conducted at the RDC site for products that will be developed here. The PFA team often consists of engineers later not involved in the project and is augmented by non-local group managers. The aim of the PFA is to assess the project, taking into consideration the availability of people, knowledge, tools and technology as well as pointing out possible risks and problems. These results are used by marketing as basis to decide on possible changes regarding parameters or specific functions. Marketing is also responsible for the development of the business case focusing on the saleability, the necessary technology and package that determine the production costs and the future price fundamentally. The test department is involved in the PFA, to ensure a design that will allow easy and fault free testing. The output of the whole process – the data sheet, team assignment schedules, the PFA, risk definitions and other specifics as well as the business case – are submitted to the Program Steering Group (PSG) for review. The PSG consists of business unit managers from RDC and U.S. and decides whether the project will start or if it needs further adjustments.

In case of project approval by the PSG the data sheet needs finalization to avoid future misunderstandings. For this task the application engineer from marketing and sales, either from France or from U.S., comes to RDC for about a week. In an intensive process of several team meetings between the application engineer and the future project members the final and detailed data sheet is produced.

> "*It is much better to talk together face to face in one room at one table. This is important.*" (Chip Design Engineer 2 – RDC)

> "*[...] to communicate this is much faster to sit at one table*" (Chip Design Engineer 1 – RDC)

The initial phase of a design project requires a highly intensive communication where fundamental decisions on very complex questions have to be discussed, verified and made, making face-to-face communication necessary or at least highly efficient compared to email or via telephone. As communication slips can make design re-spins necessary, with costs ranging over US$ 200,000, the responsibility of the respective engineers is quite high. Communication by email is perceived as problematic on two levels: first, the meticulous preparation of data and information for the communication partner is very time consuming resulting often in excess or wrong data, as response from the partner is provided only after completion and delivery of it. Second, to be able to fix results that can be used as point of departure and reliable reference many emails need to be exchanged and often ping-pong email discussions emerge. A similar problem occurs in telephone communication, where extensive discussions over the phone almost always need to be followed up by emails confirming the decisions, to ensure that both sides have the same understanding of the achieved results.

The communication between the marketing department in the U.S. and the development engineers in the Czech Republic had to evolve, so that experience could be built up to understand what the other side was communicating, especially regarding technical aspects of future products.

> "*The beginning were tough, but now it's going fine.*" (Project Leader – BDC)

The main issue were data sheets provided by marketing to the development teams in RDC. Data sheets describe in a very condensed way the product's characteristics. Although the technical description is quite standardized, based on technical and physical aspects of the device that is to be designed, complex functions and parameters of sophisticated devices need to be understood in relation to a wider integration background and the resulting technical issues with the chosen technologies. These aspects require the ability to contextualize the complex but standardized technical data. Engineers at RDC were able to build up the necessary interpretative skills only through experience resulting from many projects. Now they easily translate the standardized and condensed data of the data sheets into proper information they can base their development work on. This capability and knowledge allows for much higher levels of autonomy as work specifications can be kept to a minimum. Additionally, the project teams in RDC receive complete development projects in contrast to narrow work packages. The basic workbench style international division of labor has been superseded by an organization of development that is fully deploying the local capabilities.

During the design cycle, when IC designers, layout and test engineers are working on their assigned tasks intensive communication outside of the development center is not necessary. To solve their tasks and emerging problems engineers of the respective project team are able to communicate on a daily basis as well as contact local colleagues at RDC. General weekly conference calls with marketing in U.S. exist to ensure a constant communication process about new ideas and ongoing projects. All team members are present during such meetings and can discuss issues as well as put forward questions and solutions.

Although these meetings consist only of engineers cross-functional issues characterize the communication, as the specific engineers' communication is driven by their respective focus. While design engineers located at RDC are interested in characterizing and discussing technical issues in detail, the marketing representatives are only interested in learning about the nature of the problems and about the way to resolve them. As the cross-functional distributed teamwork is in place already for several years each side has learned about these different perspectives and levels of interest and abstraction that are relevant for the other members, guaranteeing a smoother communication. However, even after years communicative frictions can still emerge. To lower sources for misunderstandings between the internationally distributed development engineers and marketing engineers, direct communication is key as the interpretation of information made necessary by indirect communication produces misunderstandings. To keep up the personal level within the distributed project teams the marketing engineers are visiting the RDC development engineers quarterly.

At the end of the design phase Midtronic has institutionalized the system of design and layout reviews, to guarantee high quality standards as well as knowledge sharing. Here the communication is expanded to the international level to integrate various engineering communities in different development centers. Discussions that form the basis for the design and layout review are in essence technical, leaving aside other product considerations and are held between engineers of the same specialization. This facilitates communication and avoids cross-functional friction.

The hand-off of layout data to manufacturing is very much standardized and is commonly understood as not needing a close communication between designers and manufacturing engineers. At the final stage of design the test department is involved, increasing the international character of the communication. Test engineers at RDC need to work closely with their colleagues in oversea locations in Asia to gather test data and tweak tests in development. To enable this very close inter-site cooperation Midtronic is sending test personnel from its Asian manufacturing sites to RDC, providing intensive procedures training with Czech locals. This upgrading of capabilities and knowledge is seen as a very important basis for a successful future cooperation between sites. However, not only the technical part of this training is important but also the face to face communication during this time that establishes a more personal link between both sides, allowing for an easier remote communication.

Although most product development at the RDC is organized in direct customer relation there are also customer requests which are handled solely by sales and marketing as well as field application engineers. Such a centralized customer relation structure allows for a consistent communication. Typically development engineers at RDC do not communicate directly with customers. However, application engineers are one of the main interfaces towards customers and as some application engineers are also located at RDC, there is a local interface between customers and development teams. Application engineers need to build up an intimate relation to the customers, to be able to understand their requirements and communicate them to the development team. As the customer is not a specialist in analog IC design he is not anticipating impacts and consequences as well as technical trade-offs of his requirements. This quite often leads to change request after product design has been completed. The application engineer needs to provide the capability to understand the product objective of the customer provide as well as on problematic requirements.

After the product shipment has started customers sometimes need technical support with new products, provided by the technical support department of Midtronic. However, RDC does not house a technical customer support team, as most of its target customers are in Asia. This is perceived by the center's management as negative both for the customers as well as the center itself. The geographical dislocation of technical customer support for a specific product from the product's development site results in a reduced quality of support as the support engineers cannot easily tap into the experience based knowledge of the engineers responsible for the respective design. The lack of closer customer contact impedes the build up of market as well as system knowledge on the side of RDC's engineers and management, complicating a further upgrading of local capabilities.

BDC – IC development with close and long-term customer contacts

Development projects at the BDC are quite different than at the RDC in respect to final markets, product type as well as degree of customer involvement. During the development of analog and mixed-signal products for the automotive market not only much higher customer involvement has to be organized, but also much more complex products are designed that need to comply to very high quality and reliability standards. The high level of product customization renders every project at the BDC quite unique, however they can be distinguished in two main categories. ASIC projects are almost solely defined by customers who fully own the project's results, whereas ASSP projects are oriented towards the broader market with Midtronic defining the project's specs and owning the results that can be sold to various customers spreading the development costs of the project between the many future customers of the product.

Both project types are characterized by a phased structure of external involvement. During the project's initial phase various internationally distributed departments work closely together to establish specifications, deliverables and the schedule of the project either in close cooperation with the customer or for ASSPs based on product objectives derived from market knowledge. The initial arrangements with the customer are conducted on the business unit level located in Belgium. The future project leader and members of his team are involved during the pre-study that reviews the feasibility of the request and the business assumptions it has been based on. During the pre-study the team has a right to influence schedule planning, feasibility of design with regards to die size as well as packaging. After the pre-study has been completed and the project has been accepted the development team has to commit to the planned schedule and design. The pre-study results in the preliminary product specifications and the business case, which are provided to the customer for review and decision.

For ASIC projects these preliminary product specifications need to be developed in more detail directly with the customer during the design process. This detailed technical discussions are necessary for the development team to determine exactly what the customer requirements are. For such detailed technical clarifications face to face communication is important making visits of customer's representatives at BDC or trips of project team members to customer's offices necessary. While the IC design is developed and implemented in the second phase of the project, communication between the various functions of the company is declining and the focus is on the local development team.

In case the project is driven by a customer request the communication with the customer is still important as change requests are frequent. The evolution of certain characteristics of the initial ASIC project or the addition of new function are necessary as the development of a new ASIC can take up to two years. Pure technical change requests are communicated directly between the customer and the development team and can also be solved immediately if they are not too fundamental. Only if the change request results in significant economic impacts on the project's parameters, i.e. through die size or schedule expansion, the business unit's project managers need to be involved. Such significant change requests make a reexamining of the planning necessary and call for a broader communication process with the customer.

The final phase of IC development, after the chips have returned from manufacturing, is characterized by the reestablishment of communication with various functions as well as the involvement of new departments like test and assembly.

Shifts in GDN and IC development

Over the last ten years there has been a major shift in the division of work and responsibilities between customers and the chip company. Previously customers had a deep knowledge and understanding of both the system and the components they wanted to integrate into a complete product. They approached BDC with a product idea and the plan of how to make the desired function, mostly already designed with discrete components on a demo board. BDC's task was to integrate these functions onto a small piece of silicon – to design the chip – to enable cost optimization. Processes of vertical specialization and triangular restructuring described (see Chapter 3) lead to a situation where system companies increasingly tend to reduce technical capabilities for the development of product ideas and solutions. Midtronic is facing a situation where it is required to bear the risk of developing a solution for a system that it does not own and also does not know in full. In past times the division of responsibilities was clear cut as the customer was responsible for the working of his system, providing Midtronic only with the information necessary to develop a working component. The development of solutions demands a much higher system knowledge that needs to be provided by the customer, who is not immediately willing to share this essential knowledge. While these new solution requirements translate into upgrading dynamics, they are also stretching capabilities and resources of mid-sized design centers and companies such as Midtronic.

To be able to organize the sharing of such sensitive knowledge a long-term customer relation is necessary to develop trust gradually. Midtronic is facilitating this process with the focus on project families that enable a broader cooperation with the customers, which are fundamental for a long-term partnership with a deep knowledge sharing. The first projects of such a partnership are necessarily quite conservative and focused on establishing of working and communication structures, accustoming the engineering cultures on both sides and building up trust. To start with a completely new customer and be extremely creative, developing products from scratch is not only hard, but highly prone to major flaws, as oftentimes the chip company learns only in the end that it has not received fundamental information from the customers, making the abortion of the development project necessary. The organization of development partnerships around project families is based on the idea of developing successively several generations of a product, gradually approaching high levels of creativity, complexity and complete solutions.

The higher levels of vertical specialization paralleled by a push towards system knowledge on the side of component suppliers are seemingly not driving fundamental changes in the labor process and managerial strategies of control. With this industry wide structural shifts within GDN do not translate directly into changes of work organization viewed from the perspective of a particular design engineer. However, the development of interfaces as well as the requirement of more complex knowledge especially regarding the system level are increasing the demand on experience based knowledge as well as cooperation capabilities that allow for the development and maintenance of long term inter-organizational relations.

5.1.3. Work and control – dialogue and commitment

Engineering work, highly creative and contingent, is making direct control strategies at least problematic. The fact that Midtronic is focusing on analog IC design, always described as very arcane and the most creative field of IC design, only further aggravates the control problem, requiring control structures to match both the highly specific labor process as well as the increasingly complex development projects.

> "*Our working is so various, we are working in such different fields. We are not programmers for example, this is not the IT industry, where you are working in one programming environment where you can integrate something that controls you.*" (Leader of Test Group – RDC)
>
> "*I have to think about a problem and so I will think about it half an hour and it is not possible to write it down in an Excel spreadsheet.*" (Chip Design Engineer 2 – RDC)

Direct control is impeded both from the technical side, the difficulty to integrate control instruments into developing environments, as well as obstructed by the labor process of analog design as such. In digital ICs even highly complex functionalities can be assembled in a quite straight forward design process by using building blocks, so called standard cells or on a higher abstraction level semiconductor IP. This is both enabling and calling for high levels of automation in digital design. Designing analog ICs is much more problematic as these devices are working with signals that are continuously variable, translating into a low resistance to noise, as a small change in the signal can already cause a significant shift in the signal's information. Developing analog circuitry then not only requires engineers to come up with the idea of how to integrate the product's functionality, but engineers always need to keep numerous process technology related parameters in mind that affect the signal's integrity. To optimize an analog chip design engineers constantly sacrifice one parameter to enhance another, a process requiring both creativity and experience with previous designs to be able to find the right balance. The whole design is a complex system with its various parameters interacting, where the goal of the development can only be reached by finding an equilibrium between various parameters through a complex search process that needs to keep signal integrity always in mind.

Engineers report about hidden issues that can obstruct development work for days or even weeks but which need to be resolved in order to be able to move forward with the design. A too finely grained control of the progress of work would not only put stress on the engineers, but result in an ineffective development process and in the worst case in a faulty product. These very specific characteristics are mirrored in the control structures in the development process.

> "*I can't tell him: you will complete the test program today.*" (Project Leader – BDC)

Designing complex analog and mixed-signal products is a long and contingency laden process as not only people, technologies and design methodologies must be aligned but also changing customer needs have to be taken into account. This can result in development times of more than two years in case of newly developed product platforms. The first three months are focused on the development of a pre-study giving an overview of the system the component will be part of, specification of the component as well the project plan. Not less then five months are necessary to ready the first design for tape-out and wait for the first silicon. Only if the project is focused on a derivative product the design time can be reduced to one to three months, depending on the amount of changes required in the new derivative design. For newly designed projects, the first silicon that comes back from the wafer fab will require a de-bugging process as the complexity of mixed-signal ASICs is very high. Typically three such iterations take place, moving the design project between design center and wafer fab, to be able to achieve a functioning, fully debugged and verified product. There is some pressure from management at the BDC to cut development costs with shorter design project durations by lowering the number of iterations. However, from an engineering perspective it is impossible to reduce the number of iterations below three without compromising the product's quality and reliability.

The basic development project is described by the NPD[32] flow, a management procedure developed a few years ago, defining 10 essential milestones related to an accepted schedule. This schedule is based on the professional responsibility of engineers safeguarded by constant communication. Every milestone is completed with a meeting of the whole development team and the agreement of every party involved on the already existing results. The results of such meetings have to be approved by management.

[32] NPD is the acronym for new product development.

The number of milestones that the development process is broken down – the granularity of control measures – is the biggest difference in the organization of the labor process between Midtronic's Czech and U.S. development centers. The design cycle in the U.S. is fragmented into more milestones allowing management for a much closer monitoring and higher control over the work and progress of every engineer. Dividing the engineer's work into much smaller steps that always need to be realized within the planned time schedule, dilutes the ability to cope with contingencies. The personal autonomy of the respective engineer allowing him to react to contingencies in a more self-determined way, e.g. through swapping of priorities within the development cycle, is often a very important flexibility resource.

While a new project comes to life a very raw project schedule is devised based on estimation of duration of key steps. These estimations are derived from experience of design managers, that have managed numerous development projects, as well as through communication with key members of the future project, who are asked to voice their opinion on the approximate duration of key development steps. The final schedule presented on the kick-off meeting contains the detailed plan on the specific workload every engineer working in the project will be assigned. Every single engineer is participating in the estimation of his own workload schedule and needs to commit to it. The communication about the assigned workload is organized between the project leader and the respective engineer. The estimation of the duration of the assigned tasks is done by the engineer himself, regarding some realistic or average durations. For very standard products and building blocks some average duration templates that define how long the design of such devices will take exist. Engineers sometimes tend to overestimate the duration of individual development steps, as they have a perfect technical solution in mind that would need a long time to develop. However, one engineer reports that sometimes, when feeding back the estimated duration for the workload the project leader is telling the engineer to "[...] think about that, it can take more than this, let's say one week more." (Chip Design Engineer 1 – RDC)

Planning can only be based on estimations derived from experiences and can never be perfect. To know perfectly how long a project will take would require completion of the project as only then all the contingencies emerging during the process are known. Particularly customer related projects are prone to contingencies as customer change requests occur regularly. Additionally, highly detailed planning is very time consuming.

When designing well researched functions that are known and have been implemented several times, team members are able to quite accurately estimate how long the project will take. But in case of new technical specifications, e.g. requested by the customer, estimation and planning become increasingly difficult as the possibility of problems grows.

One major question is how much time for contingencies is planned into the overall project schedule. In the past planning at the BDC was based on the assumption that the whole development process will run smoothly and therefore almost no contingency buffer was included. This was putting considerable pressure on engineers as well as resulting in tensions between departments and constant schedule slips. Since the acquisition by Midtronic the situation changed for the better as the goal now is to comply with the initial plan, which is based on more realistic time estimations. As management will be held responsible for the compliance to the planned project schedule, too optimistic planning disregarding any contingencies has become at least partially confined.

At the end of the pre-study phase all team members need to commit to the schedule that defines the overall time frame as well as the major milestones. Milestones are perceived as important for the overall start of the project and to be able to monitor how far the project has moved, but they only define major project steps and related deliverables. After the respective engineer has committed to the negotiated schedule he is responsible for adhering to this schedule and needs to monitor his advances in relation to the overall time plan.

Automated monitoring of the engineers' work based on milestones is perceived as impossible, straining the quite long periods in between milestones with a low visibility that needs to be balanced by personal judgment of the respective engineers, project as well as group leaders. Project leaders are communicating with project members on a daily basis on design issues, solutions and the advancement of their work. These individual discussions are short, lasting only several minutes, but give the project leaders a direct overview of day-to-day status of the project. The engineers in Midtronic's design centers are mostly experienced engineers with long tenures that are handling their assigned tasks in a responsible way and can also assess the progress of their work quite accurately.

Project leaders provide the BDC group leader a short, mostly verbal, report based on their daily communication with engineers. The group leader expands these reports with his own information into a weekly report to the respective product leader located in Belgium.

These weekly reports give account of the assessed progress of the various projects and flag bigger timing issues that need attention and increased resources. All engineers at the center also receive copies of these reports via email, to keep them informed about the progress and occurring issues in other projects.

The core project team – the local design team without the application engineer – is coming together in weekly meetings to briefly discuss the progress of everybody's work. These meetings give both the project leaders as well as the engineers an overview of the development of the project, as both achievements as well as issues are discussed.

In case of bigger issues that will lead to problems with the project's schedule the respective engineer needs to report them immediately to his project leader. The biggest sources of issues in the development cycle are not design problems. Most schedule issues arise at the interface between the development center and manufacturing, as prototype wafer runs are seen by the manufacturing operations as interfering with mass production and oftentimes are being stalled. In case such issues could endanger the project's schedule fundamentally management is involved and helps to find a solution, e.g. by organizing help and support from other development teams located at other sites.

In a monthly meeting at the BDC a company wide review of progress is discussed. During this presentation the center's manager focuses on the company's position from a project perspective, analyzing finished and abandoned projects as well as the degree of completion of projects in relation to their planned schedules. The whole design center staff is informed about how good projects keep their schedule commitments and how BDC is performing in relation to other design centers. In a quarterly meeting engineers are presented the business development of the company. Financial data for the last quarter, year on year comparisons as well as results in relation to competitors are provided.

Microsoft Project is the only software tool used for direct control in the labor process providing a basic software environment for workflow and schedule coordination. This tool is used by project leaders to keep track of the project's schedule and progress but it is only using data fed in manually. At the BDC a web-based tool that helps to monitor the progress of work exist. Initial planning are put into a spreadsheet and every team member is feeding in his work results, with weeks as basic planning unit. The estimation of the project's progress is still based on the judgment of the group leader, who has to draw upon his experience to evaluate this quite standardized data before the background of the planned schedule. It is his responsibility to manage the various contingencies affecting schedules by shifting priorities and resources as well as postponing scheduled milestones.

The current system is already the third, and until now successful, attempt to establish a system for monitoring and time management at BDC. The first version of such a time management system failed due to technical deficiencies linked to the network speed available at the time of its introduction. Eventually the system was abandoned as it was too slow for efficient operation. The second automated and networked monitoring system failed due to the intended very high degree of monitoring that met with resistance from engineers. The system was developed to map the development process in a highly detailed way, requiring engineers to put in an unpractical amount of data, keeping them away from their engineering work. Gradually the system's required amount of detail was lowered until only milestones were put in, only before the system was also abandoned.

5.1.4. Knowledge – local sharing with international dimensions

The sharing of knowledge gained through engineering work, especially in order to learn from past mistakes to avoid repeating them, is regarded as one of the major issues that call for resolution. Although there are several instruments in place to reduce design flaws one engineer emphasizes the fact that, "it is true that mistakes are sometimes happening. Quite often." (Analog Group Leader – BDC) Developing analog ICs requires high levels of experience and a deep technical expertise to be able to work with the precision necessary to design working ICs efficiently. The design experience on the technical level is highly product specific, rendering rapid switches of design teams between various product groups problematic. It takes up to several years for a development team to build up enough experience for one product family to be able to take fully into account their very specific characteristics of the manufacturing process necessary to develop competitive products. The locally integrated character of the development teams facilitates the build up of experience through both informal as well as formal knowledge sharing, as a close cooperation between the various functions is fundamental in analog IC design.

Most engineers regard the personal contact through geographical proximity as the most important and most effective way to secure a constant exchange of knowledge and foster steep learning curves.

> "*This is probably the strongest thing, that people are located close to each other, so they know about the bugs and don't repeat them in other products*." (Analog Group Leader – BDC)

As all engineers of a specific function, i.e. design, layout, or test, are seated in one room the day-to-day exchange of ideas, solutions and past experience over project boundaries is facilitated. The prevalent way to find solutions is by inquiring with engineers with the same specialization from the local development center, who then either are able to help directly or will provide information on possible experts. The fact that engineers from the center know each other personally is seen as very helpful, as it eases up communication both on the technical as well as personal level.

This personal knowledge exchange is extended at the BDC through the institution of fortnight presentations. Engineers from the BDC are asked to present on special topics related to IC design that may be of interest for their colleagues. The presentations are problem focused based on personal experience of the respective engineer, neither dwelling too much into theoretical discussions, nor to closely connected with their particular project work. Mostly engineers present on things they learned during IC development, e.g. new ways to use well-known tools to speed up specific design steps. These presentations have a long tradition at the BDC and participation is voluntary. Engineers perceive them as an interesting opportunity to learn about practical engineering strategies and look beyond their own project work.

To inform other engineers of the design team about interesting solutions to specific problems the lessons learned procedure is used. Short presentations, lasting no longer that one hour, are organized by the respective engineer who has come up with an interesting solutions right after he was able to implement them.

Design and layout review are formal instruments for knowledge sharing that constitute an important point required by the new product development flow before design hand-off to layout or manufacturing. During the design review the entire project is presented to the local design community to both share new insights as well as have a broader peer review of the design. The schematics of the project are provided to the other designers about two days before such a meeting. During the design review meeting the data sheet is discussed from a functional perspective, while the design team presents solutions developed for the technical requirements of the IC design. The peer engineers are discussing the design, focusing on new and unfamiliar solutions, with regard to flaws as well as possible improvements. Engineers perceive this formalized instrument of the design review as a very good way to both share design experience as well as guarantee the prevention of faulty designs.

Design reviews are also performed on the international level, with design groups from other centers that are working on similar products and technologies. RDC's design community is also reviewing IC designs from other locations. The positive effects of these international design reviews are not as explicit as with localized reviews. However, sometimes designers are asking for international design review, especially when other development locations are known for a higher expertise on technical issues involved in the respective project. As oftentimes with international net meetings, time-zone differences as well as language problems make the communication for the engineers quite strenuous, impeding at least the results of such meetings. From the perspective of organizational knowledge engineers perceive these meetings as a good instrument to learn about the activities of other design groups.

Yet another channel for direct personal knowledge sharing is the extension of the knowledge sharing network to a global level through a formalized list of recognized specialists in specific fields of IC development. This company wide list, or yellow pages focused on expertise, is of great help when engineers are looking for consultation on specific issues and local colleagues are unable to help directly or to specify a possible source of information. Knowledge councils comprising of managers from various design locations are a more generalized way for personal knowledge sharing, where issues focused on specific product focus and functional fields are discussed on a high level. Results from these meeting are publicized in the company intranet. However, it seems that the amount of output produced by these councils makes working with the database cumbersome.

The IC development cycle with its many periods of waiting, especially for silicon results from the wafer fabs is leaving some time for regular studies through reading professional and academic literature. The normal practice of engineers at the BDC is to occasionally read in various engineering journals or books provided by the center's own library. A huge variety of engineering journals is at hand, mostly through IEEE[33] memberships of many engineers employed in the BDC, while Midtronic is paying the journals' subscription fees. These kind of studies provide the engineers with insights in fundamental developments in IC design that can be useful for their engineering work.

[33] IEEE is the acronym of the Institue of Electrical and Electronics Engineers.

Engineers develop throughout their career small private databases of schematics, solutions, bugs and experiences from previous projects. Besides such highly localized and personalized databases, there are various company wide knowledge repositories – instruments for knowledge sharing based on more objectified forms of engineering knowledge. However, some engineers dispute the effectiveness of this form of knowledge sharing.

> "*I don't know if the engineer who works on a particular problem can really learn something by browsing presentations of some other projects.*" (Analog Group Leader – BDC)

Three points of critique are put forward by engineers. First, as the development projects are under a constant push to squeeze their duration engineers need to rely increasingly on the time-saving mode of knowledge sharing through personal contact and not spend their time working through huge databases. Second, the myriad of projects within the database make it difficult to find a similar project that could help clarify the issue in focus easily. Third, the more formalized information becomes the harder it is to understand.

In the product development register (PDR) all relevant data for each project is stored – documentation, data sheets as well as marketing materials. Lessons learned presentations are also stored in the PDR making it a very important source for information at the start of new projects. It is mandatory for engineers to go through the lessons learned section of similar projects at the beginning of a new project to learn about possible technology and design related pitfalls. The second database is the product design changes tool (PDT) based on information concerning design corrections. Each pass of a design is described with regards to what was changed, why it was changed as well as what solutions have been implemented. This information is based on design quality improvement (DQI) sessions during which design bugs are thoroughly discussed by engineers. DQI sessions are also organized between different design centers and engineers are invited to join the discussion. Design changes can be on various levels – the design itself, the topology used as well as the technology in which the design was manufactured. Customer requests are also a frequent cause of design changes. This information enables engineers to learn about solutions within the technology field of the company's own process technologies, EDA tools and product range. The design reports saved in the PDT database are basic word documents with a quite standardized structure.

The PDT as well as the PDR are worldwide accessible databases organized as a company wide intranet. The databases are quite huge as they contain data on all of the company's numerous products. Although the information is grouped in various categories, the engineers need to go through many projects that might be relevant for the respective issues. This can be tedious and is perceived by some engineers as a strenuous or even quite pointless task which they try to evade.

> "*I think, the last thing I would do is search our database.*" (Leader of Test Group – RDC)
>
> "*We are using it because we have to fill it in.*" (Chip Design Engineer 1 – RDC)

The more efficient way to gather information for Midtronic's engineers is to talk to their direct colleagues and learn from them about solutions in past projects as well as more distant experts than are able to help. However, some engineers consider the process of working through the database as an interesting learning process, as they get to know about issues and solutions they were not looking for but could be of relevance in future projects.

As the PDT database was implemented only about two years ago many engineers are still quite unfamiliar with it, lowering the acceptance for the use of the database. Although every employee has received a training with the database, engineers only use it infrequently – about every 6 to 9 months, depending on the project's duration and milestones – and therefore have not yet become accustomed with it. The process of data entry as such is also problematic as it requires two levels of management to approve changes in documents of the PDT database. This process, in place to ensure the soundness of the description, is prolonging the data entry and causing problems for engineers, as they loose valuable time for this administrative act.

5.1.5. Knowledge – low levels of re-use and open design methodologies

In line with the whole semiconductor industry re-use is regarded at Midtronic as key to lower development cycle times. However, re-use of analog blocks is not as easy as it is in digital design. Part of the feasibility study at the beginning of every project is to check the percentage of re-use that will be possible in design, layout and test. The re-usability check is then redone by every project member after the project starts. There seems to be no re-use guidelines in place, that would define how functional blocks need to be designed to make re-use easier. As every design is quite specific, from the process technology in use up to the parameters that have to be met, re-use of blocks always involves the retuning of the most basic features of the respective blocks. This tuning lowers the efficiency gains considerably. One engineer points to the fact that only a highly experienced analog design engineer is able to re-use simple circuits without facing big risks. This is of course running counter to the main idea of IP re-use, intended as a strategy to lower costs by both employing lesser experienced engineers and easing up their engineering tasks to a plug and play mode. IC designers are using personal libraries where they are storing functional low-level blocks to ease up re-use, but

> "*[...] sooner or later it will show that you need a slightly different look. In the end the library will be kept but you are multiplying blocks in the library, there is in fact a low level of re-use. This is analog.*" (Leader of Test Group – RDC)

While using IP libraries engineers rarely re-use full blocks, but rather use them as source for ideas and illustrative material. These learning possibilities are perceived as important as the company is growing and the personal contact is increasingly obstructed. In test and layout development for analog ICs also only basic assumptions can be re-used, as almost every new circuit calls for a very specific test schematic and layout design.

Engineers at the BDC are highlighting the fact that while they are working on ASIC and ASSP products, which are main areas of re-use strategies, they are developing mixed-signal ICs with extensive analog circuitry. This is the main reason impeding high levels of re-use and highly standardized design methodologies. However, the approach to re-use has changed throughout the history of the design center and its changing owners. During the time of the former parent company re-use was very much in focus with company wide libraries of verified IP blocks. Additionally, the company paid the engineer that developed the re-usable block and the engineer re-using the block an award when re-use happened. This practice has stopped since Midtronic took over BDC. The web based company wide IP block library still exists and discussions about re-use are constant, especially on management level. Engineers of the ASSP group at BDC are only rarely re-using outside IP, as they develop highly specialized chips for in-car communication that have to go through rigorous certification procedures. However, other design centers are oftentimes re-using whole chips developed at BDC, integrating them into more complex solutions.

The design methodology at BDC is characterized by a relatively high level of technical autonomy. The design process is constantly described as very flexible with decisions left up to engineering judgment. Most engineers link this to the analog designs developed at the center, highlighting again the fact, that analog design and verification can not be easily regulated. However, during periods of the former parent company there were attempts to standardize the development process. One engineer was assigned with the task to work on a standardized design methodology for the development of mixed-signal ICs. The project failed due to technical problems as well as management obstacles. The standardization attempt was carried out in a top-down approach, without asking for feedback from the engineers, which caused both deep objections in the local engineering community as well as lowered the willingness to contribute to the project. There seems to be no immediate push from Midtronic to adapt design methodologies at BDC to its own company wide methodologies. The only heavily regulated and quite standardized phase in the development cycle is the interface between design and manufacturing. Here strict rules and tool requirements need to be met to guarantee a flawless hand-off of data structured to the needs of manufacturing and guided by the requirements of the specific process technology the project will be manufactured in.

Engineers at RDC are quite free in their choice of design tools, in case the company has licenses for different tools performing the same function. The choice depends mostly on the personal advancement with the tool, as both simple as well as complex tools mostly produce the same results.

> "*If you need some complex functions or you just want to have fun with more complex tools and show off.*" (Leader of Test Group – RDC)

There are also several ways on how to use the very same tool, that are labeled conservative or progressive. The way the engineer is using the simulator depends both on his personal preferences as well as how familiar he is with the newest methods and newest tool versions. There is no strict design guideline in place that is defining which tools need to be used in what kind of manner.

Although layout design was the first field in IC design to be automated, analog layout is still quite manual, using software tools only in a very limited fashion with a low automation level. Midtronic attempted to automate routing of the various physical elements but was not contend with the results reverting to the more manual way. Only for some parts of the chip, i.e. logic cells, automated placement and routing by tools is possible. One very experienced engineer at the layout department in RDC is developing tools that enable a automated checking of layouts and are used by all of Midtronic's layout engineers worldwide.

5.1.6. Training – experience and technical proficiency

New young engineers are described as not well equipped with many of the skills and knowledge required for their work. In university they only mastered the fundamentals of technical knowledge, that allow for an entry into the semiconductor industry. These new engineers need to gain experience in both technical, organizational as well as personal capabilities. The first three months of a new engineer at Midtronic are governed by an adaptation plan, the key process to integrate new employees into the company. During this period the engineer is learning about all the stages of his new work environment as well as receives training in various fields, not only concerning technical but also more general issues related to customer and business aspects of his work. A senior engineer is appointed as supervisor and mentor for the engineer in training. The senior engineer's specialization is in the field the new engineer will initially focus on, allowing for a week long detailed introduction in the various aspects of his future tasks. During this time new engineers are also send to external trainings, e.g. for EDA tool training, or travel to other company locations. Many of the working tasks, especially connected to sophisticated EDA tools, are heavily experience based and not easily trained within formal training courses.

> *„The best way to learn things is to do them. Some of the tools are sophisticated and it makes no sense to explain them. One has to use them and play with them to understand how it works and what is behind.“* (Manager of Modeling Department – RDC)

To learn and gain experience new engineering graduates are integrated in project work from the beginning, initially helping out with simple tasks. It takes at least one year for such a young engineer to become independent and to be able to complete simple tasks without the need for major help and assistance from senior engineers. Only after about three years an engineer has gained enough experience to become fully independent and able to carry out major development activities on his own.

There is always a trade off for a company employing and training engineers to become universally capable engineers and engineers with very deep specializations in one single field. All of the engineers at RDC are able to conduct design work for the general products and technologies in use at the company. For more specialized processes requiring a higher technical specialization and experience the company is training selected engineers. To expand the portfolio of engineers with such specific technical specializations sometimes an additional engineer is assigned to a specialized tasks, to learn about new methods and technologies and gain experience with them.

The annual review of employees is assessing accomplished working results of the respective engineer as well as focusing on the development of individual capabilities through a training plan. The responsible manager needs to develop a training plan for every single engineer in line with the planned capability development of the company and the respective development center. Engineers are encouraged to voice their interest for specializations, which should be considered in the formulation of their training plans. Besides providing technical trainings the company is also keen on developing both the language as well as the soft skills of the engineers. Working in an international company requires good English skills, which new candidates often do not have.

5.2. Iprov – small scale silicon IP design

Through its increased integration in various GDN Iprov has experienced a steady upgrading as well as diversification of product lines during the last 10 years. The integration in the GDN of Austrian IC designer Msystems had a fundamental impact on Iprov's labor process organization. The requirement to establish international quality standards in its newly formed design services promoted processes of standardization and formalization of the hitherto organically evolved design process. This involved also the establishment of formal project management guidelines translating into more formal control strategies.

5.2.1. IP development and design services – competition for resources

The development process at Iprov is determined by the company's character as small service provider both in regard to design services as well as IP provision. After IP projects have been sold customer contacts require often intensive maintenance as after-sales services are highly important in the IP service industry and are one of the major differentiating characteristics for companies like Iprov that are offering only standard based IPs. Customer requests for after-sale technical support strain Iprov's strategic development projects as engineers who have been involved in the development of the sold product instantly need to focus on them. Recently the company has taken measures to limit this influence that it perceives as impeding strategic product developments, as a constant changing between various responsibilities and projects is very demanding for engineers. To be able to approach the development of USB 3.0 IP products it was not only necessary to re-organize the design process but also a new organization of work was established, especially with regard to the division of labor between various engineers. With 11 engineers focusing on the various aspects of the design process the USB product line has Iprov's biggest design team. Most of these engineers have been isolated from any customer contact and technical support to be able to focus completely on the development of the new product line.

As Iprov is a quite small company the engineers' specialization is focusing on the specific product line they are working for. Engineers as well as managers take on various roles within the development process. Although product line managers are occupied with administrative tasks of various projects they still have far ranging technical development duties. All project line managers have voiced satisfaction with this, as they perceive themselves as engineers that want to solve technical problems. With Iprov's recently improved focus on marketing, product line managers now need to also participate in the generation of marketing documents.

At the time Iprov started to cooperate with Msystems as a design service provider it was required to systemize and formalize its design process by implementing quality management standards. Clearly defining the various stages of IP development as well as design services and their specific inputs and outputs of every stage, the development process now outlines them with regard to schedule and organization of work as well as the tool flow, i.e. the various design tools that need to be used in each stage. This design process is still in place for strategic projects, with a cut down version for smaller projects that involve re-designs of already existing products. For customer related projects, both IP development as well as design services, the design process is adapted to the requests of the particular customer.

Strategic projects focus on the development of specific product lines based on either market knowledge or the aim to have a more comprehensive offer and are mostly launched when no other projects are imminent. The decision on such strategic projects is taken by the company's management, by nominating the future project leader. His task is to develop the technical assumptions and general specification of the project as well as an initial schedule and resource requirements. The results are discussed in a meeting with the company's management, the managers of the design department and the product line, as well as various engineers. With the company's recent development of in-house sales and marketing capabilities increasingly marketing aspects come into focus in these meetings. After the management's final decision on the project, engineers are assigned to it. The engineers are asked to voice their preferences and are able to negotiate with the management on their participation in the various development projects. The assigned engineers develop the initial technical assumptions into both detailed design and verification specifications. Additionally the initial schedule is revised and matched with the technical requirements of the project and needs to be accepted by the company's management.

IP development, the actual IC design work, is described by the engineers as a process of thinking and analyzing. The writing of code[34] is the most minor part of the task, as it is basically the implementation of the very detailed design specifications developed during the first phases of the project. The company's senior verification engineer formulates the rhetorical question: "How long can it take to write 5000 lines of code?" Implementing the design specifications, i.e. writing the HDL code, would take only several days, but projects last at least half a year. After the code has been written the major part of design consists of running, simulating and checking the results. This involves the most laborious tasks, as results are never ideal after the first simulation run and need interpretation. Interpreting simulation results verification engineers take into account their experience with the tools and former projects as well as the project's assumptions or customer requirements. In case problems occur during the realization of the design informal communication is used to find a solution. This solution is then formally presented to the management and the customer in a report during a milestone meeting.

Verification and testing starts parallel to the implementation of the design specs rendering the process into an iterative feedback loop. Iprov has very strict verification procedures, driven by the requirement for high quality levels, that require 100% code coverage. Functional tests cover around 90% of the code, which is described as the easy part. The remaining 10% are very challenging and laborious as the verification engineers need to develop tests that are specific to code as well as situations and functions. This is a very labor intensive task, however not routine work as verification engineers need to develop new and innovative approaches to be able to provide a full code coverage. The high labor intensity is based on the very specific aim of verification. Contrary to the design engineer who is implementing a specific function, verification engineers need to envision every faulty situation that might happen to this function. Iprov's senior verification engineer stresses both the arduous as well as playful character of verification:

> *"Formal verification is a game. It is very good when you are entertained by such a game."* (Senior Verification Engineer)

[34] IP development is mostly concerned with the development of digital circuitry. Digital IC development is making use of so called Hardware Description Languages that look very similar to software code, which is why IP developer often refer to their output as code or lines of code.

For customer projects the company's standard development process is adapted as required by the customer. Although customers receive information about the company's design flow to be able to perform quality checks, they generally do not ask to change the flow as such. Most customers are not interested in changing Iprov's tool chain as it is using the most common EDA design tools for development to guarantee compatibility. It is common that customers request a description of the future project team regarding the various specializations and experience levels of the involved engineers. Although the customers do not decide about the composition of the project development team they use this information for the establishment of more personal communication and to learn about the future team.

Strategic projects put a high focus on the productization process with additional validation and synthesis tasks as well as more complete implementations that are aimed at easing up customer choice. Marketing relevant documentations are an additional necessary step in the finalization of strategic projects. The priority in strategic projects is on quality and easy usability, making changes in projects assumptions during realization possible even if this affects deadlines. Easy usability, or the engineering effort necessary to customize and ship an off-the-shelf product to the customer, is of high interest as it is directly linked to future costs in the operation, sale and maintenance of projects. The company has developed automation tools to be able to allow for an easy usability of the projects. Customer projects put a higher priority on the adherence to agreed schedules. Being able to deliver the finished project to the customer in time is more important than possible small technical deficiencies. Non-critical technical issues of the design are communicated to customers openly.

Iprov is facing serious problems with the delivery schedules in customer projects as customers constantly change requirements during project realization. These situations are a source of friction between Iprov and the respective customers, as renegotiations are necessary to confirm schedule extensions or price increases. As the company's engineers and managers are aware of these problems they try to integrate slack into the estimation of project duration assuming rather pessimistic scenarios. However, both project estimations as well as possible renegotiations with customers are linked to the character of the initial description of work. If customers know exactly what their requirements are the description of work is very strict and risk is very low, as in case of changes customers will be obliged to renegotiate the contract. In cases when description of work are only very vague negotiations with customers upon change request tend to be problematic.

Communication and proximity

Communication with customers depends on the character of the project in question. In the case of customizations of off-the-shelf IP cores communication during the design process can be accomplished via email as requests can be formalized quite easily. Design service projects that involve the development of designs from scratch require deep personal and reoccurring interactions with the customer. During the initial stage of design specifications and functionality development engineers from Iprov travel to customers to discuss details in face to face meetings. Mostly only the project line manager is traveling to customers for initial discussions both to help keep down the costs and to allow for discussion of business and administration issues. Such personal meetings help to define project details faster and allow to gather information about the organizational structure of the project on the customer's side. Such information is not included in the formal documents at the beginning of the projects but can be helpful for easier communication between engineers, as direct contact partners can be determined easier. After completion of a design service project it may be necessary for an engineer to help the customer's project team with integration offsite.

Also on other occasions it may become necessary for Iprov engineers to work at the customer's location. Design services on already existing customer IP involve issues concerning security and IT-system's structure. The connection of internal client-server networks across organizational boundaries is a highly problematic and expensive process. For small companies like Iprov it seems unpractical to develop customer specific IT integration capabilities. Delegating an engineer to an offsite customer location is seen as a more economical option. Such a co-location also helps to develop communication with the partner's engineers as well as to understand the issues of the already existent IP.

Iprov has not strictly formalized the communication process with customers. Direct communication with engineers from customer organization concerning technical issues via mail or phone, help an integration process, making these engineers almost part of the development team. The contact in this direct communication is almost always relayed through the manager of the respective product line, helping to tap his experience as well as allowing him to keep the overview. The more indirect communication is relayed through Iprov's post-sales manager, who is the company's major interface for customers.

Although both communication channels are perceived as effective and good, one engineer voices clear preferences for the more direct communication as it allows for a more personal way of communicating. The specific way how customer communication is organized depends on the customer's own communication standards and on the role Iprov's design services are assigned within the whole project. Engineers report about weekly teleconferences, daily mail reports and weekly reports requested by some customers. Such highly organized processes are sometimes paralleled by periodic personal meetings. Weekly reports and conferences focus on organizational issues such as time schedules, sequencing of future steps or questions regarding human resources. The project leaders gather information on these issues from their colleagues during the week and discuss them with their counterparts on the customer's side. Engineers take part in teleconferences only if major technical issues occur.

5.2.2. Work and control – schedule slippages and trust

Projects at Iprov are both scheduled and monitored in a dialogical fashion based on estimations derived from engineers' and management's experience. During the planning phase the project leader and management are communicating directly with the respective engineers about their perspective on the projects details, both regarding technical as well as scheduling issues. Customer projects need customer sign off on the estimated project duration and cost issues making rescheduling sometimes necessary with regard to project size and duration.

Estimation of the initial schedule as well as estimations during the realization of the project are of highly contingent nature. Duration of projects involving completely new technical tasks are problematic as engineers are not able to draw on their experience for schedule estimation. This leads to constant time slippages during project realization as problems are occurring that were neither envisioned by the engineers, nor where their known to them. Although estimation of project duration is based on experience its generation is perceived as quite problematic. One product manager is pointing to problems of generating this experience in projects with a long duration and a fragmented character. The contingencies in such a long process are so unique that it is not easy to take these experiences as the basis for future schedule estimations. The company's work organization is further impeding a build up of experience as it is driving the fragmented character of some projects as engineers are continuously shifted between projects and tasks while the company's limited human resources are exacerbated by its service focus.

The engineers at Iprov state unanimously that almost all projects are not completed in time, with only small projects lasting up to 3-4 months realized within schedule. Durations of bigger projects tend to get out of hand both because of estimation issues as well as the company's organization of work. During the initial schedule development some technical problems are underestimated in their complexity and possible setbacks are not considered. Furthermore engineers sometimes do not want to realize that solving such a task will take longer:

> *"[...] one is struggling with the articulation of the idea that this could take really so long."* (Product Manager 1)

The legacies of former projects keep current projects' schedules under a constant threat as engineers need to divert their attention to them, readying finished projects for delivery or tweaking new project versions for customers. Additionally, if customers need help during the integration of the delivered IP into the chip, Iprov engineers have to provide this service.

Design service projects have to cope with constant change requests from the respective customer, making the monitoring of the project's schedule even more important. Although overtime is not constant at the company, change requests can lead to substantial overtime as schedules have to be kept. Management tries to counterbalance such schedule problems through flexibility, using future development phases as contingency buffer to make overtime work unnecessary.

Although project realization of almost all projects at Iprov is characterized by schedule slippages this does not translate into considerable problems in the cooperation with customers, as the customer are reported to have also constant scheduling problems. However, for customer projects Iprov is putting a much higher focus on project realization within the negotiated schedule than with off-the-shelf IP development projects. This is linked to a different determination driving the team members, keeping mechanisms of control quite similar in both customer as well as standard projects. However, time pressure and the related finely grained monitoring of task completion are more severe in customer driven projects.

Determination of employees as the mechanism for project realization is linked by one product manager to motivation as the most important instrument of control at Iprov. Only motivated engineers will make the delivery of competitive products possible. Engineers' motivation is generated both through interesting development projects as well as a good organization of the development process. Development projects that are impeded by high frictions in the process based on a flawed organization draw away the focus of engineers from solving technical problems towards unpopular organizational problems. The manager's task is defined by a product manager as the ability to quickly find solutions in crisis situations to enable engineers a calm environment that allows to focus on technical questions. Provided with an environment where they do not have to cope with organizational problems on a regular basis the motivation for development work is perceived by all employees of Iprov as a general almost natural characteristic of engineers. There are no bonus systems in place that are aimed at generating higher levels of motivation.

> *"[...] I'd say that this is the mentality prevailing here in the company, that we work primarily for pleasure and believe that each person is responsible, so you do not have to, you do not stand over him and control him, because he came here to work, and works mainly for his own satisfaction and this work is pleasant for him."* (Product Manager 2)

The monitoring of engineer's work is organized at Iprov in a dialogical process where engineers, project leaders and managers are in constant communication about problems and project status. This communication is facilitated by the geographic proximity of the whole development department of the company. However, every 1-2 weeks there are meetings of the various projects to structure the self-monitoring of the group and allow for more focused discussions on project realization. The monitoring process is almost completely based on the subjective estimation of progress made by the respective engineers with regard to their tasks, with the company putting high trust on the determination of the engineers. Such subjective estimations have a high variability during the development process, evolving from quite positive plans towards increasingly realistic estimations of remaining duration, as more and more problems in the process occur and have to be accounted for. However, during the late phases of a development projects the frequency of checks regarding task completion is raised to build up more pressure and ensure a fast project finish.

Based on the assumption that engineers work at Iprov mostly because of an intrinsic interest for engineering there are no formal mechanisms in place that would sanction work productivity. Such forms of direct control are also impeded by process related issues. To be able to sanction the duration of task completion it would be necessary to provide evidence that specific tasks can be finished in less time, a problem which is even bigger with completely new tasks and technologies. This situation is tightly linked to the engineer's status as an expert leaving him with a considerable autonomy at least towards schedule estimations. However, the expert status and autonomy also pose much higher levels of responsibility on the engineer. Especially in situations that involve a highly specialized expertise within the company, all other team members are depending on the respective engineer and his ability to both provide a realistic estimation of task duration as well succeed in its realization. The increasing product line organization of the company is providing the possibility to develop and pool experience in a far more focused way, as engineering teams are working on similar projects and can build up estimation experience easier.

To provide management with figures that allow for a better project management and control there are two software based tools in place focusing on work time registration and project management. Every workstation at Iprov is equipped with a work time registration software providing a list of assigned tasks. By indicating the completion of specific tasks and subtasks the engineer is providing data used for the automatic generation of daily, weekly and overall project reports. These reports indicate how many hours have been worked on specific tasks and how these man-hours relate to the project's schedule and budget. However, this is more important for customer billing than control. Although task completion status reports are also generated with this tool they are highly dependent on the subjective estimation of the respective engineer and based on the engineer's willingness to cooperate on this task.

> *"But anyways, it always boils down to the fact that someone has to enter the degree of realization of the tasks in the software, and this is sometimes calamitous."* (Design Manager)

The possible accuracy of the estimation of task completion is varying between the various steps in a development process. Whereas in documentation it is very easy to both evaluate the progress as well as estimate completion date, the phases of verification and test are problematic. Here extrapolation of remaining tasks and time from the completed as well as planned tasks is very hard, as bugs that appear during the process can add a much higher number of necessary tests than initially planned.

The highly manual and subjective character of the software based control system is also putting a stress on the work of engineers. Especially with highly unstable projects, i.e. low-priority projects mostly focusing on off-the-shelf parts, the manual character of data gathering impedes both engineer's work as well as control efficiency. Currently the company is looking into the integration of its system for work time registration with project planning software that would allow for a constant adaptation of project schedules, rising schedule estimation and problem management capabilities. However, as one manager indicates, the geographic proximity and small scale of the company is providing a mechanism to solve schedule problems in a much more flexible and faster way than by using software tools.

One of the biggest issues in managing project schedules seems to be the level of task granularity. Most engineers and managers at Iprov report a very detailed schedule planning where tasks can be as small as several days or even only several hours. Such a high task granularity can have a negative influence on the capability of problem adaptation as the autonomy of decision towards the sequencing of individual development steps can be lowered. Although the planning is highly detailed at Iprov the autonomy problem seems not to occur as adaptation capabilities are provided by the highly communicative culture of the company, its small size as well as the geographic focus of the development team. However, comparisons with other companies are made with indications, that the levels of task granularity are much lower in other organizations, making work easier, as constant rescheduling of small tasks is not necessary.

5.2.3. Knowledge – informal knowledge sharing and re-use

Although there were already several attempts to establish a knowledge database, there are still no formal systems and processes in place that would allow for a systematic collection of knowledge generated both during development projects as well as regular customer interactions. Iprov’s engineers voice their need for such a database based on daily experiences of duplicated work due to lack of knowledge about proven and used solutions. Experiences with knowledge databases at other companies are another driver of these requests. The lack of a knowledge database is perceived as a problem, as important knowledge is either forgotten or their existence is unknown to other engineers. At Iprov new and young engineers are increasingly demanding a knowledge database as they do not yet know all engineers and their respective specializations, making the identification of a knowledge source harder.

As Iprov's development process is defining the need for a lessons learned step at the end of every development project, presentations evaluating the technical accomplishments and problems of the respective project exist, but are not stored in a systematic and openly accessible way. To obtain these documents engineers have to contact the respective project leaders or product line managers. Public domain knowledge, i.e. presentations or whitepapers from other organizations are disseminated through emails among the engineers. There is no creation of own documents that would contain a detailed description of solving technical problems or engineering ideas. Although engineers at Iprov perceive such a knowledge form as helpful for their work they also reflect on the adding of workload this would involve as well as general problems in the process of objectifying experience based knowledge.

> *"Because, to write down the words, to describe in words things the engineer has in his brain in an abstract form, requires quite an effort. To translate it into human language, his associations, his sense that's how it is sometimes."* (Product Manager 2)

Most engineers link the lack of a knowledge database for IC design work to the small scale of the company and the co-location of the various development teams. Both explicit and implicit forms of knowledge can be accessed by talking personally to the respective expert. Walking in one of the rooms where the IC design engineers are working and posing the technical problem is described as a common practice. This will cause a brainstorm of all engineers present, leading either to a solution or it will help to determine whom to ask for advice. The respective engineer can be sure that his colleagues will take as much time as necessary to help him with the problem. Such an informal and open culture of work and knowledge sharing is neither making the build up of computer-based knowledge databases a vital issue nor appealing as it is always draining resources from engineering work.

The low level of formalization and systematization of experienced based knowledge is also reflected in the company's re-use practice. During initial specification development of a new project the re-usability of test-benches and test-structures is checked with the aim to maximize re-use possibilities. However, there are no formal processes in place aimed at a consistent re-use driven design methodology.

An important step defined by Keating and Bricaud (1998) in their re-use methodology manual is the peer-review of code, that aims both at raising the quality of product code and knowledge generation as well as higher re-usability. Code review is also an instrument of knowledge management as experts learn about new projects in the company as well as new technical solutions. Iprov has tried to implement code review but has dropped it from its formal design methodology as the review process was too time consuming. The peer-review of product code requires a second engineer to almost re-design the whole project in his head to be able to reconstruct and understand possible problems and solutions in the design thoroughly. In case this is not done the questions engineers are able to pose during a peer-review process are only superficial and do not really help to raise the quality and re-usability of code. However, for specific small but critical parts of development projects peer-review of code is done on an informal level with the help of experienced colleagues. The informal character of this process is also obstructing the production of more formalized and standardized knowledge in form of design solution discussions stored in a public space.

5.2.4. Training – 'natural' specialization and self-learning

Iprov is a small company resulting in a low specializations of the respective engineers who have knowledge about several technical areas. There is no functional specialization, with verification being the only separate area, while product lines are the sole differentiator in the engineers' specializations. Within product lines engineers specialize on EDA tools and process technologies requiring them to keep track on developments in these fields to be able to provide this knowledge to their colleagues. As knowledge sharing is not highly formalized at Iprov these specializations function as nodes in the informal knowledge network of the company, providing resources for help as well as training. The low level of formalization of knowledge management rises the requirements for experience beyond the obvious need to learn how to apply technical knowledge.

Engineers at Iprov link experience based knowledge both with the ability to solve technical engineering problems, as well the ability to organize work and knowledge about the company's operations as an organization. IC design work involves using various highly complex EDA tools, script editors, data management tools as well as standard office software on a daily basis. To be able to work within such a complex tool chain in an efficient way the engineer not only needs to know how to use the specific tools, but also needs experience in how to sequence the various process steps to make the best use of his working time.

> *"It is above all things related to the way in which we work, we use a dozen tools on a daily basis, and if someone does not know one well, has not acquired any skill, he will certainly do it more slowly, just as he did not do it a number of times, did not meet with a problem, it is trivial, such as connected with things related to files or managing a great number, hundreds of thousands of files, to get this done well he will struggle with it all day. A second person who has experience will get it done in five minutes, it will be processed the whole day but in the background and in the meantime he will do the next thing."* (Post-Sales Support Manager)

Trainings provided by EDA companies are not able to provide this knowledge, as they only focus on presenting the new capabilities of the respective tool without talking about how this could be used in the development process. Trainings oriented on the development process would need to take several days with very high costs for the company. This makes personal contact with a colleague who already has experience with a specific tool or task very important.

As the knowledge on the development process is mostly based on experience it can only be acquired through working in the company, as university education can only provide the graduates with a general way of thinking and technical knowledge as well as basic problem solving capabilities.

> *"Experience is needed as engineering knowledge tells how something works but does not say anything about how to design it."* (Post-Sales Support Manager)

As Iprov's processes are not highly formalized and standardized knowledge about specializations of particular engineers becomes much more important for both learning processes as well as rapid help when design problems occur. Communication becomes a key capability to work in such an environment, with positions such as project integrator requiring even higher communication skills to be able to link the various involved engineers.

Initially the company relied heavily on self-learning of engineers driven by project's requirements as well as their own preferences and interests. In cases when no engineer has the required skills for a specific task mostly engineers who are specialized in an adjacent field will be given some time to acquire the necessary information and skills. Several years ago a training program was put into place providing internal as well as external training to engineers in a quite systematic way. Since the financial market crises this program was put on hold and the company is again relying on the self-learning activities of the engineers.

Former internal training programs where quite systematic, with every engineer being responsible for a topic and required to offer trainings to their colleagues. However, problems with human resources put an end to this very extensive use of engineering time. When engineers are asked to broaden their specialization, required for specific development projects or to realize strategic decisions, they are given time to learn by working freely and experimenting. The resulting knowledge is then often offered to other engineers in an internal workshop. The most important drawback of internal trainings is that they are draining resources from project related design work.

To be able to finance the quite costly technical oriented external training the company is using EU funds or is sending only a small number of people to such trainings. Decisions on training are mostly top-down, linked to the strategic development of the company's capabilities. However, engineers are asked to voice their interests in specific trainings. If the respective engineer has no time pressure from project work he will be given some freedom to venture into this direction.

5.3. Leadtech – new design center and dynamic ramp-up

Leadtech's Romanian design center (BuDC) saw a relatively fast functional upgrading, most important technical as well as managerial positions are present after five years. The local labor market situation has helped the development of integrated development teams almost from the beginning. Development projects initially lacked complexity focusing mostly on derivative products. However, through product upgrading the complexity of technology grew and new product development has been located at BuDC. Functions such as sales and marketing and higher management positions are not located at the Romanian design center. The importance of proximity to customers, in the case of Leadtech's automotive ICs to tier-1 automotive suppliers, is seen as a major reason for the absence of important management functions. As Leadtech's has no manufacturing operations in Romania all local positions interfacing with manufacturing and test operations are faced with the most international linkages.

5.3.1. IC development – integrated project teams and interface development

The well developed local labor market has allowed Leadtech to ramp-up BuDC fast regarding technical functions. Within only four years engineering positions focused on architectural decisions are in place. As the BuDC is specialized in automotive products development projects are not very complex from the viewpoint of gate count. However, complexity in analog IC design is defined in a different way as both aspects of process technology as well as environment have to be taken into consideration. The ability to generate stable products for extreme conditions such as the proximity of a hot engine block is a highly complex task.

Some of Bud's engineers are involved in architectural decisions. Concept engineers perform a variety of tasks in cooperation with many other functions to define the design specification – the manual for the future development team. In the initial phase of a development project a feasibility study evaluates if and how customer requirements can be implemented in a profitable way. This involves both technical as well as business considerations regarding process technology, packaging and functionality that have to be defined in cooperation with the customer, application engineers as well as the sales and marketing department. Experienced IC design engineers are participating in the assessment of the technical aspects of the feasibility study and definition of the basic architecture. The basic architecture allows to assess the size of the chip and the resulting manufacturing costs, which again allows the sales and manufacturing department to estimate the price and profits. The feasibility study is characterized by a dense communication in cross-functional teams with the customer, application engineers as well as business representatives from the sales and marketing department. The following translation of the results into the design specification is focused solely on technical issues. The development of the functional model of the future chip is a process where the concept engineer has a relatively high level of autonomy compared to standard IC design work as he has both the freedom of tool choice as well as has to make decisions on how specific functionalities will be implemented.

> *"In this phase you can work by kind of drawing the blocks but in parallel you have to do some simulations with some high level languages like SystemC, Matlab, VerilogA, VHDL, it depends on how comfortable you are feeling with the language, with this kind of tool. There is not a must to work with Matlab. Personally I am using VerilogA, it is something I know very well, I am comfortable with it, but my colleagues use Matlab or SystemC. […] You are going down to each block and defining each one, some times if its very, very new block you can go close to the transistor level. But not simulating, not designing it. Because sometimes the block has some advantages, you have various ways to do this kind of blocks and then if you want something specific you can go and say use this one, because this is the most suitable for my design."* (Concept Engineer – BuDC)

The results of the development of the functional model are again brought into a wider discussion process as both the customer and the particular engineers have to review functionalities and features of the future design. After the functional model has been signed-off by the customer the role of the concept engineer shifts again, now towards a control function. During implementation of design specification by design engineers, the concept engineer's role is to control the development team's conformity to his architectural choices and intentions. However, when problems occur during this phase design engineers can voice change requests to the design specifications as well as the overall concept. This can result in a re-working of parts of the chip's architecture as well as require negotiations with the customer. The concept engineer is moving away from the project during this phase and either taking up a new project or is involved in the final phases of older projects. After initial chips have been manufactured they need to be measured by the concept engineer, to see whether the chip is meeting the functional requirements. Measurement is also performed by every design engineer on his particular design block, as only the designer knows the required behavioral specifics of the design.

Design specifications are fixed before design implementation starts and project managers define the work packages for particular engineers. Customer driven development projects exhibit a fluidity of specifications that can result in constant changes of minor specification. Work requests are then highly driven by customer choice and repeating changes often lead to frustrations on the side of IC designers. Abandoning already found solutions or tweaking them towards new specifications is not seen as technically challenging and furthermore leading to growing time pressures as only in some cases change requests are accompanied by extension of the project's duration.

The design methodology at Leadtech's Romanian design center follows the company wide standard establishing the common division of labor between IC design and layout. This is regarded by some engineers as negative both on a personal as well as purely technical level.

> *"At Leadtech it is very clearly separated, which I don't find a very good idea. Because it is expected from the designer to ask the layouter how to make the layout. The problem is that me as a designer if I am doing something and not touching the layout ever, it is very hard to ask from the layouter: you should do it like this, or that. How do I know, how should I ask him? And then there are several tricks which you have to take into account when you are making the design, if you want the layout to look in a certain way. You have to remember to make a transistor not just in one piece, but maybe 4 pieces because they will fit better, you will have a better performance and so on. And if you never did layout you are doing a design which then in layout is a very big problem to implement, and the layouter can say: please split this into four pieces, please split this like this."* (Senior Analog Design Engineer – BuDC)

The development of technical knowledge depends on the exposure to the specific field of practice. This is, as the engineer describes, especially important to be able to both understand implications of specific design choices as well as to be able to communicate with other specialists. As analog chips are very prone to problems related to their material structure, knowledge about layout is fundamental for IC designers. A functional overlap in a less separated division of labor allows for more efficient communication and design.

Apparently management of the design center has realized this situation and is trying to develop broader specialized layout and design engineers. Management is actively seeking engineers who are interested in learning more about the adjacent field. Career development, at least of some engineers, is linked to their willingness to develop a broader specialization.

The work of IC designers is determined also through the specific organization of the relations towards manufacturing. Fabless and fab-lite companies working with foundries as their technology providers have to rely heavily on highly standardized interfaces to manufacturing.

> *"In the previous company we were a fabless company, we didn't have technology in-house, we were working with technology providers that were selling technology. And they were giving a very complete file of the technology, what are the rules, what you can do and what you cannot do, and everything. But if you had a question you were just reading the manual of the technology and it was clear. We were only calling the guys in U.S. to approach the sales department of the technology provider when we had problems, because they were charging for each call you made to them. Answering to you is no problem, but I charge you for it."* (Senior Analog Design Engineer – BuDC)

Leadtech's automotive department is organized as an IDM, where both manufacturing and design are only separated by geography. As internal and direct communication is possible and not burdened with high costs the interface between manufacturing and design is less standardized. The documentation of the technology is not highly detailed, resulting in denser communication between the particular engineer and the manufacturing department. This organizational proximity to manufacturing allows design engineers to gain a deeper knowledge about manufacturing processes. Design engineers have intimate details about characteristics concerning their particular design idea helping them to tweak their design to the limits that are defined by the process technology.

Test engineers are one of the most internationally interfaced positions at BuDC, next to project managers and concept engineers. They are the cross-functional and cross-locational hinge within the product development process of the company.

> *"We are the link, usually the development team interacts locally, everybody is here, but our specific job is to send the test application to the fab, so we need to interact with the development team, the fab guys everybody from the fab. We are the glue that keeps everything together, more or less."* (Test Engineer – BuDC)

Test engineers need to cooperate with design engineers and manufacturing operations. Test engineers need to develop skills that go beyond technical knowledge and experience as one of their major tasks is to be able to work on intra-organizational interfaces. To be able to communicate in a stable way test engineers often travel to the manufacturing operations located in Asia to develop personal relations to their cooperation partners as well as learn about technical characteristics on location. European design locations also often have visitors from Asian manufacturing operations that learn about processes in the standardized design methodology affecting their test operations. Besides such official efforts to develop and stabilize these fundamentally important interfaces test engineers report about independent initiatives.

> *"It is easier to spend some time on one day to make a pseudo-training, a little training, to discuss certain specification, which you find recurring, and then you think how to discuss it, not to make it personal, saying you are stupid, that's not the point. Let's discuss about this, this is delicate, we have to be careful here and here. And if you do this, this is happening, this is electricity and then it works ok. It took some discussions but in the end we got the results. I was happy because next time they did it by themselves." (*Test Engineer – BuDC*)*

Such pseudo-trainings are not covered by any process at the company. Reliance only on official interface building procedures would not allow test engineers to work efficiently and would result in work intensification as glitches and frictions within the internationally organized process would amount to fundamental problems for the projects' schedules. Social ingenuity and the associated subjective capabilities of test engineers are necessary for such geographically complex processes to function sufficiently smooth.

5.3.2. Work and control – tight schedules and dialogical control

The entire product development at Leadtech is governed by a standardized and formalized process defining overall 11 milestones, starting with the initial product idea generation and ending with stabilized mass-production. But, only three stages of the process define the milestones for design engineers, where the actual IC design, or implementation takes place. Design engineers are involved in other project phases as they have to overlook the physical implementation, or layout, as well as do measurements and tests when first test chips arrive from manufacturing. However, as the actual design work is governed only by three milestones this process is not overly finely grained. The product development process is the standardized framework within which more subtle and dialogical processes take place that control and monitor the particular work packages and schedules.

The initial project schedule is developed with the customer. Although the product lifecycles in the automotive market are not at such break-neck speed as in consumer electronics, customer driven projects are often characterized by tight schedules.

> *"Quite tight, due to the fact that the timeline is mostly negotiated with the customer and the customer wants the chip fast. You are talking about two or three years he is always talking about 1 year 1,5 years. They have every 3 years a new platform in average and then you have every two years a new chip for them."* (Concept Engineer – BuDC)

Leadtech has a system of two timelines per project that is used as the framework for communication with the customer, integrating from the onset flexibility into the project's schedule. The best and shortest scenario, or X-30, has a probability of accomplishment of around 30%, whereas the more relaxed scenario, or X-80, has a probability of 80%. These two scenarios are also used for internal communication with the development team and every team member advised to try to be on X-30. However, as contingencies are always present achieving X-30 seems not realistic, and as one project manager states: "Ideally if you are a good planner you should be somewhere in the middle […]" (Product Manager – BuDC) of X-30 and X-80.

While customers specify the project's basic schedule experienced engineers, often from the future development team, are assessing the planned schedule and can voice objections during the feasibility study. The preliminary schedule and the associated work packages are discussed with the development project team and every engineer has to assess his work package and the required development time. There is a possibility to reject the initial schedule, which results in new negotiations with the customer. The task of the project manager is to plan realistically with the various contingencies that occur in development projects. The result of this dialogue is the establishment of ownership for every work package that is linked to a specific schedule commitment. Engineers are able to voice estimation uncertainty, especially when they are designing with very new blocks.

> *"Sometimes you can get a very, very new block and you can have a problem with this kind of estimation, due to the fact that you don't know what to expect. And then you let your gate open: I don't know if I will do it in 2 months, but please be prepared to help me yourself or give me a person. It depends from person to person, from case to case, but it can be negotiated. […] You have to start to cry in the beginning: I cannot do this in 2 months and maybe the team leader, or resource manager will allocate another person, or a better one, or a person to help you, but you have to start crying at the beginning." (*Concept Engineer – BuDC*)*

The schedule is negotiable depending on the specific technical complexity as well as the subjective ability to see and voice future problems. Negotiation and organization skills are fundamental in this process for engineers. Only if an engineer is able to establish his position right at the beginning of the process will he be able to accomplish his work without excessive pressure and resulting stress.

As the schedule is planned based on estimations and the system of two timelines allows for some flexibility overtime is neither regular nor encouraged by management. Most of the interviewed engineers and managers put an emphasis on the idea, that overtime is not facilitating efficient and productive engineering work and is therefore avoided. Despite this individual attitude, the system of milestones, as the overarching framework, can cause overtime. When milestones are approaching and specific deliverables have to be completed overtime is sometimes necessary. However, there are no direct sanction, such as salary decreases, if milestones cannot be met.

The amount of overtime is related to the position of a particular engineer within the product development process and seems to be endemic in functions that are responsible for the final part of chip design, i.e. physical design or layout.

> *"Unfortunately a layouter has some very easy periods, when the design is starting the layouter has nothing to do, because you are waiting for the first schematics to be finished. And in the last weeks you have a very, very hard time. Overtime, nights here in the office. This happens in every project."* (Analog Layout Engineer – BuDC)

Despite the flexibility within the system of two timelines the project's schedule defines in a quite strict way the moment when the so called tape-out, i.e. the delivery of data to the manufacturing operations, has to happen. IC design engineers know that they have a time buffer located outside their task, which they seem to use to absorb contingency related scheduling problems within their own work. Although IC designers cannot overrun their schedules indiscriminately the organization of the development process in a sequential way establishes a hierarchy of time autonomy between the various engineering functions. Some design engineers perceive this situation also as problematic. However, as most of the contingencies within the design process are caused by customer change requests design engineers are only partly able to mitigate this situation.

To be able to monitor the labor process management is using both software tools as well as a finely meshed system of meetings and reports. The most fundamental instrument of control on this level is the development of trust between management and engineers.

Besides standard tools for project resource and schedule planning such as Microsoft Projects as well as Excel Leadtech has an internal tool, where not only milestones but also more detailed information on costs and the overall progress of the project is gathered and processed. However, this internal tool is only receiving data once a month, when engineers put in the amount of hours they have worked on specific tasks in various projects.

More important than these broad management tools are the various regular meetings. Here the focus is on the task and its completion and not on the time that has been worked by every engineer. However, although a flexible time schedule exists engineers still have to fill out timesheets. During weekly team meetings engineers report about progress and problems enabling the project manager to have a constant overview of the project's status. Discussing a particular problem within the team enables the project manager to understand and assess it in the context of the whole development project. However, these weekly meetings are mostly focused on organizational issues, as technical problems can be discussed directly between the particular specialists and the project manager. Cross-functional involvement in such team meetings is limited to problems fundamentally affecting schedules. In such cases marketing and sales are involved, who need to understand what the problem is and how fast it can be resolved. However, marketing and sales are not interested in the technical side of possible solutions. The project manager outlines the results of the weekly meeting in a report delivered to his superior. Day to day communication within the project team as well as with the project manager is one of the most important control tools for management. This personal and direct communication establishes the necessary levels of trust on both sides that allow for the necessary level of autonomy. As project managers are often very experienced engineers they are also contact persons for technical problems.

In the initial phase of the design center weekly reports from every engineer were mandatory, where engineers had to report on every day of the work in detail, resulting in a bloated administrative overhead and driving work intensification. This lead to resistance from particular engineers against this finely grained control.

> *"Of course we had a lot of discussions about this. I did not want to fill in another document. I am going crazy, I need to do my stuff, I am employed as engineer and not to fill out documents. Let's find a way to limit the number of documents. Let's do it on a bases that is not interfering too much, not too many meetings for discussions."* (Test Engineer – BuDC)

The result of this resistance was that the weekly reporting was cut down to the production of a very synthetic report consisting of one Powerpoint slide, where engineers provide an overview of the progress of last week. The compliance of engineers to this process is partly governed by the yearly evaluation of their progress. One part of the yearly evaluation of every engineer is his professional progress, based on the development of his technical skill. The administrative development, i.e. constant delivery of precise reports about his work, is also a factor in the yearly evaluation. However, not all engineers are fully adhering to this mandatory reporting process, which results in direct communication with their supervisors.

5.3.3. Knowledge – knowledge management and practical knowledge generation

Knowledge management at Leadtech is based on a system of standardized databases and direct communication as well as instruments for practical knowledge generation. Most of these processes are projected on a global scale integrating all of Leadtech's R&D operations, however, frictions of remote communication confine dense knowledge sharing dynamics often to the particular design center. Locally organized communication, as well as self-organizing direct personal relations between engineers based on proximity are perceived as most valuable both by management as well as engineers.

Leadtech's main global database is a collection of data from lessons learned sessions as well as general documentation on the various blocks and whole chips developed in the company. This database is accessible for every engineer and is an essential part of the development process as both information on possible re-use has to be accesses as well as particular milestones require the input of documentation into the database. The standardized development process requires the project manager to develop a list for his development team based on the lessons learned database. This list defines the suitable information for the future project while establishing a specific control structure as engineers have to sign off their completion of checking the defined data. However, many engineers and local managers voice their critique on this process, as well as on global knowledge database in general.

> *"It is not feasible for the engineer to go though all lessons learned results from old projects. But you end up in being aware of some problems. [..] When you start a design, nobody will say now let's see what did the others do. You have a long list and you study (laughter). Because you never end up. From this lesson learned list you know what were the most important mistakes you did in the past, or your team did in the past."* (Department Manager 1 – BuDC)

> *"Global databases are mostly useless. Too big, too long to work through. Just a waste of time."* (Product Manager – BuDC)

The efficiency of using formalized knowledge from a global database is further decreased as the design of analog chips is exacerbating the problems in transferring solutions between the various process technologies used by Leadtech. Engineers use these databases often as sources for ideas, or concepts but still need to develop the particular solutions for their problem on their own. As development projects at Leadtech are characterized by tight schedules global databases face another limit as a preparation of knowledge for formal knowledge databases takes time engineers generally lack. Although documentation and lessons learned are part of the standardized development process they are often pushed into the background by schedule issues. The task of preparing tacit knowledge in such a way, that it will be understandable without the integration into the situation of a presentation where questions can be posed and discussions emerge, often exceeds the time assigned for formal knowledge sharing.

The huge organizational effort to enable a global database is underlined by a department manager at Leadtech:

> *"I don't know how to manage that, the problem is that when you have multiple sites dealing with almost the same projects, the same knowledge, databases, they tend to create different databases, not synchronized. Sometimes one of the sites is not updated to what was created at the other site. But it is very difficult to create such a database."* (DMb-BU)

However, this organizational problems are not perceived as grave as most of the knowledge sharing is based on personal relations. This personal level of knowledge sharing is not only bolstering the drawbacks of global databases but is also allowing engineers to develop their own, relatively independent knowledge networks. As project managers and engineering experts, such as senior design engineers, attending lessons learned sessions are involved in various project teams they aggregate and distribute knowledge generated in this process also on a global scale, through the identification of helpful intersections. However, much more important for knowledge sharing is the integrated structure of the development teams as it allows for the development of extensive local databases that are both project oriented as well as based on the particular functional engineering specialization.

Despite the fact that the documentation of lessons learned is not put into such an extensive use as intended by management, this mandatory and standardized process supports the development of communication within and between development teams. The very process of presenting lessons learned to engineers of various specializations triggers communication as well as allows for the acquisition of organizational knowledge about limits encountered in other functions.

The localized structure of sharing knowledge directly linked to project work can also help to alleviate the fundamental problem related to translating highly formalized knowledge.

> *"Sometimes this is harder as the secret is in the mind of the person, it is not anything written. In this kind of situation you have to talk with him. We are talking and I experienced that they are open to share information with us. I don't see any blocking points here. About 90% of information you can find over the intranet or local net and the other 10%, if you are able to identify the person which knows, he will be open most of the time, if he has time."* (Concept Engineer – BuDC)

This necessary direct personal communication needs to be organized by the engineers independently. The engineers need to develop the interest to communicate extensively with their colleagues both on a local level as well as the global level. Integrated development teams lower the requirement for international knowledge sharing, however as both experience levels are still different as well as product lines and technologies are not organized in a pattern of highly specialized development centers, engineers need to gather knowledge from other locations. Global databases provide an information mechanism on the various specializations of the particular engineer, while the knowledge exchange still needs direct communication. Issues of trust building are important as fears of internal competition and dynamics of offshoring always resonate in international knowledge sharing processes.

> *"We have somehow a system but I think nobody is using it. I noticed that our German colleagues have a great problem sharing their knowledge, just on a formal basis. They are not responding to that. But if you talk with them on the phone, or if you meet with them and talk, you develop a trust relation you can talk about this. This is mostly how the knowledge is being shared. Even in our team."* (Analog Design Engineer – BuDC)

Although checking for re-use possibilities is a mandatory step in the design process the process of re-use itself is not standardized at Leadtech. Engineers link this low level of organization to the limits of re-use in analog chip design. Re-use is based mostly on informal relations engineers use to check both the possibility of re-use of specific blocks for their design as well as can exchange ideas about issues and technical pitfalls. Re-use databases are used as a directory, listing the various specialists and linking them with particular IP block. However, here too developed personal relations are key for a smooth knowledge sharing process.

> *"Right now we don't have a very clear re-use process. Usually we approach the designers and then we are talking with them by phone or by meeting. They are guiding us. Or we are guiding them, because it happens, I had a small block which was re-used. They called me, how is this, how is that."* (Analog Design Engineer – BuDC)

> *"There are some databases for technology and for let's say different circuits. But you see, once you are another technology, Leadtech has a lot of technologies, then it doesn't' really work, this re-use. You have to rethink the concept. And it could take as long as to build it from scratch. I am encouraging this personal connection more that the database. [...] We also check the database, check it on a personal level. If I take this block and I know this guy who has designed it I can ask him to explain it. He knows me then for sure he will do this. When the block was designed by somebody I don't know, never heard about, I can pick up the phone and ask him, but he is going to tell me something like I am busy call me in two weeks. In the end we are all people, so we have to have these connections."* (Product Manager – BuDC)

Design reviews, mandatory within the development process, facilitate the development of direct communication and informal relations. Design reviews at Leadtech are an iterative process of at least two meetings where the adequate engineers convene, both engineers responsible for a certain design block as well as specialists for the particular topic. As the complexity of the discussed issues is high, after specific solutions have been presented and initial discussions took place, special review teams are appointed that are responsible for the detailed review of specific characteristics and presentation of review results in the following meeting. International review teams are initiated when complex or interesting design issues need to be reviewed. This gives engineers the possibility to discuss technical solutions with experienced specialists from other design locations and allows for the development of individual organizational knowledge and informal expert networks that go beyond the local design center team.

Leadtech has implemented various knowledge sharing instruments that facilitate the development of personal communication structures both within the particular design centers as well as across its global design network. The most general is a meeting of the entire product development team, i.e. all engineers from the design center, which takes place every fortnight. In this general technical meeting every development project is presenting the current status of its work as well as the encountered issues. This allows for short technical discussions on possible solutions as well as gives engineers an overview of current development outside of their specialization and development project. These discussions are followed by a technical presentation prepared by a volunteer. Technical issues and innovations regarded as interesting for the entire development centers are presented. Such presentations are either directly related to generalizable issues from development projects or represent results of individual technical interests of particular engineers.

The product line and project team organization is generating a structural problem for knowledge sharing as this vertical structure is establishing communication barriers within the particular engineering specializations. To facilitate the necessary horizontal knowledge sharing within specializations such as design, test and layout local communities of practice meetings have been established. Presentations from these meetings are stored in a local database allowing engineers to find topics and the related specialists easier. Tight project schedules and differences in progress and status of the various development projects can impede these monthly meetings.

Communities of practice have been also established on the global level of the entire company. Such communities of practice are organized mostly through telecommunication only once or twice a year, as their organization is even more complex than local communities of practice. Sometimes Leadtech also organizes internal symposia held at a specific design center, where many of its global specialists gather and can discuss and exchange experiences and technical insights. Global communities of practice give engineers the possibility to listen to and discus presentations of highly experienced specialists, so called technical gurus.

These various meetings are perceived as both very helpful as well as interesting by the engineers as they allow to satisfy the general interest in technical issues as well as broaden the ability to learn on a more independent base. However, sometimes engineers lack both time as well as impetus to prepare presentations, as often these meetings are not integrated into their basic schedule planning.

Besides the exchange of practical knowledge through knowledge sharing instruments Leadtech established a possibility for engineers to put their innovative technical solutions to the test. Multi-project wafers allow engineers to test a specific design solutions that is going beyond the normal design rules. Within a normal design schedule such design solutions would mostly not be used, as the risk of design flaws and the resulting costs are too high. Especially in the automotive industry quality considerations are one of the important factors in product design. However, such necessary high risk aversion could stifle innovation in the long run. Engineers at Leadtech can negotiate spare time with their project manager and the HR department to be able to develop and implement such a risky design solutions for a specific functional block. When such a prove of concept is successful this new design concept can be used in future designs.

5.3.4. Training – broadening of specialization and training requests

Leadtech is offering quite extensive training possibilities for its engineers focusing on the broadening of their specialization rather than developing overspecialized technical experts. The individual HR development is based on a feedback process where both supervisors and the particular engineer discuss and assess the personal results of the past as well as define goals for the coming year. This yearly assessment also involves the establishment of training aims which can be driven by proactive engineers. However, to be granted the demands for technical or managerial training put forward by an engineer always need to be in agreement with the strategic development of the design center. The training budget is also defining another limit for specific training requests.

> *"You can not ask for everything. But if your reasonable, and asking for something which is indeed good for you at 80% of cases you can receive what you ask for. It was hard last year to have trainings. But looks like the next year we will have training budget back."* (Concept Engineer – BuDC)

As the training budget is quite big and is not connected to the short-term development of a design center it is one major source of financial flexibility for the company.

As management positions are increasingly staffed with local talent engineers can also receive management training. This possibility is mostly offered by the design center manager to specific engineers who have shown good abilities in project management and organization. As semiconductor business is a very specific business dependent on high levels of technical understanding, Leadtech is focused on developing managerial talent from its engineering ranks rather than searching for already experienced management talent from other local IT industries. This strategy opens up a second career ladder for local engineers that are interested in moving towards a managerial position.

The individual HR development at Leadtech is focused on facilitating a broadening of the specialization of engineers. To advance their technical career engineers are obliged to choose an adjacent technical field besides their initial specialization.

> *"[…] because we have here this career ladder you cannot go up the ladder with only one field. I am a very good layouter and I will get to be even better every*

year, but to go up the career ladder I have to do 20% design or 20% ESD[35]*. This is how we do it here. We put this into goals for the next year, and I do my best to grow."* (Analog Layout Engineer – BuDC)

5.4 Labor process organization in development centers in CEE

The three case studies from the semiconductor industry in CEE allow differentiated insights in various aspects of the labor process organization of engineering work. The overall identifiable managerial strategies tend towards responsible autonomy. Although responsible autonomy is a general characteristic of the engineering labor process, this finding is a highly interesting observation for peripheral locations within the internationalizing semiconductor industry, as it is another tangible evidence for shifts in internationalization dynamics. Moving away from structures of complementary international division of labor a new phase of internationalization has already begun. The still existent hierarchies cannot anymore be read off from the specific geographical location of a particular operation within a GDN. Now a more focused view is necessary to determine the technical and organizational capabilities as well as the organization of the labor process to be able to understand what kind of positions a particular design center is taking in the hierarchical GDN.

Characteristics of normative control based on responsible autonomy are prevalent in all three case studies, yet strategies of direct control exist and are undergirding and at some points even facilitating management practices specific for autonomous work. The dialectical relation between various strategies of control is enabling an organization of work in an international context where management can assert control over the labor process while leaving enough room for engineers to innovate. Work organization and control are developing within the process of upgrading and specific local characteristics, in particular a highly stable workforce and limits on the local labor markets. As the case studies describe different companies and locations there are obviously dissimilarities in the labor process organization driven by company size, network position, product markets as well as local labor market characteristics. The depth and breadth of standardization in the labor process is a major differentiating characteristic between the case studies. The small IP developer from Poland neither has the resources nor the imminent necessity to develop highly standardized knowledge management processes and design methodologies

[35] ESD is an acronym referring to necessary safety measures for every electronic device preventing damage from electrostatic discharges.

as its few dozen engineers are all co-located making communication and knowledge sharing much easier than in a design center that houses more than hundred engineers and is integrated within an intra-organizational GDN with a complex international division of labor.

The most important insight from the case studies is that functional upgrading of design centers within a global design network and the development of integrated teams are fundamental steps to develop an effective system of layers of control that allows for efficient production. Such an organization of the international division of labor allows to reduce interfaces and the requirement of their standardization as the most important technical functions are co-located. Lower levels of interface standardization can help to raise autonomy in the labor process allowing to access the engineering creativity and facilitate motivation through more complex projects and technical responsibility. High management costs of implementing highly standardized interfaces are lowered while engineers are not required to invest too much time on the necessary development of stabilizing informal relations. Simultaneously, integrated development centers allow for direct personal control measures that are necessary to bolster the high autonomy levels of normative control and are perceived as less intrusive and coercive. Fundamental problems knowledge management is facing in a globally organized knowledge company are reduced as local knowledge generation and sharing is pushed more towards the center of attention and enabled by the spatially integrated development teams.

Functional upgrading facilitates both more complex systems of control and labor process organization as well as dynamics in engineering work that facilitate technical complexity perceived as positive by engineers. Yet, it is not definite which process is triggering the dynamics, as functional upgrading can be the necessary solution for problems of control, commitment and motivation. The causal correlation is not determinable from the data in the case studies. Throughout the entire study we see the effects of a dialectical process between the local and the global, making a clear answer to this question seemingly not possible. The important insight is that processes of functional upgrading are not solely driven by strategic decisions of cost cutting, customer requirements or market proximity. The capitalistic imperative (Thompson 1983) to organize the labor process efficiently and profitably by asserting control over it through appropriate managerial strategies is an important driver in processes of upgrading. The establishment of appropriate control measures that aim at facilitating the utilization of the entire capabilities and experience based knowledge residing within the particular engineer can make functional upgrading and the development of integrated development teams necessary. A complementary international division of labor, with a high number of international interfaces needs more standardization and facilitates tendencies to direct control, subduing the creative forces of work (Friedman 1977) in the course of implementation of such managerial strategies.

The negotiability of technical as well as organizational specifications of the development projects is the major similarity between the three case studies. As all three companies have based their labor process organization on their specific implementation of normative control, negotiability is a major instrument of integration and the manufacturing of commitment. However, despite the similarity in the broad characteristics of this instrument, the particular framework within which this process takes place is different, especially regarding Iprov. At the IP company from Poland negotiability is extended towards almost every aspect of the development process, as the standardization has not reached comparable levels to Leadtech and Midtronic. But, simultaneously, with its very small size and the important role of the company's founders negotiability at Iprov is also confined by more personalized than standardized limits. These are additionally superimposed through restrictions driven by Iprov GDN position as small IP and design service provider.

5.4.1. Labor process organization, work and upgrading

Engineering work at the design centers of Leadtech and Midtronic is organized in a R&D oriented labor process, characterized by highly complex and variable tasks performed by engineers under a layered system of managerial control. Not too different, the labor process at Iprov is comparable to work organization in a prototypical small engineering start-up in the software sector, where technically driven experts work in a somewhat unstructured organization that allows for a lot of autonomy. Low levels of organization are in some areas perceived as negative by Iprov's employees especially regarding knowledge management and schedule slippages connected with time pressures. However, this does not effect the identification and commitment of engineering with the company, as the head-hunting situation shows (see: Chapter 3.2.2). All three case studies show a distinct orientation of the companies to offer high employment protection for its technical experts. Even during the crisis 2008 lay-offs were limited only to Midtronic due to its global cost saving program. As for Leadtech and Iprov employment protection is an essential tool to develop high levels of trust as well as an instrument to cope with the overall tight labor market for IC design engineers.

For Leadtech and Midtronic technical specifics of analog chip design are drivers of relative high levels of originality in the work of the particular development engineer. Existent re-use strategies put procedures in the development process in place to check for and raise re-usability within new projects. However, the one-to-one adoption of already developed IP blocks is constrained by the constant re-test and re-measure requirements. This makes re-use, potentially the most mechanical and routinized part of IC design, also a quite complex and original task, as technical contingencies have to be recognized and taken care of. The complexity and variety of tasks that a single engineer needs to perform to accomplish his part of the design task is high, ranging from genuine design tasks like the definition of schematics to the manual evaluation of chips. Furthermore, the integrated character of both analog chip companies' design centers in Easter Europe allow the IC design engineer to work closely with the local layout engineers based on personal communication. This work organization lowers standardization essentially while continuous direct communication allows IC design engineers as well as IC layout engineers a higher level of discretion in their engineering work.

Work at Midtronic's DST department is characterized by a very research type organization of tasks. This is especially interesting for the discussion of the development of the international division of labor. Both the location of this research related company division as well as the very autonomous character of its labor process are an example for the limits of simple ideas about dichotomies and hierarchies in the international division of labor in development work. This development shows how the location of specific R&D functions can be driven by local characteristics. The existence of very experienced local technical talent as well as infrastructure coupled with the very low labor costs in the Czech Republic were the essential facilitators for this locational decision. The proximity to the manufacturing operations, that allowed the development of this kind of interface between manufacturing and product development were also important but only initially. For the historical development of the local department's importance the stability of the engineering workforce was essential, as the work and its quality is based on experience and the ability to understand the various manufacturing and technology development operations both technically and personally.

The task organization has evolved organically at Iprov, leading to relative high levels of task complexity and variety. Upgrading facilitated by the integration into specific GDN and leading to a more service oriented business model have caused shifts in the labor process. This increasing customer focus has partially lowered the originality of tasks as after-sales service, performed by all design engineers, is often occupying engineers with similar bugs and technical problems. Layers of direct control strategies have been introduced to organize the labor process with an increased focus on schedule compliance in customer related projects. The low levels of work organization in respect to functional labor division increased the intensity of work gradually as engineers have to switch between development tasks and customer technical support regularly. Work requests are therefore often structured by the suddenly emerging requests for technical support. Such a fluid labor process shifting constantly between development and service work is requiring a high level of commitment and identification on the side of the engineers. Simultaneously, this is also lowering the ability of long term company development as strategic projects are constantly delayed through customer support request amidst a situation of tight engineering personnel.

The development of derivative chips, perceived as one of the more routine design engineering tasks includes some level of complexity and originality. The sheer number of process technologies that Midtronic and Leadtech use for their various chips require engineers to form a very broad knowledge about the various pitfalls of the particular technology. This translates into a distinct engineering specialization allowing to quickly analyze and avoid possible issues in the process of transferring already existent circuitry to other process technologies. However, the case of derivative products at Leadtech's BuDC shows how engineering work and its labor process organization are formed by different upgrading paths. Functional upgrading, as the main process in the development along the value chain, with integrated teams as its most important effect on engineering work, is not unambiguously related to dynamics in task originality. Local product upgrading based on already existing development capabilities can have more important effects in increasing both task originality and complexity in the local labor process. Product upgrading, or the initiation of development projects that employ the various locally existent engineering capabilities to develop a partly or completely new product, expand the ability of the particular design engineer to develop original technical solutions. Functional upgrading without product upgrading leads to an uneven distribution of characteristics of task organization within a location. The work of concept engineers at the BuDC illustrates this tension. Their labor process is characterized by high levels of autonomy on various levels, starting with tool choice and high task originality as they have to conceptualize new architectural solutions combined with their alternating between technical and managerial functions. Although the difference in work organization between concept engineers and design engineers always exists, based on a hierarchy of work roles, product upgrading is reducing the distance between these engineering functions as especially task originality rises for design engineers. Task variety on the other hand is almost completely a function of functional upgrading and the development of integrated teams. Design estimation, implementation and review, measurement and test, communication with layout and documentation are tasks only possible to conduct in their whole depth in a design center that houses the entire development value chain locally.

Test engineers display a very specific part in the labor process, especially with respect to their informal knowledge management strategies. The case at Leadtech's Romanian design center shows how their ability to organize pseudo-trainings is a sign of the relatively high level of autonomy in the (test-)engineering labor process as these trainings, which are temporarily re-organizing their work completely, are not backed by any official procedures. The control in this engineering labor process, although organized within an intricate layered system, is mostly focused on work, i.e. specific deliverables on a pre-defined date. The work effort of the particular engineer is not in the focus, as long as he is able deliver in a timely fashion the required technical solutions. How the engineers succeed with this is left to their own choice, of course within the limits of the standardized design methodology. These very broad formal limits and standardized interfaces are especially unstable for processes that are not locally integrated, requiring test engineers to develop own strategies to stabilize these communication and cooperation channels. Such informal strategies are drawing heavily on subjective capabilities of individual engineers to communicate, organize and temporarily alter the labor process. These capabilities are used to be able to meet with the schedules and quality standards defined by the standardized product development process.

Despite the relatively high task variety the labor process at Leadtech's BuDC is characterized by a division of labor that is viewed often as a standard in chip design. The organizational separation between chip design and layout is lowering the direct dependence of Leadtech on a particular engineer, as well as allowing for specialization.

However, this control strategy of segmenting engineering work is not suited for the specific technological and knowledge requirements of analog chip development and is impeding the development of an efficient work organization. Leadtech has recognized this and is trying to lower the level of segmentation though efforts aimed at broadening specializations of engineers, especially to bridge the distance between design and layout. Although this strategy is aimed at organizing the labor process in a less segmented way, simultaneously it is linked to a practice that is asserting control over the entire process. By conditioning career development for engineers on the need to broaden their technical specialization, Leadtech is establishing direct control mechanisms on the procedural level.

The still prevalent organizational integration of manufacturing and product design at Leadtech has wide ranging influences on the labor process organization. The procedures governing the cooperation and communication between manufacturing and product development are less standardized than in cases with inter-organizational barriers that separate these functions. Intra-organizational communication allows for relatively high levels of non-formalized as well as even missing parts in the data manufacturing operations are providing for design engineers. This results in the need for broader and deeper communication initiated by design engineers, giving them ample possibilities to learn and broaden their technical knowledge that is extending beyond their own technical specialization. Although this can be arduous in the direct situation where technical solutions need to be found, engineers positively perceive this learning process. Such lower level of interface standardization can result in a higher propensity to innovate as technological contingencies can be communicated and used for design tweaks, giving engineers a much broader possibility to play with the design. This is enlarging the limits within which the engineers are allowed to tweak and search for technical solutions. The expanding of technical autonomy is integrating engineers, as it is facilitating areas where their intrinsic drive to technical work can be acted out, potentially helping to increase motivation. Additionally, as Leadtech's BuDC has no local manufacturing operations these interfaces have an international character promoting requirements for engineers to develop both communicative skills as well as informal relations based on trust.

Intense customer orientation affects the labor process in all three case studies and is most visible in the definition of work requests, which are fundamentally driven by the customer and his product specifications. The feasibility study and the subsequent implementation of the design specifications involve technical and organizational negotiations where engineers from the development team often participate, enabling them to voice problems and limits and influence the specifications. However, the limits of the influence of the development team is always defined from the outside. The profitability of the product, assessed in the feasibility study is the internally set limit, while the customer and his product request is the externally set limit framing the whole process. Such an open but limited structure of iterative negotiation of the design can be viewed from two perspectives. First, opening up the communication process to involved engineers allows to benefit from their technical insights and experiences in a much broader way increasing quality levels of products. Second, integrating engineers in the definition of the specifications of the future projects is expanding the technical autonomy while simultaneously also commitment levels, as engineers strive to develop good solutions based on technical and not only economical considerations.

The high levels of customer involvement can be especially problematic for small companies where the development of the functional division of labor is limited by the number of available engineers. Constantly switching between development tasks and customer technical support is not only arduous for the particular engineer but is also impeding strategic development projects at Iprov. This situation has led Iprov management to a partial reorganization of work through compartmentalization. The USB product line development team has been separated from most customer support request to be able to develop future products in a more stable work environment. With this more direct control of customer relations, management is able to resume control over the labor process in this particular product line, while simultaneously rising the autonomy of engineers towards customer requests. This new organization does not lead into a lowering of complexity and variety of tasks. As customer support work has been limited to a minimum, the relative amount of task originality is potentially growing with engineers being able to develop new solutions and not focus on recurring bugs.

Although the development process at Iprov has been standardized it is in a constant flux for customer related projects. Customers are requiring the adaptation of the development process to their needs through the addition and subtraction of particular steps in the development process. Numerous change requests during project implementation are leading to a constant rescheduling of projects regarding size and duration. This is increasing the fluidity of the development process further making a strict specialization of the limited engineering personnel impossible as well as adding to the problem of work intensification. Iprov lacks both engineering personnel as well as managerial capabilities to be able to establish a more standardized and rigid development process. For the specific engineers this is resulting in both problems with work intensification as well as relative high levels of autonomy and variety in their day to day development work. Despite the higher levels of direct control in customer related projects the labor process at Iprov is still governed by a managerial strategy based mostly on responsible autonomy.

Intense customer orientation, especially the constant change requests are a practice of direct control in the engineering labor process (Upadhya 2009). Change requests directly affect the work of engineers, disrupting procedures while making the owners of affected blocks directly responsible for the implementation of the requested change. Although the general tendency of the engineering labor process is to focus on work, intensive customer orientation is shifting the focus of control back towards the particular person. As the ownership of design blocks is personalized customer driven change requests directly cut through to the particular engineer. Moreover, change requests not only affect the technical side of design but also make organizational adaptation imperative, leading also to overtime. This is most visible in the specific work organization of layout engineers at Leadtech who are at the bottom of the design hierarchy. Their labor process is completely governed by hierarchies resulting from the sequential work organization and tight schedules defined and disrupted by the customer. Total time flexibility is here not a characteristic of a high level of autonomy as it is not connected to a situation of time autonomy. Layout engineers are forced into the situation of time flexibility and the associated regular overtime by the specific organization of the labor process.

At Iprov direct control through customer related projects is also visible. The initial step was the implementation of quality management to accomplish the integration into Msystems' GDN, which resulted in a standardization of the development process at Iprov. The associated establishment of a system of milestones implemented a cyclical control structure based on deliverables and direct responsibilities. Situations where customers ask for information about the particular members of the development team responsible for their project are ambiguous. Although this is mainly used for an easier establishment of necessary personal communication contacts, the direct access to a particular engineer is also rising the possibility to call upon his responsibility. Clearly monitoring of specific tasks is facilitated by such a system. The overall accountability of work progression established through regular reports and conference calls is extending direct control in the labor process considerably.

The relative high degree of freedom at all CEE design location described in the case studies is facilitating an environment in which engineers are perceiving their work oftentimes as a playful activity. Such a positive attitude towards solving technical problems could be impeded by higher levels of standardization and formalization. Attempts to introduce more standardized design methodologies by the former owner of Midtronic's BDC have stalled mostly due to a highly top-down approach that left no room for the integration of the engineers' interest. Standardizations based on technical considerations are mostly well received by the engineering community as they allow for easier development of increasingly complex systems. However, attempts to implement standardizations that are mostly based on managerial and organizational rationalization assumptions and lower degrees of freedom in engineering work, meet with considerable opposition. This is much in line with the differentiation between commercial and engineering logic in rationalization processes Beirne et al. (1998) have applied in their analysis of software development. Although both logics often complement each other their relationship is characterized by a fundamental contradiction. Both are based on a different rationality, where economic pressure and the need to control costs can run counter to technical requirements and the need to allow for tight process control.

5.4.2. Control and negotiability

The control structures in the labor process in all three case studies are based on the system of milestones. However, the granularity of milestones as well as the managerial practices in place that fill out the space in between the particular milestones are quite different between the three companies. The most important similarity in all three case studies is the negotiability that is a fundamental instrument in the control of the engineering labor process. In terms of knowledge management, negotiability of schedules is a potent instrument to access experience based knowledge on technical as well as procedural issues without expropriating this highly important capability, that needs to remain at least partially with engineers, to enable a constant development.

The overall managerial strategy is based on formalized and standardized procedures that define the entire development process dividing it into milestones. At the end of every milestone predefined results delivered by every team member are reviewed for their integrity as well as quality. However, this highly formalized control structure is not resulting in constant high levels of control and monitoring. It is rather forming a framework and specific segments within which relative high levels of autonomy are enabled. The definition of scheduling and work requests are intricate processes that give engineers possibilities to influence both technical and as well as timing issues. The monitoring of engineers and their work is characterized by layers of autonomy and control.

Leadtech's development process is not only framed by the system of milestones but also by a measure of the probability of project completion. Milestones define only a relatively coarsely grained framework within which procedures and instruments, both informal and formal, are used to assert control over the engineering labor process. These procedures and instruments are mostly based on dialogical processes, which are also producing the necessary information for software based automatized control systems. Leadtech's X-30/X-80 procedure to define and communicate both externally and internally the probability of project completion sets up a framework for responsible autonomy based on high levels of autonomy. The flexibility communicated by this system, that is translating into a relatively high level of time and work autonomy, is simultaneously reversing itself as it has the possibility to perform more efficient and faster inscribed in its very own communication.

The definition of the future project's schedule is a detailed and highly formalized process in all three case studies, where ownership relations between particular engineers and design blocks as well as schedule commitments are iteratively established. The result of this negotiation process is always limited by schedule constrains pre-defined by the customer. This negotiability of project schedules is the focal point of the system of layered managerial control strategies that governs the labor process of engineers at the three companies. By involving engineers in the definition of their own schedules management is able to appropriate important organizational knowledge and feed it back into the production process. Although engineers can voice their reservations within these negotiations the final decision is taken by management and the customer. While benefitting from the engineers' organizational knowledge that allows for a more realistic project planning, this dialogical albeit hierarchical decision process prevents uneconomical designs, that would cater more for the technical ingenuity than fast project completion. However, the integration of engineers in the definition of schedules establishes major pillars of responsible autonomy as autonomy is upheld and the commitment through such an open culture is produced. But as the definition of project schedules is still negotiated in a hierarchically structured system, as project managers are responsible for the planning of contingencies, project schedules are tight. Although this is connected to the longer experience of project managers and their ability to estimate future contingencies better, there is a component of control in this situation as the amount of planned in contingencies defines the future intensity of work as well as time autonomy for the engineers.

IC designers in Midtronic's three design centers are integrated in the formulation of their tasks in future design project. They are also enabled to voice opinions on the entire architecture of the future chip influencing the more abstract and higher level of the entire product they will be developing as project team. This dialogical process results in a work request that is detailing characteristics of the future product quite meticulously. However, this data sheet is not specifying ways how the solutions of particular technical problems have to be executed. This translates into a relative high degree of technical autonomy for the particular engineer within the project team. The major difference between customer and standard products development projects is the possibility of change requests during project execution. Customer driven projects are much more prone to such change requests translating into a more hierarchical work request communication. However, this does not imply a higher detail of such work request as compared to standard product development projects, as the design knowledge of customers has decreased in the last years. From a control perspective such direct customer interference is a practice of control as the customer is affecting directly the task organization, the responsibility as well as the time autonomy of the particular engineer.

Similar to defining the specifics of work request the scheduling of work is organized as a dialogical process. Only for very small and highly standardized tasks at Midtronic's BrDC are general task times set. Otherwise scheduling is a negotiation process where both engineering experience is integrated as well as contingencies considered. As every engineer needs to define his own schedule and commit to it, this dialogical and relatively open process is linked to a personalized control structure. The definition of both technical and scheduling issues are integrated into a process that results in formalized commitments of every involved engineer. This is a point where the interplay of practices of responsible autonomy and direct control is visible as dialogically determined schedules translate into personal responsibilities. Responsible autonomy based on identification with the company and commitment is underpinned with standardized and formalized procedures used to construct this commitment within the labor process.

These procedural measures of control result in a shift of the management of schedules and tasks towards the individual engineer who needs to cope with contingencies emerging during development within the time he set for himself in the beginning. Planning for contingencies as well as the system of responsibilities becomes the fundamental factor in such a work organization. The ability of engineers to negotiate contingency buffers is based on their experience to estimate possible issues as well as their individual negotiation skills. Communication and negotiation as well as time management capabilities are essential for engineers to develop a strong position within the system of negotiability. These highly subjective capabilities are the base of such open processes putting pressure on engineers that are not endowed with them. Skill shifts towards soft skills that stress the subjective level are a major result. However, the new system of responsibilities for contingencies at Midtronic's BDC illustrates the important role of middle management in planning. By establishing direct responsibility for project completion at the management level it was possible to limit unsustainable time planning that resulted in unacceptable work conditions.

The negotiability of schedules is extending time autonomy beyond the ability of a particular engineer to relatively autonomously organize the tasks that will allow him to deliver the pre-defined work package on time. The ability to influence the schedule framework itself is establishing a time autonomy of second order. This second order time autonomy is important for the legitimization of the labor process organization and work intensification. Integrating engineers in the definition of the period within which a development project will be conducted rises the levels of responsibility and expands ownership from work packages towards the entire project. In arduous times of work intensification and overtime a discursive element already exists that potentially averts the sole responsibility for such a situation from management.

As the negotiability of schedules is extended towards the implementation of the schedule itself it is establishing and reproducing hierarchies of time autonomy within the system of sequential work organization. The recurring re-negotiation of delivery dates leads to shift in the relative point in time of particular tasks while the general project schedule is kept constant. This leads to the elimination of almost all time autonomy from engineers that have to perform the last steps in the sequentially organized development process. Here the power structure within the labor process and between various groups of employees becomes visible. Hierarchies between workers are related to their centrality of tasks as well as the value add provided by their work (Friedman 1977). For the IC design labor process this translates into a decline of power the more the process moves towards the physical implementation of the design.

Managerial strategies of responsible autonomy are based on high levels of trust, both as commitment requires reciprocity as well as standardized and more open control procedures need data on the status and progress of the project. Although trust has been developed at Leadtech's BuDC and control is focused more on work than on people, engineers need to fill out time sheet, which are an instrument of direct control focusing on people. This situation is a depiction of the recurring contradictions in the internationalized engineering labor process between autonomy and control, that are on the one hand essential for a system layered control, on the other hand do often result in frictions.

Trust can lead to a more autonomous labor process organization. However, it is evident that resistance is also important in the shaping of control in the labor process. Engineers at Leadtech's BuDC were able to lower the intensity of the extensive system of reporting only through their direct resistance, arguing that their task is not to focus on administrative processes but on technical solutions. Although they were able to fight back impeding control, the reporting system is still one of the main and most intrusive moments of managerial control strategies, as the compliance to its requirements is linked to the yearly evaluation of every engineer that is influencing future career possibilities. The framework of responsible autonomy is guaranteed at least in parts by a system of evaluation and rewards on a more general level, which is nevertheless exhibiting characteristics of direct control. The observing of certain standardized organizational rules is guarded by rewards and punishment.

The attempts at Midtronic to install software based tools for direct and automated monitoring of engineering work failed due to both technical as well as organizational problems. The most important obstacle was the engineers' negative perception of these tools and their declination to cooperate. The monitoring tools now in place gather only broad data and are still dependent on the cooperation of the particular engineer, who has to put in the required data. Both management and engineers reflect this problem and perceive these tools not as fundamentally helpful.

The small scale of Iprov's operations is allowing for spatially very integrated development teams, making proximity the main base for control. Monitoring is mostly based on a mixture of self-monitoring as well as personal communication with the project leader and product line manager. Although software based monitoring tools are in use their main aim is to regularly generate reports for budgeting of customer projects. Such an automated process reduces the work for the project leader in the communication process with a particular customer. Although the development process has been standardized and a milestone based control system put in place, the formalization of the overall process of monitoring and control is quite low. The management strategy is based on the fundamental idea of responsible autonomy that engineers do have an intrinsic drive to deliver technically sound solutions within the time frame they helped to define and committed to.

This intrinsic drive is linked at Iprov to the motivation of engineers which is perceived as the most important control instrument. Both factors defined as leading to high motivation point to the very character of Iprov as a truly engineering company, only recently transforming towards a more business driven model. Interesting projects give engineers ample opportunities to solve technical problems that both challenge their technical knowledge as well as allow to learn constantly. Organizing the development in such a way that organizational issues are kept out of the day to day work allows engineers to focus on the technical aspects of their work. Most interestingly is the perception of the transfer of project leader responsibilities not as a promotion but more as a nuisance as it requires a shift away from the technical aspects of development. This is linked to the fact that a managerial career track is not existing mostly due to the small size of the company, therefore project leadership can not be perceived as a possible step towards a managerial career even by engineers who would be interested in it.

The fluidity of the development process at Iprov has adverse effects on specific aspects of engineering work and knowledge generation. The development of knowledge about scheduling and the required time for a specific tasks is impeded by the highly fragmented work organization. Shifting constantly between tasks and projects not only lowers time autonomy of the particular engineer but also results in problems in the development of scheduling experience. Besides being driven by constant change requests, the notorious delays of project completion are also a sign for the lack of sufficient time planning capabilities. The resulting overtime is adding to the already existent time problems of engineer. However, both management and engineers try to dissolve scheduling slippages through shifts in the development process. Lowering the number of customers change requests seems to be a major task requiring specific bargaining capabilities which are linked to the company's position in the supply chain. The company's low position in the GDN is not facilitating its situation in the bargaining process.

The close personal monitoring through the daily communication with the project leader is a very important instrument of control. The role of the project leader epitomizes the dynamic of control within a changing international division of labor. Local project leaders are a major step in the functional upgrading of design centers as managerial responsibilities are located locally and are opening the way for the establishment of a managerial career track. Remote project management requires high levels of formalized monitoring and control as the responsible manager is not at the location but continuously needs data on the project's progress. Openly direct control strategies based on continuous reporting are the result of such an international structure. Local project management allows for a much more intimate monitoring while simultaneously lowering the required amount of reporting of every single engineer. The possibility to talk daily to every project member gives the local project manager the ability to establish a system of personal monitoring catering for the needs of engineers. This very personal control allows for the development of higher level of commitment if the project management is able to develop an understanding for the particular engineer. The results of this daily monitoring are routinely aggregated and forwarded to higher management, however the particular engineer is not anymore caught up in this process of data generation. With this personal control the project manager and acts as a suspension between management and engineers. This personal monitoring is formalized in the weekly team meetings where scheduling and technical issues are discussed and their impact on the progress of the entire project. This establishes also a specific personal control through the various team members as slippages can result in the inability to conform to their respective schedule commitments.

At BDC the awareness on the level of engineer about monitoring and the progress of the project work is re-instated through the weekly reports that are communicated to the entire design center. With this the team based control structure is being expanded towards the entire design center, augmenting it with a specific form of competitiveness that is striving for a constant decreasing of schedule slippages. The monthly and quarterly project and economic progress reports that span the operations of the entire company are further increasing the economic awareness through a transparent albeit hierarchical communication. This communication aims at a specific form of constant evaluation that is not directly linked with sanctions. However, the construction of such a broad economic awareness rises the levels of subjective control through this invasion of the economy into the engineering work.

The formalized procedures for development projects require design reviews at certain points of the development process that are organized both locally and internationally. In line with aims of quality management design reviews establish a specific form of control that integrates both the monitoring of people as well as work. As specific design results can be linked to particular engineers, reviewing them focuses on both levels while trying to assure certain quality standards. Simultaneously design reviews are an important instruments of knowledge management as they establish specific communication processes important for knowledge sharing. Design reviews are based on direct personal communication allowing to access certain levels of tacit knowledge developed in the process of finding specific technical solutions. Situations that allow for story-telling support the process of objectification of knowledge and assert a certain level of control over the engineers by managing their knowledge in a more differentiated way. Such non-hierarchical communication processes are important beyond the immediate knowledge sharing, as they allow for the development of organizational knowledge about the location of specific experts as well as the establishment of personal contacts with them.

5.4.3.Knowledge management

The limits of knowledge sharing based on purely explicit knowledge are exacerbated by the complex international division of labor. The problems triggered by product data sheets containing highly formalized and standardized information are a very interesting example. High levels of standardization are often seen as fundamental for modularization by lowering possibilities of misunderstandings and making distant communication easier. However, the complexity of the formalized information is linked to rising requirements towards the process of interpretation that allows their translation into meaningful instructions or applicable knowledge. This translation, or decoding, is only possible when engineers have both enough experience with similar data and its practical implications from previous projects as well as are able to contextualize this explicit knowledge to be able to evaluate the implications of design decisions that go beyond the immediate development task. Such a contextualization is only possible when engineers have good knowledge about the system and technology levels of the respective project. This experience based knowledge is fundamental for a modularized development process within a sophisticated international division of labor. However, it can only develop slowly in modular development networks as communication between the various engineering functions is impeded and information flows are highly regulated. This is once again an argument for a more integrated modularization that aims at integrating as many functions as possible within one location.

Experience required for the translation of explicit knowledge into applicable information is related to complex learning processes based on upgrading. This is an important point against positions that theorize problems between engineers within global design networks only on the cultural level (Mahadevan 2007). Such arguments are based on a very static perception of local skill sets and fail to integrate the level of different knowledge forms necessary for a frictionless communication. The need to describe work tasks in an almost pedantic way for engineers from low cost locations is only partially determined by their different cultural background. This requirement for such detailed work instructions is also driven by the lack of context knowledge, as both experience and system knowledge have not yet been developed. This experienced based knowledge can only develop over time increasing the capability for a more autonomous labor process in the peripheral design centers. However, time is not the only factor in this process, as only upgrading can gradually provide for an increasingly global view of the development process and enable local engineers to learn about both the system level as well as process technology implications.

Midtronic's specific international division of labor based on highly integrated development centers that are specializing on products and technologies is an essential prerequisite for the organization of a working multi-layered system of knowledge management. A complex system is in place comprising processes that are organizing personal knowledge exchange on various levels, feeding results directly into knowledge databases accessible for the company's engineers worldwide. The process of knowledge objectification is organized in a relatively smooth way. However, the process of accessing this knowledge is more problematic as the required level of cooperation of engineers is much higher. This problem is also prevalent at Leadtech, as the feeding in of data is much easier to monitor and control, than the usage of the data in the everyday work of an engineer. The refusal to utilize the official databases, to access this standardized form of knowledge is also a specific strategy of resistance as engineers are fully aware of the control strategies that such systems embody. Falling back on informal networks to access information not only gives an engineer knowledge of a higher quality but also allows for the further development of social networks that can be advantageous in the future. Not using knowledge databases also obstructs their spreading within the organization.

Midtronic's knowledge management is centered locally on the respective development teams as well as the peer groups of the design center facilitating the exchange of both focused as well as more broader experience based knowledge. Lessons learned sessions and design reviews allow for sharing quite focused practical knowledge regarding project specific design problems and solutions. The immediate character of both meetings, right after the solution of a problem and before tape-out, ensures a prompt spreading of important practical advice both within the project team as well as the whole design center. The fortnight meetings at the BDC on the other hand have a much broader and less project focused aim of extending the practical IC design knowledge of the center's engineers. Leadtech has quite similar instruments for an non-structured knowledge sharing at its design center in Romania. These instruments are securing that both explicit as well as implicit knowledge is shared between engineers ensuring that the company will not grow too dependent on particular engineers and their deeply individualized experience. Providing engineers with ample possibilities to learn and extend their engineering capabilities through looking into practical problems and solutions is on the other hand a very good integration mechanism, rising the identification of the individual engineer with the organization as well as their commitment.

Within Iprov communication is not structured by management, especially as no formal knowledge management system is in place. The lessons learned process is the only formal knowledge management instrument existent in the company. However, as there is no data repository where lessons learned presentation are stored the knowledge that could be potentially generated through this process is lost. Design review as a tool for both knowledge sharing and quality assurance has been cut down to a minimum due to time constraints of all involved parties. Interestingly engineers clearly voice the need for a knowledge management system as the extensive loss of knowledge in the current system is perceived as disturbing. However, a knowledge management system would not only provide already existent knowledge helping to lower work intensification but could also translate into additional work linked to the necessary regular updating of the documentation and data base.

The output of most of the institutionalized forms of knowledge sharing is collected in Midtronic's two major knowledge databanks that allow access for all engineers worldwide. For engineers from different development centers the presentation slides offer only the raw information in technical terms on how the problem in question was approached, containing only a fraction of the experience based knowledge as the dialogue with the engineers is missing. This is also the main driver why many engineers regard the use of these databases as not beneficial for their work. The specific product focused organization of design centers offers much better and more efficient possibilities for direct personal knowledge access.

Although the concept of re-use is also being propagated in the analog IC design the technical obstacles are far higher than in the world of digital ASICs. The quite low efficiency gains through re-use in analog are pointed out by the fact that to be able to utilize it to some extent the engineer needs to be very experienced. Besides being able to use IP blocks several times, the idea of re-use also implied the ability to employ lesser experienced engineers. Re-use considerations are part of the whole development process at both analog chip companies but there are no stringent re-use guidelines in place that would clearly define a re-use oriented IP block development. However, re-use strategies at Midtronic have a clear effect on the task organization of the particular engineer. On the organizational level the company has set up a company wide IP block library, which is used to check whether similar projects have already produced IP blocks that could be re-used. Most engineers report that such blocks are only used as sources for ideas, not as blueprints that can be dropped into the design. With such an approach re-use libraries become more a way of knowledge sharing allowing the engineer to develop own solutions for the respective problems.

The labor process at Midtronic's CEE design centers involves various forms of structured communication. Many of the non-hierarchical communication situations are used for organizational and knowledge management aims. The degree of communication in the development process is high. However, the three phases of communication point to a very important control strategy most visible on the communication level. The efficiency of development projects is linked to their locality as the complexity of the communication processes that need to be organized can be reduced significantly. Management's ability to both structure communications as well as obtain authority over the labor process and the knowledge produced in it is dependent on the possibility to develop integrated development projects. The development of international interfaces is a very time consuming process that needs both large financial resources as well as the engagement of the involved parties.

Some knowledge management strategies collide at Leadtech with task organization and standard processes of scheduling. Although knowledge management is integrated in the standardized procedures of the development process and are guarded by formalized control mechanisms the regularly tight project schedules collide with the requirements of the development at usage of a globalized knowledge management system. Furthermore, engineers as well local management voices resistance against automated and formalized global knowledge sharing databases as they are perceived as inefficient. The definition of automated global knowledge sharing strategies is the task of strategic top management. Such global strategies often do not take into account the practical implications and problems of implementation of such strategies into a highly time constrained labor process. Aiming at the appropriation of knowledge the strategic focus such global knowledge databases is, at least in parts, reproducing the basic aim of knowledge management strategies. Enabling the reduction of dependence on particular design centers through such databases is following a fault strategy.

5.4.4. Labor market

The local labor market characteristics are an important factor in both upgrading as well as the specific design of the labor process. The relatively lower levels of control, especially through fewer project milestones, are linked to the specific characteristic of the local labor force. The labor market is highly limited for both the company and its employees. This results in long tenures and requires relatively high investments in the recruitment of graduates. Long job tenures allow for the build up of trust which is important for upgrading processes. For the organization of the labor process the reliability provided by long job tenures provides a framing that allows for managerial strategies aiming at higher levels of autonomy. The risk of loosing an important engineer during a development project is minimized, while simultaneously the experience levels of the particular engineers are rising. As upgrading makes locally integrated project teams possible and knowledge sharing is also enhanced. Viewed from the other side, functional upgrading and the development of integrated teams is required to control this low fluctuation as well as to keep motivation of engineers at a high level.

The high levels of commitment visible at the company became apparent during the head-hunting incident (see: Chapter 3.2.2) at Iprov. Although the company raised salaries of experiences engineers considerably the company could not offer the same levels as the multinational companies. However, most of the experienced engineers remained loyal to Iprov. Big gaps in payment levels are a prevalent characteristic in locations integrated into global networks of production and design. Often there are fundamental differences in the payment levels between local companies integrated into GDP or GPN and global companies with local operations, although they all belong to the same sector. Small local companies are the third and lowest category in the payment structures of such globalized localities (for production networks see Lüthje et al. 2012).

The situation on the labor market as well as the lack of financial resources at local universities is facilitating a process of integration between the semiconductor company and universities. This very broad and deep cooperation is a specific form of control as both the labor market as well as the relations on this market are structured by the company before graduates enter it. This is not only enabling the company to organize the labor market favorably for itself, but also to lower the initial frictions when a graduate is starting to work as a young engineer.

The situation of such underdeveloped labor markets make it necessary for the companies to develop and organize their talent recruitment from the bottom. This effort is smoothly integrated as a part of the layered system of control. Companies are able to control the specifics of the engineering training in detail as well as closely monitor potential future job candidates. The ability to provide university lectures through their own engineering experts allows the companies to direct the education towards specialized issues and concepts necessary for, sometimes, proprietary technologies and methodologies used in their very own development process. This of course rising the dependency of the particular engineer, or future engineer, from the company as such highly specialized knowledge is only applicable at the particular company.

Iprov is highly dependent on its staff both due to their long experience of up to 10 years, as well as due to the limited labor market. Simultaneously this very deep experience is increasingly limiting career opportunities for Iprov's engineers as there is no labor market for hardware design engineers in Poland. However, this labor market situation has a decisive effect on the labor process organization as Iprov can draw on the commitment and experience of its engineers without the imperative to establish a closely knitted and organizationally complex control system.

The development of internal labor markets is an important effect and cause for functional integration. To be able to offer engineers a greater variety and depth of careers, the establishment of the managerial career track is very important. However, not all engineers perceive the managerial career, or even any managerial task as a positive personal development possibility. For many the engagement with administrative tasks is only a distraction from their main focus of interest – technical work. But there seems to be a consistent perspective on the managerial career track, as the career path that offers the biggest potential to develop. This view has to be perceived both in term of international division of labor as well as HR dynamics. The technical career only offers sparse career options, as higher engineering positions are still reserved to engineers from central locations. This mostly related to the necessary long year technical experience, which the young locations still lack. Experience levels of 20 years cannot be leapfrogged. Managerial careers, although also dependent on experience, offer more dynamics career opportunities as the fluctuation rate is much higher within this group, constantly opening up possible new positions.

6. Engineering work in the internationalizing semiconductor industry

Chips are at the heart of the current industrial revolution. The steam-engine powered loom and the train as the main symbols of the textile and steel industry were the initial drivers of the first industrial revolution and capitalist development. The car industry with its mass manufacturing ideas tightly connected to the chemical industry's achievements in petroleum technology continued the restructuring of capitalist production and reorganization of work and industries. The development of the first integrated circuit marked the first step towards the microelectronic revolution that started to take off in the 1960s and 1970s with the development of mainframe computers and subsequently microcomputers. Since the 1980s the microelectronic revolution is successively taking over every single aspect of human life from production, to distribution and communication. Chips are reshaping the way how people work, live and play. Chips are also reshaping how industries, not only the electronics industry, are re-organizing. Simultaneously, chips are an important factor in the reshaping of the capitalist geography.

The semiconductor industry bristles with innovation dynamics. All of its aspects, from technology, to spatial and functional industry organization and labor process organization are driven by the constant push towards smaller, faster and more complex electronic systems. However, the technological possibilities described by Moore's Law and its reference to the speed of technology development, are only one major driver shaping the industry. Economics on the sectoral level as well as the global financial and product markets are also major drivers for the almost breathless pace of innovation characterizing the semiconductor industry. The role of labor in this process is sometimes pushed into the background by the overwhelming size of the economics involved and the sheer technological dynamics. However, capitalist development in general, as well as the development of the semiconductor industry in particular is fundamentally linked to labor, its characteristics as well as its often antagonistic relation towards capital. Capitalist development needs labor to perform the necessary actions of production and therefore is seeking to access labor that is fitting its production process both in economical as well as organizational terms. Moving beyond such a concept of labor as a passive factor in capitalist development, it is necessary to analyze labor in its active role as fundamental agent of capitalist development. Labor's resistance both organized and individual is a major force shaping how capitalist production and the broader field of expanded reproduction is organized (Selwyn 2008).

This study set out to provide an analysis of the current state of the semiconductor industry and the work of chip design engineers, both of which are shaped by processes of internationalization. With its long history of internationalization beginning with manufacturing in the 1960s and moving towards product design and technology development in the 1990s, the semiconductor industry is a very good object of inquiry for studies on the development of the international division of labor. This already mature internationalization allows to move the analysis beyond the initial phases of building up new oversea location. With at least partly stabilized relations, such already matured offshore locations experience processes of upgrading that are of most fundamental significance for both the industry organization as well as the engineering labor process. By focusing on engineering work the study aimed at providing a view into one of the more complex parts of the production chain. The analysis of the location where engineering work is being offshored to and also how it is organized in these new locations is of fundamental importance for studies of the international division of labor. Starting with the analysis on the level of the global economy and the industry structure and moving increasingly towards the particular places, the firms and design centers allowed for a constant recalibration of the analysis. This enabled a better understanding of local dynamics within global processes. Only a closer look on work and its organization can allow statements about globalization that go beyond a mere declaration of its existence.

6.1. Sector wide dynamics of triangular restructuring and internationalization

Industries are characterized by a constant shifting of their organization, giving rise to new models of production and distribution. This development is neither smooth nor straight but is often driven by crises. There is never a single best way but a multitude of organizational options exist. The already classical question whether a firm's organizational model will tend towards hierarchies or markets (Williamson 1977) has to be answered almost daily. In recent time networks have emerged as a third category both in the theoretical discussions (Williamson 1985; Granovetter 1985; Grabher 1994) as well as in empirical studies (Lüthje 2001; Sturgeon 1997). These three models are distinct answers to the question of control within the organization of the process of production and distribution. Determining the right amount of control, that allows for an efficient organization, is one of the fundamental factors of economic success. Market competition is unrelenting in its selection of inefficiencies. However, market competition is not fully determining the way how production is organized. While specific models dominate particular periods of capitalist development there always exists a number of deviating production models. These can be remnants of previously dominant models or the nuclei of a future industry organization. The resistance exercised by (organized) labor is another powerful factor in the history of industry organization.

Since the 1970 the dominant model of production in the semiconductor industry was the integrated device manufacturer, or IDM, selling chips to electronic system manufacturers. Companies such as Intel, AMD or Texas Instruments integrated technology and product development as well as wafer manufacturing within their organizational boundaries. This allowed for economies of scale necessary for the production of complex general utility microprocessors as well as memory chips. The relative uniformity of the products did not call for customization that would have driven an overstretching of existent product development capabilities. However, as these products were highly complex both in their development and manufacturing an integration of both activities within an organization enabled steep learning curves on both sides. Mutual learning processes facilitated high yield rates in manufacturing and less errors in design. The increasing spread of personal computers which turned into a wave sweeping companies as well as private homes provided an absorptive and ever growing market.

With the development of the electronics industry markets for more customized semiconductor products increasingly developed during the 1980s. As semiconductor manufacturing matured the interfaces between design and manufacturing gradually became standardized. Companies providing CAD and EDA software based development tools rendered outstanding services to the standardization of these interfaces. As highly specialized companies within the semiconductor industry they offered the technological backbone for the next step of specialization. Chip design houses – fabless companies that were specializing only in the development of customized chips and had no own manufacturing operations – were enabled by this development. Both kinds of companies were mostly located in USA, even more precisely in the Silicon Valley in California. However, across the Pacific a development took place that helped this new model of innovation and production to come to full existence. In the course of its development policy the Taiwanese state had invested in major semiconductor design and manufacturing projects. With the help of international companies from the U.S. and Europe foundations for a local semiconductor industry and research organization have been developed. Out of their follower position Taiwanese companies developed an innovative production model that was going to change the semiconductor industry fundamentally. With TSMC the first foundry was established offering wafer manufacturing as a service to its customers. This was a perfect fit for the developing chip design houses in North America that were now not anymore dependent on the manufacturing overcapacities of IDMs. Within two decades the model of foundry and design house has become dominant in the most dynamic parts of the semiconductor industry.

The rise of the vertically specialized foundry model with its division between manufacturing and development is often analyzed as another step towards an increased market modularity in the electronics industry (Funk 2008; Langlois 2004). However, the development is neither moving towards the market driven model nor modularized networks. Driven by financialization, sector specific economics of exploding costs and levels of technological complexity that require more than simple interface standardization a new model of a network based industry organization is emerging. The links in these very broad networks are based on long term relations and high levels of cooperation countering arguments about forms of modular network organization that allow for quick shifts between suppliers. The complexity of the semiconductor technology together with the enormous capital investment requirements for manufacturing operations are driving the rise of the levels of control. Networks consisting of vertically specialized companies require a controlling instance that has enough power throughout the entire Global Design Network to develop and set standards in cooperation with other companies. Foundries such as TSMC and its competitors UMC and Globalfoundries are increasingly developing integrated networks where they take on the role of lead companies. These networks are both hierarchical and increasingly closed as the lead companies need to secure their capital investments by binding customers through proprietary formats and high service levels. Interfaces between manufacturing and design are often organized as through specialized companies that integrate specific capabilities and have steep learning curves through economies of scale. In the case of TSMC dynamics of vertical re-integration are present, as the company is building up own deep chip design and IP development capabilities. This network structure with high levels of control and integration is paralleled by increased cooperation in technology R&D. Here also costs and risk of technology R&D are being shared in broad networks such as the IBM common platform where major chip companies are cooperating.

Since several years many former integrated chip companies are increasingly moving out of wafer manufacturing. This trend towards fab-light seems to support the assumption that the foundry based production model is becoming the dominant model of the semiconductor industry. However, the development of industry organization is often characterized by the concurrent existence of opposite production models (Lüthje et al. 2012). The semiconductor industry is currently characterized by such a situation. The biggest companies in the semiconductor industry by sales – Intel, Samsung, Texas Instruments and Toshiba – are organized as IDMs. It will be interesting to see what the future will bring for the IDM. Recent developments point to a further deterioration of its existence at least in major market segments of the semiconductor market. Samsung has been offering foundry services for several years already and is willing to move into this market with full force. Intel has announced recently a second foundry customer. Although Intel's aims are not clear, it is at least yet another small but remarkable crack in the IDM front. Qualcomm one of the precursors of the fabless model in the market for mobile chips has entered the top 10 of biggest semiconductor companies. The mobile chips market is currently the most dynamics and important for the semiconductor industry. Its focus on specialized companies such as Qualcomm and Broadcomm has been fundamentally challenged by Apple's organizational model that is favoring the development of proprietary application processors that are the heart of every smartphone and tablet computer. However, this challenge only strengthens the role of foundries. Both Samsung and Huawei, a Chinese manufacturer of network equipment and mobile terminal equipment have announced the development of an own application processor for its future smartphones, successfully following Apple's strategy. The future importance of foundries as providers of technology and wafer manufacturing services seems thus to be on a rising path. Their role as network organizers will become also increasingly important as technological and organizational complexities are rising continuously.

The parallel existence of opposite production models is not only encountered on industry level but sometimes also within one particular company. Texas Instruments has moved completely towards a fab-light model in its digital chips business while clinging tightly to the integrated model for its analog products. The entire analog semiconductor market is characterized by high levels of integration also driven by economics and technology. The costs for analog manufacturing operations are in no way comparable to digital, while efficient analog chip development that is able to meet the necessary high quality standards requires the integration of product development and manufacturing. However, there are already first foundries, IP and design service providers in the market for analog chips. But their future success seems sketchy as major efficiency gains in analog are located in vertical integration. The standardization of interfaces through EDA and CAD software is impeded by the very characteristics of analog chip design, often referred to as black magic. The functionality of analog chips is often linked to highly specific and proprietary process technologies that defy an industry wide standardization.[36] The absence of standardization on these two fundamental levels of industry will impede the vertical specialization of analog chip segment essentially.

It is remarkable, but not surprising, that the role of network organizer is taken over by the manufacturing side, i.e. the foundries. In recent years manufacturing has been seen at most as an appendix to innovation and highly central areas such as product development. Many analyses of the development of the electronics industry saw knowledge work at it center. Knowledge work and innovation was heralded as the most important function and its existence and mode of operation depicted quite detached from manufacturing. The resurgence of the importance of manufacturing for leading edge technology industries poses a fundamental threat for Europe as a location of the semiconductor industry (Lüthje/Pawlicki 2009). As European companies have been moving towards the fab-light and fabless model the interface to manufacturing has been increasingly severed both organizationally as well as geographically. Most of the leading edge manufacturing operations are located outside of Europe bereaving it of fundamental innovation capabilities. Ideas brought forward to establish an European chip company and thereby retain the remaining leading edge manufacturing operations seem too late (Borel 2008). However, by broadening the perspective towards analog chips there are still potentials in the European semiconductor industry. Europe houses major manufacturing operations and product development capabilities of analog chip companies. These European and overseas companies are building their strength in Europe on economies of scope. Markets as well as major companies in the automotive industry and power generation and transmission industries increasingly requiring analog and mixed-signal solutions are located in Europe. The future of major parts of the semiconductor industry lies in these markets. However,

[36] For digital chips the CMOS, or complementary metal-oxide semiconductor, process technology was established already in the late 1970s as the quasi-industry standard.

the role of the state is highly important in industry development. Both by setting standards as well as by organizing the environment for manufacturing and development state agencies can take important steps towards a dynamic European semiconductor landscape. Here a fine line between subsidies and market competition needs to be found that will allow for competitive companies to grow. However, it seems highly important to invest in the future of this industry, to retain what is left of the technological and manufacturing capabilities.

A second dynamic is endangering the future of innovation in the European electronics industry. The vertical specialization and simultaneous re-integration in the electronic industry are driving shifts in the innovation interface that is defining the place where innovation is located both organizationally as well as geographically. On the level of development and manufacturing of electronic systems such as PCs or mobile phones the production model of contract manufacturing has become dominant (Lüthje et al. 2012), with Original Design Manufacturers, or ODM, that integrate product development capabilities becoming increasingly important. Offering fully designed systems and their manufacturing ODM have shifted the innovation interface. Brand name companies driven by financial markets to increasingly focus on core competencies of technology development and marketing are facilitating this shift. As innovation moves towards ODM and contract manufacturers offering product development services, it also moves towards Southeast Asia, as most of these companies have their manufacturing and development centers in this region.

On the chip level similar dynamics are occurring as system companies are sourcing entire solutions from their chip suppliers. Driven by financial markets system companies try to limit their engagements in expensive and risky development projects to central aspects required for product differentiation. As chip technology allows to integrate entire systems on one chip, system companies increasingly require chip companies to provide such systems. From the perspective of system companies they are loosing fundamental capabilities for future product and technology development as their overview of technology dynamics becomes narrower (Brusoni 2003). Chip companies on the other hand are facing high risks as they are entering systems development from the backdoor. Their position within the Global Design Networks is impeding the build up of required contextual knowledge. Developing systems is both changing the development process as well as putting the development capabilities of chip companies to a test as they have to move out of their knowledge domain. These developments are rising the risk within the entire innovation system of the electronics industry. The highest margin within Global Design Networks are not anymore directly connected to the most expensive innovation capabilities, i.e. chip firms with the responsibility to provide solutions. Thus vertical specialization on the level of component technology is driven even further, as technological and organizational complexities are rising.

These rising instabilities in the innovation system of the electronics industry are yet another threat for Europe as location for semiconductors. Proximity to semiconductor manufacturing is growing in importance shifting the focus of chip development further to Asia, as the most important network organizers in the foundry space are located in Asia. Brand name companies are now in a triple bind pulling them towards this region. First, major markets are developing in India and China which are currently the most dynamic worldwide, promising huge growth possibilities. Second, with the rise of the contract manufacturing and especially ODM business model most parts of system manufacturing and increasingly also important segments of system development have moved to Asia. To maintain well functioning innovation interfaces brand name companies from developed countries need to establish development centers in proximity to their highly integrated suppliers. Third, chip companies are shifting their development focus towards Asia to sustain proximity with both markets, customers and foundries. With this the innovation interface of brand name companies for components is also moving to Asia. However, this does not translate into a complete demise of the European electronics and semiconductor industry. There are still many often dynamically growing specialized markets, such as automotive or power generation and transmission. Despite their existence and their manufacturing and development focus on Europe this will not continue to be a stable situation in the medium term. Since 2008 China is the world's biggest automotive market (Ying 2008) and is also advancing in the development of its photovoltaic industry and market. Again it is important to understand the merits of a concerted industrial policy that is both developing internal markets as well as fostering an innovative business environment. In Europe such initiatives have to be coordinated on the level of the European Union which is encompassing a market with sufficient size. However, due to the neoliberal agenda of the last decades it will be very hard to convince policy makers for an active industrial policy that goes beyond framing economic development and moves towards regulatory and direct initiatives.

The concept of triangular restructuring (Lüthje 2007a) enables to integrate the analyzed simultaneous dynamics of vertical specialization and re-integration. A networked industry structure is evolving through the continuous specialization while on particular nodes of the hierarchical network – mainly linked to manufacturing – massive processes of re-integration take place. Yet, the re-emergence of the traditional model of industry organization based on highly integrated firms (Chandler 1977) is not imminent as the network character is despite all of its drawbacks and instabilities allowing for high profit margins for companies located on important network nodes. However, as industry organization is not a straight path leading towards one best solution competing models exists. Samsung Electronics is defying the trend of vertical specialization. The company is developing and manufacturing major components (advanced application processors, memory chips, LED displays) for its highly successful consumer and communication electronics which are designed and manufactured in own operations. In the markets for consumer and communication electronics, semiconductors and LED displays Samsung is a major player. Its fast follower strategy in system development is enabled through both its high levels of integration as well as its technological leadership on the level of electronic components.

Triangular restructuring points to the fundamental shifts in the hierarchical global networks of production and manufacturing. Within the vertically specialized network the manufacturing side is taking on an important role. In semiconductors the manufacturing side or foundries have moved into the center. Roughly speaking, manufacturing is driving R&D. This calls for a broadening of the view on innovation integrating the fundamental importance of manufacturing into its analysis. The massive capital requirements in wafer manufacturing generate a leverage in the industry that is toppling over the alleged exclusive role of small start-up companies in the electronics industry. These are still important to keep up the fast pace of innovation. However, as the highly verticalized industry needs high levels of control the focal point of integrated manufacturing services is growing.

The initial structure of the vertically specializing electronics industry was characterized by dyadic structures, where system companies where cooperating directly with their integrated chip suppliers. The rise of fabless chip design companies and the increasing shift towards fab-light strategies of formerly integrated chip companies has put an end to such simple network structures. Triangular restructuring is driving a form of global networks of production and design where several important and a myriad of second and third level suppliers need to be integrated. Foundries and EDA companies are supplying the technologies to manufacture and design chips while organizing the required interfaces between the participant of a particular network. Contract manufacturers are on the other hand the suppliers of system development and manufacturing services. For brand name companies the development of effective supply chain management capabilities that are able to cope with these increasingly complex structures is important. As the power within these networks is also shifting towards major technology and service suppliers brand name companies are under pressure to organize networks that allow to generate sufficient profit margins.

Triangular restructuring has major implications for the geography and international division of labor in the electronics industry. Processes of upgrading have moved the manufacturing operations in Asia from simple extended workbenches to integrated leading edge manufacturing capabilities. These dynamics on the manufacturing level have come into the focus of public debate at least since the financial market crisis in 2008. Calls for a stop of offshoring of manufacturing jobs flared up once again in Europe and North America. Incidents such as the series of suicides at Foxconn in 2011 have forced a refocus on labor issues in the manufacturing operation in China that churn out millions of electronic gadgets for the developed countries. However, the fact that the innovation interface has moved also towards China while the shifting international division of labor is increasingly integrating also various other previously peripheral regions is still not discussed broadly. But, just like manufacturing, innovation is also being offshored to oversea locations with an increasing speed and a changing quality. What started with simple auxiliary work for design projects has developed into fully integrated engineering capabilities. Product innovation and development is already taking place in these formerly peripheral regions. Upgrading and triangular restructuring have driven major shift in the international division of labor of the electronics industry giving peripheral locations possibilities to move out of their often disadvantaged positions.

The case studies on semiconductor companies in CEE show that very developed design centers exist in this region implementing high level product design and technology development projects within locally integrated project teams. This supports the perspective of triangular restructuring most importantly on the level of international division of labor while accentuating the dialectical relation between the global and the local in the process of internationalization. Global dynamics and strategies driving the internationalization of engineering work are touching down in highly peculiar localities that need to be integrated in the global networks of design. The local characteristics that firms come across in these localities are an important factor in the way how the newly established design centers are being integrated into their design networks. In this way global strategies already anticipate local factors and adapt to them. An obvious major factor is the amount and the quality of the local labor force. However, it is important to analyze internationalization as a dynamic system that is constantly developing driven again by both global and local factors. As newly established design centers mature processes of upgrading can occur that allow for major shifts in the role of the locations. The case studies have shown how upgrading is largely driven by local characteristics. High retention rates of the labor force and long tenures of engineers in design centers in CEE are major factors in the changes within global firm strategies towards these locations. Highly integrated engineering teams are a vivid example of a changing international division of labor. Engineers in CEE are not any more receivers of detailed instructions but develop completely new projects from start to finish, while providing essential technical expertise to other design centers worldwide. Dynamic local characteristics also drive major changes of global strategies. The drying up labor market in CEE forces companies to further embed locally. Various cooperation relations with universities are necessary to ensure enough engineering talent for a smooth future development. Simultaneously, these relations also allow local knowledge communities to develop further.

Design centers with such characteristics and a developing deep local linkages have exposed the limitations of Sachwald's (2008) category of global design centers. Although most of the studied design centers have started out as global design centers upgrading processes have moved them beyond this category. But, these design centers are neither pure home base augmenting nor central or headquarter R&D locations (Kuemmerle 1997). The global design center category pointed to dynamics within the offshoring of engineering work. As internationalization unfolds it becomes evident that for design centers such as those in CEE a new category of integrated globalized design center is necessary. The relative peripheral location is the starting point for such integrated centers. Their main characteristics is the high level of local integration. They feature broad technical and managerial capabilities that enable full project implementation and almost entire project planning and management. As they lack central management capabilities such as sales and marketing they are not able to develop new project fully on their own. With this these integrated design centers are still dependent on the headquarter for specific capabilities. However, the knowledge flows are not any more unidirectional flowing only towards these centers but they are contributing to both product as well as technology development within Global Design Networks.

Sachwald's (2008) global design centers are representing the impetus for a micro-modularization that has been put forward by highly optimistic scenarios of chip design factories (Chang et al. 1999). Advocates of flat world perspective (Friedman 2007) with entirely internationalized project teams have developed the idea of micro-modularization for the entire field of knowledge work. The case studies oppose this analysis and show that when technical and local factors are given such as limited project team sizes and a sufficiently qualified and stable labor force local integration will take place. With this Pavitt's (1999) thesis on the stickiness of innovation work is coming back full circle but with a different angle. Now the stickiness of knowledge and knowledge related tasks is driving offshoring of engineering work as already existent peripheral design centers are being upgraded to utilize their capabilities in full.

6.2. Network position, upgrading and labor process organization

The study of the labor process organization in the case studies has further supported the Global Design Network driven analysis. A GDN driven analysis often states local engineering capabilities as given without delving into the organization of engineering work, by going into the location in question in full to understand how the hierarchies of the design network play out in everyday life. With the labor process framework it is possible to additionally qualify the particular capabilities present in a design center. What is evident is that the labor process in the design centers in CEE is organized to accommodate for the requirements of highly creative and quite independent engineering work. The labor process organization is very often similar to central engineering locations underlining the major developments in the international division of labor. Besides an increasing adjustment of technical capabilities in various design locations the organization of the labor process in the periphery is also developing fast. This will not result in a harmonization of labor process organizations as regulatory, institutional and cultural factors are driving local differences. Despite their obvious local anchoring these insights are useful to inform further research on the factors in the development of the globalized economy. However, it is important to acknowledge that the offshoring of engineering work is not only driving upgrading of capabilities but also of labor process related issues. As with all upgrading these are precarious processes that are ultimately always dependent on the global strategies of companies and their decision and ability to further invest in a particular design center.

One of the main insight of this study is the break down of the relationship between spatial and organizational position within Global Design Networks and the labor process. Friedman's (1977) basic spatial model of differences between central and peripheral labor processes does not suffice anymore to describe and analyze the dynamics and emerging structures of internationalization in the semiconductor industry. Hierarchies within the (international) division of labor have not ceased as particular locations are still assigned with specific tasks. However, the simple division of central and peripheral functions between central and peripheral locations has undergone a fundamental change. As the internationalization of engineering work has matured and processes of upgrading have taken place in the particular design centers central capabilities of product development have been located there. Furthermore and almost more important the particular labor process organizations have been adapted to this situation. This has driven major shifts in the international division of labor making an easy deduction of the character of a particular labor process from its geographic location impossible. Local factors such as labor markets and the stability of the labor force are decisive for the development of a new design center as well as for the evolution of the local labor process. Design centers in peripheral countries such as Romania and Czech Republic house a labor process organization that is comparable to design centers in mature capitalist economies in respect to levels of autonomy, technical complexity of tasks and the organization of project work.

Similarly the connection between the particular organizational position within a Global Design Network and the managerial strategies employed in the specific locations are not directly linked. Suppliers located in peripheral countries as well as design centers of multinational chip companies in such countries are both located in relatively low positions of Global Design Networks. In the automotive design networks chip suppliers are on the second tier working for system suppliers. Although system suppliers in the automotive industry are developing and manufacturing entire systems their primary focus is on car manufacturers with whom they define system specifications. In their negotiations with system suppliers chip companies face therefore much stronger technical and organizational limitations. However, this position in the Global Design Networks does not fundamentally affect labor process organization in the particular design centers of chip companies with normative control as a specific mode of responsible autonomy being prevalent. Technological and local characteristics are the driving factors for this situation. Analog chip design is still opposing a thorough industrialization through automation and high levels of standardization. With an experienced and very stable work force managerial strategies can be developed that utilize the entire knowledge and creativity residing in engineers while lowering organizational costs.

While the position in the Global Design Network is not affecting the fundamental orientation of labor process organization specific aspects of the labor process are determined by this situation. Customer orientation of product development taken together with network position and business model are factors that can impose limits on labor process organization. Generally speaking, limits both technical as well as linked to time frames are always set by the customer, who again can be limited in his specifications by his customer relations, leading into a controlling cascade of contractual commitments. These constraints drive the development of specific aspects of the labor process. Negotiability has been discussed in this study as an integral part of responsible autonomy allowing to integrate essential knowledge from engineers while manufacturing consent through involvement. This specific managerial strategy is superimposed by customer relations as the labor process is constraint by a second limit from outside. As the chip companies of this study are second tier suppliers certain limits driven by customer relations are not negotiable reducing the playing field of the internal negotiability.

On the level of work requests, which is directly linked to negotiability, the superimposition is even more visible. Here certain developed customer relation can shift the labor process towards direct control. Disruptions of work through change requests are a major problem in the development process. The formalized process of negotiability is bypassed as the development process has moved already to the implementation phase. However, change requests can have decisive effects on technical aspects of the project as well as translate into major scheduling problems. Although specific procedures are in place when customer change requests are fundamentally affecting the schedule of a project their enforcement seems often problematic. With change requests overtime is often imposed at least for engineers that are located at the end of the sequential development process. These engineers loose their time autonomy almost completely, as a highly flexible time regime is imposed by change requests. Days without work are followed by weeks of intensive work characterized by overtime and weekend work. With their specific position in Global Design Networks chip companies partially loose control over their labor process as scheduling is driven by intensive and demanding customer relations. With the industry wide changes of triangular restructuring and the shifting of system development capabilities to chip companies through demand for chip solutions this problem is only aggravated. Chip companies are required to manage increasingly bigger and more complex development projects while their network position remains, imposing the illustrated constraints. However, as the increased project complexity calls for broader and deeper knowledge and experience it is not certain that this development will translate into tighter managerial strategies of control.

Comparing Iprov with Leadtech and Midtronic it becomes evident how the process of superimposition of customer relation over managerial strategies is amplified by particular positions within hierarchical Global Design Network. As IP and design service company Iprov is providing highly commodified products and services to chip companies. With this it is residing on a quite low position in the outer zones of Global Design Networks. Despite its labor process organization being based in managerial strategies of responsible autonomy engineering work at Iprov is characterized by many instances of customer and network related effects that trigger strong constraining processes. The imperative to often switch instantly to tedious, repetitive and uncreative tasks related to customer service and support is the most grave example of such superimposition. It is not only obstructing engineering work and constraining the autonomy of the particular engineer but is also impeding the strategic development of the company as innovation activities are constantly put on hold due to customer requirements. This situation was so serious that Iprov re-organized its development process and carved out a new product development group that is almost entirely separated from customer related tasks.

Iprov's position in Global Design Networks and its willingness to upgrade also impacted labor process organization. To be able to enter Global Design Networks as design service provider the company was required to establish and implement a stringent and standardized quality management. With this a process of standardization of the engineering work took place as design methodologies had to be defined and formalized. However, although this is definitely rising the level of control within the labor process simultaneously the company could undertake more complex projects with new design customers. On the level of task originality and variety engineering work has been thus advanced countering the higher levels of standardization and control. The contradicting and complex processes of labor process organization within Global Design Networks need always a close examination to not fall into mechanic argumentation.

Despite perspectives on the extending industrialization of engineering work (Braverman 1974; Schmiede 1996; Chang et al. 1999) through its taylorization, increased control and internationalization the presented case studies have shown quite different managerial control strategies and labor process organizations. Responsible autonomy based managerial strategies constitute major parts of the engineering labor process in CEE. However, as managerial strategies of control are not forming a single and overarching control system but are composed of layers of control that integrate sometimes contradicting strategies through a dialectical relation (Barrett 2004), also other more direct control mechanisms were found. Responsible autonomy, or its subcategory of normative control are providing the control framework within which various control strategies are used simultaneously and often separately. The work organization does by no means resemble a highly industrialized process with detailed and small scale assignments that can be implemented by engineers with little experience. With functional upgrading and the development of integrated design centers engineers have been given the position of technical experts. Their work tasks are broad and the level of technical autonomy high. Aside from limitations through development tools and design methodologies engineers are enabled to tackle the given technical problems in their own ways. Among the most obvious industrialization instruments in chip design are re-use guidelines and knowledge management. Either based on technical limitations or on covert resistance these industrialization drivers are not enforced in design locations in CEE. However, strategies of direct control are also existent stabilizing the system of responsible autonomy. A gradual development of the managerial strategies is evident driven by upgrading as well as workers' resistance.

The processes of triangular restructuring are increasingly shifting system development capabilities towards chip suppliers. These sector wide dynamics are driving the requirements for system knowledge and contextual knowledge at the level of chip companies. Local integration is important in the development of necessary contextual knowledge that enables the understanding of highly formalized objective knowledge. This insight is especially important in the general discussions on the offshoring of knowledge work. The discussed frictions in international teams through cultural differences are only too often misleading. By focusing on undeniable cultural differences an ahistorical perspective of offshoring and international cooperation is assumed. In such a perspective specific capabilities are given and almost no dynamics, besides cultural learning, are evident (Mahadevan 2007). The solution then is focused on the development of a better communication through growth of the density and breadth of communication. However, the fundamental problem is being overlooked, although it is directly linked to communication. Frictions in international teams due to necessarily highly detailed work instructions are often connected with lack of contextual knowledge and experience at offshore sites. The development of contextual knowledge is directly driven by higher levels of local integration as engineers learn more and more about the entirety of the development process and the product. The location of architectural engineering positions, such as concept engineers, further increases local technical as well as organizational insights. Upgrading dynamics are driving the development of skill sets and experience thus allowing for contextual knowledge to develop to such levels that frictions within international teams are reduced massively. Only when talking at eye level engineers can easily cooperate on complex issues across distances. Frictions in international teams then are much more the result of highly hierarchical divisions of labor than cultural differences. Culture merely obscures fundamentally structural problems.

Knowledge generation and knowledge management are dependent on and also in parts driving functional upgrading and shifts in the labor process organization. Within a system of micro-modularization where single engineering teams have various locations knowledge sharing needs to be organized on a daily basis with elaborate methods and instruments. With locally integrated product teams, requirements for knowledge sharing across the organization and spatial distance is decreasing. The most effective knowledge databases have a localized and bottom-up characteristic. This does not exclude global knowledge databases, but makes their utilization a contingent process. While data input is relatively easy to monitor, the use of these databases in engineering work is neither the norm nor readily controllable. Even formalized processes to access knowledge databases cannot guarantee an effective utilization of such global databases. Here again the very peculiarities of analog chips come into play. Re-using existent knowledge stored in global databases is not easy as the particular specifics of the process technology, functionality and context dependence come into play. To be able to anticipate possible implications on these three levels engineers need to be experienced and will need to re-design major parts. With this, knowledge sharing methodologies such as re-use loose their fundamental impetus to enable the employment of less experienced engineers driving down costs.

Labor process based autonomy in the internationalized labor process seems to become a fundamental factor of success in the development of Global Design Networks. However, this is the result of a longer process where the gradual development of appropriate managerial strategies is driven by various factors. Upgrading is playing a decisive and complex role in the evolution of the labor process. Local factors such as labor markets, labor fluctuation attitudes as well as workers' resistance are the other major driving forces behind the development. It is important to perceive the development of the labor process not as driven by upgrading processes but to view these processes as co-evolving in a mutual interdependence that is defined by both global strategies and local characteristics. On the other hand the control imperative (Thompson 1983) is existing in every capitalist labor process despite its levels of knowledge and experience necessary for the particular tasks. The offshoring of engineering capabilities to new design centers only rises the control imperative as in addition to issues related to a particular labor process, organizational issues with interface design and the overall division of labor need to be established, stabilized and developed. The complementary division of labor with its high levels of control is consequently often an appropriate strategy for the initial phases of offshoring. As upgrading processes take place simultaneously the labor process is developed to accommodate for the rising technical demands and responsibilities formulated towards engineers. Technical, managerial and innovation capabilities are gradually built up at new centers through functional upgrading. The localization of various technical and managerial capabilities allows to refocus specific aspects of the labor process organization. As central management is learning about the various technical and organizational capabilities of the new design center trust is being build up that again allows to shift control more towards responsible autonomy, to enable a labor process required for increasingly complex and experience based product development. However, the development of the labor process in conjunction with upgrading is not only a process driven by management's strategies. Workers' resistance is a fundamental factor shaping important characteristics of work organization. Most importantly resistance against rigid and extensive monitoring processes are often in the focus of engineers.

In the intra-organizational Global Design Networks of Leadtech and Midtronic upgrading and network position are linked in a complex process that can be analyzed as essential in the organization of the labor process. Functional upgrading and the development of integrated teams are the initial steps to establish an effective labor process, in which responsible autonomy is setting the tone and various strategies of direct control are used to stabilize it and anchor control in particular areas. The localization and co-location of most important technical as well as major managerial functions allows to reduce international interfaces governed by standardized processes. This opens up areas of autonomy where direct communication between local engineers is developing while standardized and formalized procedures are not required. With this possibilities to access engineering creativity are raised as well as motivation through more complex projects and technical responsibility is enabled. High management costs of implementing highly standardized and formalized interfaces are lowered, while engineers are not required to invest too much time on the necessary development of stabilizing informal relations. Simultaneously, integrated development centers allow for direct personal control measures that are necessary to bolster the high autonomy levels and are perceived as less intrusive and coercive. Administrative tasks directly linked to monitoring and control can be organized differently, relieving engineers at least partially of these tasks and enabling them to focus on their technical responsibilities.

While functional upgrading develops the preconditions for an effective control system that tends towards responsible autonomy, processes of product upgrading are necessary to establish essential technical prerequisites for a good functioning of this system. Satisfying the intrinsic interest of engineers in working on complex technical problems and solutions is a fundamental factor in the establishment of consent in the engineering labor process. Integrated engineering teams that focus only on derivative projects, or projects of low complexity will develop resistance practices, that can disable an effective development process. Motivation of engineers is important to be able to rise efficiency and productivity in particular design centers. To keep up motivation, rising the technical complexity of development projects is much more important at Midtronic's and Leadtech's design centers in CEE than offering managerial career tracks. Even in not too dynamic local labor markets, changing employers is an important resistance practice. This strategy is a way for the individual engineer to develop his career through experience accumulation and broadening of technical specialization. To evade such a situation and establish a stable and working labor process functional upgrading has to be coupled with product upgrading. While functional upgrading establishes the role of an technical expert through rising the level of independence, product upgrading acknowledges this role by offering appropriate development projects.

However, the development of locally integrated development teams is not a mechanic process of functional adaptation. Local factors play a decisive role in this process. Appropriate regulatory frameworks and institutions are necessary to provide stability and fundamental resources. The characteristics of the local labor market as well as labor force are most important in shaping the process of upgrading. The stability of the labor force coupled with the increasingly narrowing local labor market generate localized pressures on the strategic focus of the respective design center's development. The accumulated engineering experience is translating into localized technical and organizational capabilities that can be put to use by the companies through upgrading. To be able to keep their engineers the companies need to locate increasingly complex development projects in CEE. Simultaneously, these local characteristics also drive the specific labor process organization. The integration of local engineers into product development as experts shifts their role from passive to active participants. To fully access their technical and organizational expertise management needs to rise the autonomy of engineers. This development is driven also by resistance from engineers that use their role as technical experts as leverage.

Functional and product upgrading driven and directed by local factors are co-developing with the extension of managerial strategies based on responsible autonomy. Integrated design centers are a fundamental step towards the establishment of certain levels of negotiability in the labor process as necessary functional structures are developed. While negotiability is correlated with higher levels of autonomy it is also driving specific skill set dynamics as it is putting a higher focus on subjective capabilities of engineers. How an engineer is able to position himself within the process of negotiating schedules depends on highly individual capabilities. The double movement of functional and product upgrading facilitates both more complex systems of control and labor process organization as well as dynamics in engineering work that drive technical complexity perceived as positive by engineers. Yet, it is not definite which process is triggering the dynamics, as functional upgrading can be the necessary solution for problems of control, commitment and motivation. The causal correlation is not determinable from the data in this study. However, as we see throughout the entire study the effects of a dialectical process between local and global a clear answer to this question seems not possible. The important insight is that upgrading processes are not solely driven by strategic decisions of cost cutting and proximity to customers or markets. The capitalist imperative to organize the labor process efficiently and profitably by asserting control over it through appropriate managerial strategies (Thompson 1983) is also an important driver in processes of upgrading. Workers' resistance continuous to be an important factor in the development of labor process organization even for highly qualified technical experts such as engineers.

Upgrading is a process that is both requiring and building trust at the same time. This predicament is mostly resolved through a successive development of the international division of labor within Global Design Networks. Within the labor process and the relations between engineers from different design centers trust is essential for knowledge exchange. Besides personal contacts and face to face relations organizational stability is of fundamental importance for the development of trust. Insecurities about the future of central design centers are jeopardizing the build up of trust towards engineers from peripheral locations. Withholding knowledge is a major method of resistance in the internationalization of engineering work. An international division of labor based on integrated and product focused design centers that are not competing against each other, is fundamental for engineers to cease such resistance practices. Such a situation facilitates the exchange of knowledge focused more on technological aspects across product boundaries. Trust is a major factor forming central management's perception towards new design locations. Functional upgrading cannot guarantee that both local management and engineers will be able to deliver the expected results. Locally integrated design centers initially are only responsible for low-risk designs. Upgrading on the product level is only possible when local technical, managerial and organizational capabilities have proved successful and trustworthy.

Supplier relations, especially on the lower positions of the Global Design Networks where many silicon IP and design service companies operate, are stabilized by trust and continuity. The fundamental idea of silicon IP was an almost seamless integration of the various building block provided by competing IP suppliers. However, despite highly standardized on chip interfaces IP sourcing companies cannot blindly rely on the quality of silicon IP as the projects at risk are too big. To ensure a working system chip companies need to set up complex verification processes for their sourced IP. Another strategy is to establish long term relations to IP suppliers so that enough trust can be build up to lower the amount of necessary quality checks. The concept of modularity based on a fast substitution of suppliers is shifted towards a more stable network character, where also highly standardized and commodified parts of the network apparently are experiencing a deeper integration.

What becomes visible on the levels of work, firm and network is that trust is a central aspect of internationalization. As the international division of labor is developing beyond simple structures of command and complementarity towards a more integrated and systemic character trust is both the driver and the resource stabilizing and helping to further develop relations and positions within the ongoing triangular restructuring of the industry. On the industry level this emerging characteristic is further rising entry barriers for start-ups and small companies. In addition to economic factors now also other capabilities play an important role in network entry and as long term relations are increasingly important new and small companies that do not have the necessary resources at hand are kept at a distance. On the firm and work level however the rising importance of trust and the stabilization of relations is a very positive development. Labor processes are developed further towards higher levels of autonomy while competition between different locations is often constrained. There is no guarantee for the latter development within Global Design Networks. However, as upgrading in engineering work is also often connected to wage rises in peripheral locations, the competitive disadvantages of central design centers is at least lowered. From these conclusions, it becomes evident that there is a major area of future research focused on the role of trust in processes of internationalization and upgrading.

Sector wide developments of vertical specialization and integration are driving shifts in the innovation model of the electronics industry as system developing companies are increasingly consigning major parts of system development to chip companies (Lüthje 2007a). This restructuring process on the sectoral level affects also upgrading dynamics and labor process organization. The increased localization dynamics, through functional and product upgrading in the various design centers in CEE, is driven also by the need to increasingly develop local system knowledge and capabilities. The architectural positions located in recent times in CEE further drive dynamics of local labor process organization as they require even higher levels of autonomy both on a work as well as control level. But also on a broader level upgrading is continuously taking effect on the development of the labor process organization. Product upgrading is now becoming the major driver of these developments as increasingly complex projects are located in the development centers. With this, local engineering work is moving towards even more creative parts of IC design, while task variety and task originality are increasing. So called innovation projects are requiring a more open control structure as contingencies are rising. This will not translate in the complete abandoning of direct control managerial strategies. As we have seen these are of fundamental importance to secure and anchor the layered system of responsible autonomy. However, the labor process organization will be developed further as the international division of labor is becoming more complex. Upgrading and labor process dynamics fall together to drive the development of the international division of labor that is putting the previously relative simple system into question. By taking into account labor process organization this study enabled a characterization of the development of international division of labor within Global Design Networks in detail, showing how upgrading and control are co-developing. The local and the global are intertwined in complex ways calling for an analysis that tries to transgress both top-down and bottom-up perspectives in favor of a more integrated view of internationalization.

7. Annex

7.1. Interviews at Midtronic

Number	Location	Sex	Function
1	RDC	m	Test Engineer
2	RDC	m	Leader of Test Group
3	RDC	m	Manager of Modeling Department
4	RDC	m	Chip Design Engineer
5	RDC	m	Chip Design Engineer
6	RDC	m	General Manager of Design Center
7	RDC	f	Layout Engineer
8	RDC	m	Sr. principal Device Engineer
9	BDC	m	Project Leader
11	BDC	m	General Manager of Design Center
12	BDC	m	Analog Project Leader
13	BDC	m	Analog Project Leader
14	BDC	m	Analog Group Leader
15	BDC	m	Analog Design Engineer
16	BrDC	m	Design Manager
17	BrDC	m	Human Resources Manager
18	BrDC	m	Design and Layout Engineer
19	BrDC	m	Project Manager

Table 6.3: Interviews with employees at Midtronic Czech Location A (RDC) Location B (BDC) in Slovakia (BrDC)

7.2. Interviews at Iprov

Number	Location	Sex	Function
1	IP	m	Product Manager / Design Engineer
2	IP	m	Product Manager / Design Engineer
3	IP	m	Design Manager / Design Engineer
4	IP	m	Department Manager
5	IP	m	Post-Sales Support Manager / Design Engineer
6	IP	m	Senior Verification Engineer
7	IP	m	Manager of Pre-Sales Customer Services / Design Engineer
8	IP	m	Marketing Manager
9	IP	m	CEO

Table 6.1: Interviews with employees at Iprov Poland (IP)

7.3. Interviews at Leadtech

Number	Location	Sex	Function
1	BuDC	m	Senior Analog Design Engineer
2	BuDC	m	Department Manager
3	BuDC	m	Analog Layout Engineer
4	BuDC	m	Test Engineer
5	BuDC	m	Program Manager

6	BuDC	m	Digital Design Engineer
7	BuDC	m	Product Engineer
8	BuDC	m	Concept Engineer
9	BuDC	m	Department Manager
10	BuDC	m	General Manager for Design Center

Table 6.2: Interviews with employees at Leadtech Romania (BuDC)

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