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MASTER THESIS

Management of Technology

Investigating Project Complexity at NXP Semiconductors B.V.

An exploratory study based on the TOE framework

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Make everything as simple as possible, but not simpler.
Albert Einstein, physicist

Simplicity does not precede complexity, but follows it.
Alan Perlis, computer scientist

Executive Summary

Keywords: *semiconductor industry, projects, project management, case study, complexity*

In high-tech industries, projects play a central role in the development of new products and processes. Since these projects can be quite complex, it would be useful to look at where complexity in projects comes from and how these complexities influence these projects. The research project described in this thesis aims to increase the understanding of this topic in a company in the semiconductor industry, NXP Semiconductors. Products that are produced in the semiconductor industry play an increasingly important role in our lives. Products ranging from mobile telephones to cars to lighting are all equipped with semiconductor products and the performance of these products is steadily increasing with time. Therefore, the development of these products and the processes, which are needed to produce the products, are becoming more complex.

The research project To describe the complexities that are encountered in the process engineering industry, a framework (the TOE framework, where TOE stands for Technical, Organizational and External) was developed earlier. The TOE framework consists of 47 elements (which are categorized into the three aforementioned categories) that describe aspects that can contribute to a project's complexity. To understand the complexities that are encountered in the semiconductor industry, this research project has applied the TOE framework to this industry. The goal of this research project is twofold: firstly, it aims to understand where complexities in projects in the semiconductor industry come from; secondly, it would be useful for the company if the company would be able to understand which complexities could play a role in a future project and this could be used to come with the right measures to cope with these complexities.

The main research question that this research project aims to answer is:

What benefits does the application of the TOE framework provide for projects at NXP?

This question is answered by doing a combination of desk research and case studies on projects in the company. In the desk research phase, the current practice related to development projects at NXP is investigated and a tool is described that calculates the design complexity of a new product design: Numetrics.

Case studies To understand what complexities play a role in NXP projects, 16 projects have been investigated. The projects that are studied are from a wide variety of departments within NXP, but all projects (except for one) involve development of a new product or process. From each project, one person (the project manager) was interviewed. During the interviews, these project managers were asked to explain what the project entailed, which complexities were encountered during the projects, what influence these complexities had on the project and how the project managers coped with the complexities. The project managers were asked to indicate too which degree the complexities in the TOE were applicable to the project and if any complexities were missing in the framework. The complexities in the TOE framework that scored highest on the TOE scoring list are:

- Involvement of different technical disciplines
- Technical risks
- High project schedule drive

- Level of competition

These high scoring complexities reflect the image that development projects in the semiconductor industry require multidisciplinary teams, that technical risks are often high (since it is not always known whether certain solutions will provide the required functionality), that there is high drive to develop new products quickly and that there is a high level of competition on the market.

Next to the complexities that are directly related to the TOE framework, interviewees were also asked to share their views and experiences with the Numetrics system. A number of observations and recommendations with respect to this system are presented in this thesis.

Adaptation and application of TOE From the original TOE framework, five elements were considered to be not applicable to the projects by the interviewees. These elements are not present the adapted version of the TOE framework for use at NXP. The interviewees also indicated that a number of complexities were missing or not precisely enough described in the TOE framework. In total 13 elements are added to the existing framework (4 technical, 5 organizational and 4 external elements). These adaptations lead to a new version of the TOE framework, that is modified to meet the situation at NXP. A preliminary version of a score chart is made, on which a project manager can indicate which complexities could be present in a project that is under planning. However, further research would be needed to successfully implement the application of TOE in practice. A possible way of applying TOE would be to use a similar approach that is taken by Numetrics – a tool that is currently being used at NXP to assess the design complexity of product developments. Since the relevance of Numetrics is limited to product development projects, the TOE approach would have an added value by also addressing other types of projects, such as process developments.

Next to the version of TOE that is adapted to meet the needs of NXP, a suggestion is made for the inclusion of four new elements, which were the result of the case studies that were performed in this research project.

Conclusions The research project shows that the possible application of the TOE framework could have benefits for NXP. As the case studies show, complexities can have a large influence on the project's execution and success. Therefore, a tool that can assess the complexity and sources of complexity of multiple types of (development) projects would be of value to the company.

Recommendations Towards the company, a number of recommendations are given. Firstly, although the BCaM framework is of much value to the company, one of the outcomes of the interviews was that the time between gates can be quite long. This can have a negative effect on the focus in the project team and including more steps into the system would increase the focus in the team. Secondly, we believe that the implementation of TOE in the planning phase of projects can add value by giving the project manager insight into the types of complexities that are expected to be encountered in the project under planning.

Contents

Chapter 1

Introduction

Complexity is a phenomenon that has been studied increasingly in multiple scientific fields in the past few decades (Erdi, 2008). This research is aimed at investigating project complexity, in particular in the semiconductor industry (in particular at NXP Semiconductors B.V., the company in which this research project was executed). This thesis reports on the research that has been done on this topic, as part of the master thesis project for the degree Management of Technology at Delft University of Technology.

To give the reader an overview of the context in which this research project was executed, a number of subjects are introduced in this chapter. The first section provides an overview of complexity science, what it entails and which research has been done on this topic. In the second section, a more extensive view on complexity in projects is given. The third section introduces the semiconductor industry. Finally, in the fourth section a short synopsis is given of the thesis.

Complexity science

Everyone has their own idea of complexity, but what is complexity exactly? Despite - or thanks to - the inherent vagueness of the concept, complexity received a lot of attention in a large number of fields (Solomon and Shir, 2003). To be able to do sensible research on the topic, a workable definition of complexity is needed. Some recurring properties of complex systems are: *emergence*, *indeterminacy*, *nonlinearity*, *interrelatedness* and *dynamics* (Cooke-Davies et al., 2007). To understand what we mean with these terms, a short description of each term is given below:

- *Emergence* is the phenomenon where the aggregate properties of a system cannot be deduced from the behaviour of the single components of which the system consists. In other words, the output of the system is different from the total sum of its components.
- Complex systems are *indeterminate* in the sense that the outcome of such a system is not always clear on beforehand. This goes against the mechanistic or Cartesian world view, which states that when all initial conditions are known, the future evolution of a system is known for all time.
- *Nonlinearity* means that the outcome of a system is not linear, in the sense that a system's response with respect to its input is sensitive to small changes in the input (e.g. the famous "Butterfly effect").
- *Interrelatedness* in a complex system means that the components of the system cannot be seen apart from each other, which makes a reductionist approach of understanding a complex system a hard task.
- *Dynamical* systems are systems that are not time-invariant, i.e. the properties of the system change over time.

Complex systems are studied in many scientific disciplines, both in natural science (such as mathematics, physics, chemistry and biology) as in social science (psychology, sociology, economics, managerial science) (Solomon and Shir, 2003; Stacey, 1995; Anderson, 1972). Due to the interdisciplinary nature of the concept of complexity, there are almost as many definitions of complexity as there are studies on it. One of the first descriptions of complex systems was given by H.A. Simon, in which Simon discusses four aspects of complexity in complex systems: complexity in the form of hierarchy; the evolution of complex hierarchical systems; the dynamic properties of dynamic system and the ability to subdivide these systems into subsystems; the relation between complex system and descriptions of these systems (Simon, 1962). Another view on complexity is given by Stacey (1995), who related complex systems to strategy processes in firms: next to the existing views of strategic choice (in which firms determine their own path, *"adaptation through choice"*) and ecology (in which the environment determines the faith of the organization, *"adaptation through competitive selection"*) a third view exists: complex adaptive systems. Because of a number of properties of these systems (such as positive feedback and emergence), the outcome of strategic processes cannot always be found out deterministically.

In the context of the development of complex technical products, a definition was introduced by Hobday (1998): Complex Products and Systems (CoPS). Examples of these complex products and systems are technical systems that are developed uniquely (i.e. not in mass production), such as bridges and semiconductor fabrication equipment. Since CoPS often consist of multiple subsystems that need to work together, the architecture of the system plays a large role (Henderson and Clark, 1990).

To cope with complexity, a number of approaches were developed by different disciplines (Hobday et al., 2005): for the design and development of complex technical systems, systems engineering was developed by engineers; on the other side, managers developed new tools for the management of projects in which these systems were developed. For an overview of the history of systems engineering, project management and operations research see for example Johnson (1997).

One of the approaches to understand complex entities is the systems engineering approach (Hitchins, 2007). Systems engineering was developed to study the behavior of (complex) systems as a whole (holistically). This is done because Cartesian reduction does not always provide a way to understand the behaviour of a complex system (since the outcome of a complex system is more than the sum of its parts, due to emergent behaviour). Although systems engineering was initially developed to solve engineering problems (of which one of the most appealing engineering challenges would be aerospace projects, such as the Apollo project), it has also found its way to the business world (Hitchins, 2007).

Complexity in project management

In the context of project management, a number of authors have reviewed the literature on complexity and project management (Baccarini, 1996; Remington et al., 2009). Baccarini (1996) recognizes different sources of project complexity, namely organizational complexity and technical complexity. In each form of project complexity, complexities due to *differentiation* (meaning that complexity comes from the many parts of a system) and due to *interdependency* (meaning that different parts of a system have a certain degree of connection) can be identified. Complexities related to the organization have to do with the organizational structure of a project, i.e. the way the project is organized. Complexities related to technical aspects are, as the name implies, related to the actual contents of the project. Another view on complexity in project management is given by Remington et al. (2009). The authors of this paper identify four dimensions of complexity: *structural*, *technical*, *directional* and *temporal* sources of complexity. Each of these dimensions has a certain severity in a project, and together they determine the complexity of the project.

Shenhar and Dvir (1996) and Shenhar (2001) give a typology of engineering projects in two dimensions: system scope (the extent of the system under development, i.e. the place in the hierarchy going from an assembly to an array) and amount of technological uncertainty (from low-tech to super high-tech). This typology is also used by Hobday et al. (2005), to extent this framework to the CoPS concept.

Williams (2002) gives a description of complex project management from a systems engineering point-of-view. The use of system dynamics allows the modeller to implement certain characteristics of complex projects into a project model, which can aid in planning the project or in risk management. Cooke-Davies et al. (2007) go back to the fact that project management emerged from a Cartesian type of reductionism, but notes that there are certain characteristics of complex project that make this reductionist approach problematic.

There are several (complementary) descriptions of project complexity. Bosch-Rekveldt et al. (2010b) give an overview of different definitions of project complexity. In the mentioned article, a third dimension of complexity is added to the complexity framework of Baccarini, namely complexities that are caused by the environment. These three aspects of complexity (technical, organizational and environmental) together form the TOE framework (where the acronym stands for the sources of complexity). The TOE framework is described in more detail in the next chapter, where the context of the research problem is investigated further. Hobday (1998) also introduces a breakdown structure of project complexities that can occur in (technical) projects.

The semiconductor industry

The semiconductor industry is a relatively young industry, since active semiconductor devices were discovered relatively recently: the first semiconductor transistor was developed in 1947 at Bell labs (Jenkins, 2005). Since then, developments have gone so rapidly, that in the modern world life without semiconductors is almost unimaginable. For example, a history of the evolution of microprocessors and the market for these components is given in (Tredennick, 1995).

Semiconductors are - as the name implies - materials that conduct electrical current moderately, but are not completely resistive. By injecting low concentrations of other atomic species (so-called dopants) into certain parts of the semiconductor, the local conductivity of the semiconductor device can be adjusted. In this way, engineers have the possibility to design devices which can perform a multitude of tasks. By integrating several active and passive components in a single device, the integrated circuit (IC) was developed. The best-known semiconductor is silicon. The word "silicon" is often used as a synonym for semiconductor devices or related technology.

The large-scale production of semiconductor devices became profitable in the 1960s and this allowed for the creation of the semiconductor industry (Walsh et al., 2005). Since then, semiconductor devices have exponentially increased in complexity. This has even put into a law-like form, by Gordon E. Moore in 1965 (Moore, 1965). In this "law", Moore stated that the number of components in an integrated semiconductor device double approximately every two years. This prediction has held until today.

However, not only the amount of transistors per chip is important. For some applications, it is paramount that chips do not fail under any circumstances (for instance the electronics that control the working of automobiles or medical applications). Other chips need to be able to work under harsh circumstances or have special requirements regarding the amount of power they need to be able to operate in combination with high frequency operation.

Although semiconductor products are produced in mass production (and therefore cannot be considered CoPS in the strict sense (Hobday, 1998)), the development of these products has a number of parallels with the development of CoPS: often, the development of these products is a unique endeavour. In some cases, products are developed that are derivative products of a "platform", but in many other cases, the product under development requires completely new design and architecture. Therefore, the development of new semiconductor products can be quite complex. In fact, complexity and uncertainty (and the ability of companies to cope with these) is directly related to the success of R& D (that is, the processes in which new technologies are developed and applied to create new products) (West, 2000). In another article, West and Iansiti (2003) observe that two processes are responsible for the accumulation of new knowledge in semiconductor industry R& D: experience and experimentation. These processes are subsequently coupled to particular company strategies which could strengthen each of these processes.

West (2000) identifies three processes in semiconductor industry that give rise to an increase in complexity, uncertainty and risk: firstly, the increasing product complexity also leads to increasingly complex production processes: since more process steps are necessary to produce a product, the chance of failure in one of these steps also goes up; Second, since semiconductor devices often operate near the limits of what is physically possible, it is often unclear what the maximally attainable performance of a semiconductor device is, so this increases the uncertainty about what the possible performance of a device is at the start of the development; thirdly, increasingly complex production processes require production facilities that are increasingly complex and therefore increasingly expensive. The increased capital costs for these production facilities give rise to an increased investment risk.

Because of a number of properties of the industry, an interesting parallel can be drawn between the semiconductor industry and another industry: the pharmaceutical industry (Lim, 2004). Although these industries produces products that are quite different in nature, there is an important similarity: the costs of research and development are high and the unit production costs are low. On top of this, both basic and applied research play an important role in R& D activities in both industries.

In the semiconductor industry, project management is applied extensively to develop new products or processes, or perform other tasks. Since new technologies are developed rapidly in the semiconductor industry, the execution time of projects is of critical importance. An insight into the complexity of projects would provide valuable knowledge towards the efficient and effective execution of projects.

Thesis outline

The thesis has the following structure:

- In the problem definition chapter (chapter 2), we give an overview of the context of the research problem, the research objective and research questions, and a section is dedicated to the scientific and managerial relevance of the research project. Finally, the deliverables of the research project are presented.
- In the chapter on research approach and methodology (chapter 3), an overview is given of the methodology that is going to be used to execute the research project. The research approach is explicated and the actual research methods that are used are elaborated upon. Also, some attention is given to the different aspects of validity of this research project.
- The chapter on projects at NXP (chapter 4) aims to shed light on projects and project management at the company. This is done by analyzing current practice in project and looking at the way complexity is currently being monitored and controlled in the company.
- The empirical research that has been done on project complexity at NXP is described in chapter 5.
- To understand the findings of the empirical research and extract useful information from it, chapter 6 reports on the analysis of the empirical data, and the application of it to an existing framework for project complexity.
- Finally, conclusions are drawn in chapter 7 from the research that has been done, the findings are discussed and suggestions are given for further research on the topic.

Chapter 2

Problem Definition

The research problem that is under investigation is introduced in this chapter. Firstly, more context is given to the research problem, to motivate the reason for doing this research project. Secondly, the research objective is stated and the research questions that are to be answered in this research project are introduced. Thirdly, the deliverables of this research project are presented. Fourthly, the relevance of this research project, both scientifically and managerial/societal, is given. In this section, the research gap that this research project aims to look at is further expanded on.

2.1 Research problem

This study is concerned with identifying project complexity in the semiconductor industry, in particular at NXP Semiconductors. The TOE framework Bosch-Rekveldt et al. (2010b) provides the basis for doing research on project complexity in this research. This framework has been developed at the faculty Technology, Policy and Management of Delft University of Technology. TOE was originally developed in the process engineering industry. It would be interesting to test this framework in different industries, for instance in the semiconductor manufacturing industry. Several other research projects have been executed or are in progress to investigate project complexity in combination with the TOE framework in other areas of business, for instance in maintenance projects (Wentink, 2010) and IT projects (van Helvoort, 2011).

2.1.1 The TOE framework

The TOE framework (TOE stands for Technical, Organizational, External) was developed to structure different aspects of projects that are related to the complexity of projects (Bosch-Rekveldt et al., 2009, 2010a,b). In this framework, a distinction is made between three categories of factors that make a project complex. These factors have been found by literature research and empirical research. The empirical research was done by interviewing professionals from the process industry. The framework, based on engineering projects in the process industry, consists of 47 elements, of which 17 are technical, 16 are organizational and 14 are environmental (Bosch-Rekveldt et al., 2010b). The elements that constitute the existing TOE framework are presented in table 2.1 and are further explained in appendix A. The forementioned article identifies three categories of elements that contribute to the complexity of projects. These categories are technical, organizational and environmental. Each of these categories will be shortly discussed next.

Technical Aspects

As was defined by Baccarini (1996), technical aspects of project complexity are related to the technical contents of a project. Sub-categories within the technical aspects are: goals, scope, tasks, experience and risk.

Organizational Aspects

Organizational aspects were also defined by Baccarini (1996), where organizational aspects are related to the context in which the project is executed within the organization. Sub-categories within the organizational aspects are: resources, project team, trust, risk.

External Aspects

External (or environmental) aspects were not explicitly defined by Baccarini, but they are a part of the TOE framework. These aspects are related to the environment of the project. Sub-categories within the environmental aspects are: stakeholders, location, market conditions and risk.

Technical Complexity	Organizational Complexity	External Complexity
Number of project goals	High project schedule drive	
Non-alignment of project goals	Lack of resource & skills availability	Number of external stakeholders
Unclarity of project goals	Lack of experience with parties involved	Variety of external stakeholders' perspectives
Uncertainties in scope	Lack of HSSE awareness	Dependencies on external stakeholders
Strict quality requirements	Interfaces between different disciplines	Political influence
Project duration	Number of financial sources	Lack of company internal support
Size in CAPEX	Number of contracts	Required local content (forced cooperation with local parties)
Number of locations	Number of different nationalities	Interference with existing site
Newness of technology (worldwide)	Number of different languages	Weather conditions
Lack of experience with technology	Presence of JV partner	Remoteness of location
Number of tasks	Involvement of different time zones	Lack of experience in the country
Variety of tasks	Size of project team	Company internal strategic pressure
Dependencies between tasks	Incompatibility between different project management methods/tools	Instability of project environment (exchange rate, oil price, raw material price, etc)
Uncertainties in methods	Lack of trust in project team	Level competition
Involvement of different technical disciplines	Lack of trust in contractor	Risks from environment
Conflicting norms and standards	Organizational risks	
Technical risks		

Table 2.1: The elements of the version of the TOE framework, that was used in this research project (Bosch-Rekveldt et al., 2010b). The TOE framework is based on research in the process industry.

2.1.2 The semiconductor industry

In the introduction chapter, a short introduction was given of the semiconductor industry. In this section, the economic aspects of the industry, the different sectors within the industry and related industries are discussed. In 2010, the total revenue of the semiconductor industry amounted to $ 304 billion (Ford, 2010). This amounted to an increase of revenue of 32.5%, from $ 230 billion. The geographic distribution of companies, ordered by revenue in 2010, is shown in table 2.2. The location of a company is determined by the location of the company's headquarter.

Semiconductor products can be characterized in a number of ways. One characterization is to distinguish between the type of data the chip handles. In principle, there are three types of devices: digital,

Region	Percentage
Americas	48.5%
Asia-Pacific	21.5%
Japan	21.0%
Europe, Middle-East and Africa	9.1%

Table 2.2: Geographic distribution of companies' headquarters, by revenue. The largest share in revenue is made by companies, based in (North-) America, but Asia (including Japan) follows closely.

analog and mixed signal devices (the latter type combines the handling of both analog and digital signals). The industry can also be divided into different applications of the semiconductor products, such as data-processing applications (such as NAND[1] and DRAM[2]), automotive applications, wireless communication applications, CPUs (Central Processing Units, the primary processing unit of a computer) and image sensors. Some companies have specialized in one type of semiconductor device, others manufacture chips for a multitude of applications.

Arita and McCann (2002) give an overview of the different activities that are needed for the development process of a semiconductor. The development of a new chip consists of three stages:

1. The first stage of this process entails the design of the chip. In this stage, the functional logic is determined and the transistor circuits are designed.

2. In the second stage, silicon "wafers" (thin slabs of very pure silicon) are processed by lithograpic techniques. These lithographic techniques "write" the desired structures onto the silicon base layer, which provide the desired functionalities of the chip.

3. The third stage involves "dicing" the circular wafers into much smaller rectangular chips, which are then further processed for the particular application of the chip.

How many of these process steps are carried out by a single company (i.e. the degree of *vertical integration*) varies between different companies of different sizes. For example, there are companies that only make chip designs (step 1 in the process) and have these designs made into physical products (steps 2 and 3) by other companies (companies that do not design chips themselves, but manufacture products for other companies are called *foundries*). Other companies integrate all process steps and manufacture the chips inside their own production facilities (factories where chips are manufactured are also called *fabs*). Wafers often have standard sizes, ranging from 1 inch (25.4 mm) to 300 mm in diameter. The smallest structure that can be made with a certain lithographic technique determines the possible sizes of elements in the chip. According to the International Technology Roadmap for Semiconductors[3], the current (2011) limit is 22 nm, roughly the size of 200 atoms. In this research project, one semiconductor company will be studied, namely NXP, which has its headquarters in Eindhoven, the Netherlands. NXP operates world-wide, with its main locations in Europe, Asia and North-America. In the next subsection, this company will be further discussed.

2.1.3 NXP

This research project will be carried out at NXP Semiconductors B.V. NXP is a producer of semiconductor products, which operates worldwide in several markets[4]. In terms of revenue, NXP was the number 17 producer of semiconductor products worldwide in 2010 (Ford, 2010), with a revenue of $4.4 billion in 2010. As was described in the preceding subsection, semiconductor products can be divided into a number of categories. NXP is specialized in developing and fabricating High Performance Mixed Signals (HPMS) products. The company consists of four business units (which are responsible for developing new products in their application area) and several supporting organizations. We will shortly describe the company structure (although this is not a complete overview, only the parts of the company that are relevant to this research are shown in detail).

[1]Short for Not-AND, a type of flash memory
[2]Dynamic random-access memory
[3]`http://www.itrs.net/`
[4]More information about NXP can be found on the company website, `http://www.nxp.com`

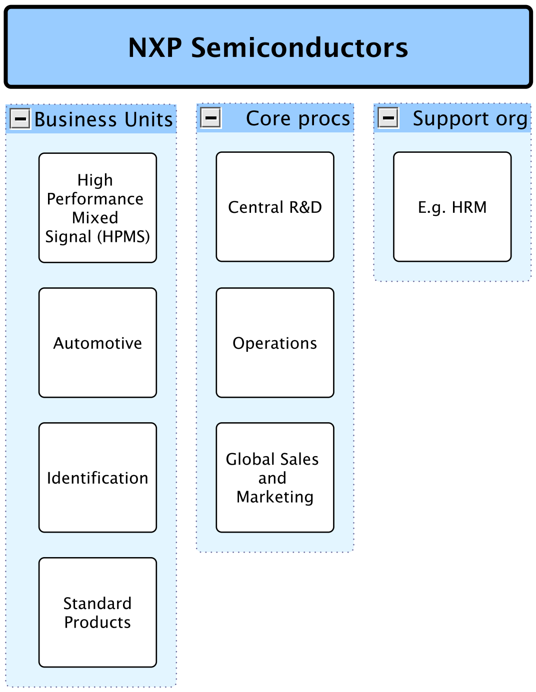

Figure 2.1: A schematic overview of the organization of NXP. Not all support organizations are shown in this figure, but these organizations are not subject to this research project.

As is shown in figure 2.1, the company is divided business units, core processes and support organizations. The four business units, Automotive, High Performance Mixed Signal, Identification and Standard Products are responsible for creating new products. To assist the business units and to develop new concepts, a central R&D department is present. The (mass) production of products is the responsibility of the operations department. Several other department play supporting roles within the organization. The business units are further divided into business lines and product lines that specialize in certain areas within the scope of the business line.

Within NXP, projects are distinguished in different types and hierarchies, these types and hierarchies are further explained in chapter 4. The project management framework that is used at NXP is called BCaM (Business Creation and Management). For each business line, the product development process needs to comply with the BCaM framework, although each business line or product line can adapt the BCaM framework to meet its needs, as long as it is documented well. Project managers are being trained according to the principles of the Project Management Institute (PMI [5]) with PMP (Project Management Professional) certifications. Chapter 4 provides further explanation on the structure of the BCaM framework and on how it is used at NXP.

2.1.4 Numetrics

A tool is used at NXP to assess the complexity of a future chip design. This tool, called Numetrics[6], is used to assess the (design) complexity of semiconductor product development projects. A project manager can enter characteristics of the design project that he is managing into a system, which then gives an impression of the degree of complexity of the project. In principle, the Numetrics model can be used for planning a project (by entering the information before the project is executed) or for benchmarking of the project (to assess the performance of the project team and to compare the project to other projects). This benchmarking does not need to take place after the project is finished, Numetrics can also be used to benchmark a project schedule to projects in the Numetrics database (to assess whether certain aspects of the planning are comparable to other projects). This approach is called *schedule risk*

[5] http://www.pmi.org
[6] http://www.numetrics.com

analysis. Section 4.2 will provide an in-depth discussion of Numetrics, and in particular how it assesses the complexity of a design project.

2.1.5 The research gap

In the context of this research project, it would be interesting to compare the TOE framework to the Numetrics approach. Since the Numetrics approach mainly takes into account technical aspects of project complexity (and in particular the complexity of the *design*, note that this is not the same definition of technical complexity as is defined in the TOE framework), the TOE framework could provide interesting opportunities to expand knowledge and awareness on complexities that are associated with projects. This can be interesting for the company, since project complexity can have an influence on project success (Bosch-Rekveldt, 2011). A second research gap that this project aims to address is the difference in project complexities between different industries. Since this research project is limited to a single company in a single industry, it only partly provides the knowledge needed to fill this research gap. To be precise, in a single *high-end manufacturing* industry, which means that that products developed by one company differ significantly to products developed by another company, as opposed to bulk production industries, where there is not such a big difference between products from different producers.

2.2 Research objective and questions

The objectives of this research project are the application and matching of the TOE framework to project complexities at NXP. This research project aims to show how the TOE framework potentially can be adapted to cover the complexities that are found in projects at NXP. To be able to fulfil the objectives of this research project, a number of research questions have been formulated. The questions consist of a main question and supporting sub-questions.

Main question

The main research question is:

What benefits does the application of the TOE framework provide for projects at NXP?

Sub-questions

To be able to answer the main question, a number of sub-questions have been formulated. Not all questions can be considered research questions, in the sense that answering these questions generates new knowledge. However, answering these preliminary questions is essential to be able to answers the other research questions. Therefore, we have defined a zeroth sub-question, which is in fact not a research question, but a necessary step in the research.

0. *What characteristics define projects and project management at NXP?*
1. *Which factors play a role in the degree of complexity of typical projects at NXP?*
2. *What possibilities does Numetrics provide to model and manage complexity?*
3. *How is Numetrics currently being used at NXP?*
4. *How does the TOE framework potentially need to be adapted to meet the needs of NXP?*
5. *How can the TOE framework be applied at NXP to help managing project complexity?*

2.3 Deliverables

The main deliverables of this research project are a thesis, in which the research project is described and findings are presented, and a complexity framework which could be suitable for use at NXP. Next to this, a suggestion is made for the extension of the general TOE framework on the basis of the empirical finding of this study.

2.4 Scientific and managerial relevance

The research project has to be of importance for both the university as the company. Therefore, aspects of this research project that are beneficial to these parties are elaborated upon in this section.

Scientific relevance

From a scientific point of view it is interesting to see in which manner complexity differs between projects and between different sectors. By executing related projects in different sectors, one can see how the framework can be applied in general. This research project could contribute to the total research effort that tries to understand project complexities in different areas, and in particular in the context of the application of the TOE framework to different industries (Bosch-Rekveldt, 2011). At this moment, the TOE framework is solely descriptive in nature, i.e. it only identifies the project complexities that are present in executed projects. The research gap that this project is hoping to fill is the possible application of the TOE framework at NXP.

Managerial relevance

For the company, it is interesting to see what causes complexity in projects, so this can be taken into account and dealt with in the future. The outcome of this research project should result in a comprehensive framework to identify project complexities. This should increase the understanding of these complexities and in principle this could lead to increased project success. The improved understanding of aspects that lead to increased project complexity can also help in selecting the right project manager for the right project, by matching particular characteristics of the project managers to the demands that the project imposes on the project manager.

Since Numetrics is currently being used to assess the complexity of new product development projects, it would be interesting to look at how Numetrics defines complexity and how knowledge about complexity is used in practice. Firstly, the research looks at the difference between the possible use of Numetrics and the actual use of Numetrics. Secondly, by comparing the TOE framework to Numetrics, the strengths and weaknesses of each approach can be assessed. The application of the TOE framework to the current practice at NXP aims to raise awareness on what exactly constitutes complexity in projects. This could potentially benefit the company by enabling the company to identify complexities and anticipate on the influence that these complexities have on these projects and on project success.

Chapter 3

Research Design and Methodology

To get from the definition research problem to the actual execution of the research, the research needs to be designed and the right methods need to be chosen. In this chapter, the research design and methodology is further elaborated upon.

3.1 Research design

To reach the research objective that was introduced in chapter 2, a main research question was formulated, together with a number of sub-questions. The answer to these sub-questions should provide sufficient information to answer the main question. In table 3.1, the research questions that were introduced in chapter 2 are related to the type of knowledge that is needed to answer the question, the research method that is appropriate to answer the respective question and finally, in which chapter of the thesis the questions are answered. The types of research that are mentioned in the title are based on (van der Velde et al., 2004). Next to the short overview that is given in table 3.1 and the research framework that is depicted in figure 3.1, we will shortly discuss the sub-questions, how these questions relate to each other and how the questions are operationalized:

- By answering the zeroth sub-question, we try to understand how projects are managed at NXP. This is done to understand the context in which projects are managed and to provide a starting point for the case studies that are performed at a later stage in the research project. Together with the second question, this question will be answered by desk research (consulting both internal documents and relevant scientific literature). The answers to the zeroth and second question provide the starting ground for the empirical part of the research.

- The first sub-question follows from the zeroth sub-question and its aim is to understand the complexities that are encountered in projects at NXP. The answer to this question should provide insight in how well the existing TOE framework coincides with complexities that are encountered at NXP and which complexities are missing in the existing framework. Together with the fourth research question, the answer to this question should come from empirical research at NXP. To get a broad overview of projects that are performed at NXP, projects with several characteristics are chosen to be studied.

- The second sub-question is aimed at understanding the possibilities of Numetrics and how this system should be used at NXP (in other words, this sub-question is related to the way Numetrics should be used in theory, i.e. the *soll*-question related to Numetrics).

- The third sub-question is also related to Numetrics. However, the aim of this question is to understand how Numetrics is actually being used at NXP (the *ist*-question). This question relates to the second sub-question, part of the objective of this sub-question is to see what the discrepancies are between the intended use of Numetrics and the actual use.

- By answering the fourth sub-question, on the basis of the empirical research that is performed, the TOE framework is extended and adapted to meet the requirements that were found in the case

RQ #	Type of research	Research Method	Chapter
0	Descriptive	Archival research/literature studies	4
1	Descriptive & exploratory	Case studies	5
2	Descriptive	Archival research	4
3	Descriptive & exploratory	Case studies	5
4	Exploratory	Case study analysis	6
5	Exploratory (& Prescriptive)	Case study analysis	6

Table 3.1: Overview of research questions an appropriate research methods.

studies. The needed knowledge to answer this question are the answers to the first sub-question (the aspects that contribute to project complexity) and the second sub-question (the project complexities that are identified by Numetrics).

- Finally, in the fifth sub-question, we take a first look at a possible application of the TOE framework at NXP. This questions follows naturally from the fourth sub-question, since it applies the findings of this sub-question to the current practice at NXP. Since the time that is available to this project is only limited, this step will probably only be a first step towards a mature implementation of the TOE framework. Therefore, the "prescriptive" classification of this research question is put between brackets in table 3.1.

The combined answers to these sub-questions should give us enough indications for the possible benefits of applying the TOE framework at NXP, in order to understand project complexity.

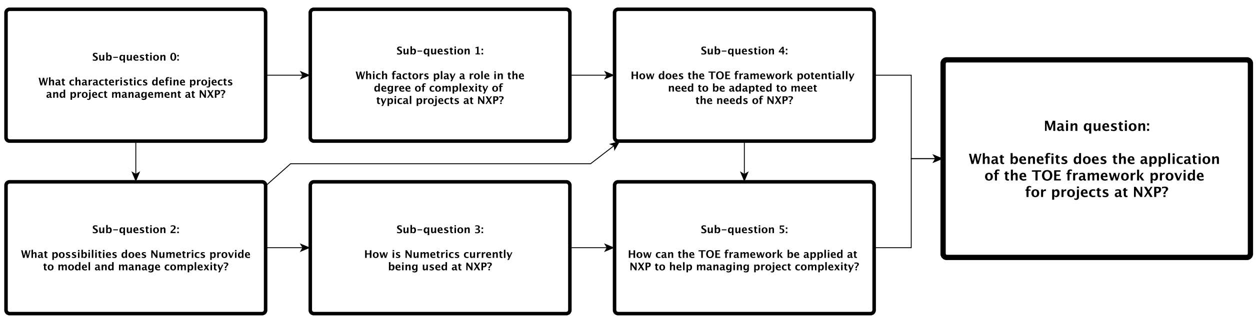

Figure 3.1: The organization of research questions in this thesis.

3.2 Methodological background

In the preceding section it was made clear that this research project is divided into two parts: a part in which existing scientific literature and internal documentation is used to study the context of the research project and an empirical part, in which current practice at NXP is under investigation. The research methods that are associated with these two parts of the research, desk research and case studies, will be discussed further in this section. Next, the different aspects of research validity are discussed and the restrictions of this research project are identified.

Desk research

Desk research is defined by Verschuren and Doorewaard (1995) as a research method, in which no primary research is done, but where one makes use of existing publications. In this research project, it will mainly consist of literature study. The literature study will be performed to study the context of this research project, to get a better understanding of the the cases that will be studied in the empirical part of the research. The literature that is studied is a combination of scientific literature on projects and project management in the semiconductor industry in general (where databases of scientific literature are used, such as Scopus[1] or ScienceDirect[2]), and internal company documents, which describe the particular practice at NXP. Because probably not all knowledge about the current practice at NXP that is needed for this research project will be available in documentation, experts at the company are consulted to also get an overview of the non-codified information.

Case studies

For the exploratory part of this research project, case studies will be performed. We have chosen for case studies as the research strategy to do the empirical part of the research, because we are studying a contemporary real-life situation on which the researcher does not have a strong influence (Yin, 2003). This kind of research environment, in which the researcher does not have a strong influence is also called a *natural experiment* (Diamond and Robinson, 2010). Since the nature and amount of data to be collected does not lend itself for statistical analysis, the data will be analysed on the basis of reasoning. Also, the research questions that we aim to answer are qualitative nature. These combined properties make a case study approach to the research more appropriate than other types of research, such as surveys, (laboratory) experiments or historical (archival) research (Yin, 2003; Diamond and Robinson, 2010).

The unit of analysis Yin (2003) of the case studies will be an NXP project (we will later clarify which class of projects is selected to be studied). Since we would like to have a broad overview of the different projects that are executed, we would like to treat a large number of cases. Because of the limited time that is available for this project, this means that only one person per project is interviewed, which means that a larger number of cases can be studied than when multiple persons are interviewed per project. The downside of choosing one person per project is that this one person might not give all the needed information about the project that is necessary to fully answer the research questions. Therefore, the person that is being interviewed should have the most extended knowledge about the project of all the actors that are involved in the project.

By having a broad overview of the projects that are executed at NXP, we should be able to identify certain characteristics that might be unique for a particular project or characteristics that can be generalized for a certain category of projects. In the terminology of (Yin, 2003), the method of choice will be a multi-case holistic case study. Multi-case should be self-explanatory and holistic means that there is only one unit of analysis per case (i.e. a project is seen as a single case in the case study). It would be interesting to see how different cases differ from each other, caused by different variables (which variables are present should become apparent through the research). After the interviews have been conducted and worked out, the result will be sent back to the interviewees for feedback. This way, we can be more certain that the right information came across and this confidence should improve the quality of the end result.

A number of project managers at NXP was asked to participate in this research. Each of these project managers is responsible for one project, and interviews were held with a project manager concerning a single project. Taking into account the limited time and resources that are available for this project, 16 cases are studied in this research project. This number of cases to study is chosen, because it provides a good balance between sufficient broadness of the research project (the ability to do an analysis between projects with different characteristics), sufficient depth (so enough information is gathered about each project to draw conclusions about each project) and the available time to execute the research project.

To execute this research project, we were given the possibility to do the research at NXP Semiconductors B.V.. This allows us to study real-life examples of projects that are done in the semiconductor industry. Because NXP is a rather large company, products that are developed at NXP are fairly diverse in nature. This allows us to analyze the differences between different products from different business lines.

[1] www.scopus.com
[2] www.sciencedirect.com

Because of the exploratory nature of the research, the interviews that will be performed will be semi-structured (van der Velde et al., 2004). This way, there is more opportunity to explore new knowledge than in a structured interview. We are not choosing for completely unstructured interviews, because it is important that different cases can be compared to each other and to make this possible, the structure of the different interviews should be similar throughout the whole set of interviews.

Validity and limitations

This section discusses a number of aspects of validity: construct validity, internal validity, external validity and reliability (Yin, 2003; Cook and Campbell, 1979):

- Construct validity is concerned with the choice for the right operational measures to study the subject of the research project(Yin, 2003). The construct validity in this research project is safeguarded in a number of ways. First, by performing interviews with people that are directly involved in projects, the researcher has the ability to be more flexible in posing questions, compared to a questionnaire. The researcher is able to directly react to information the interviewee provides, enabling the researcher to uncover knowledge that had not been foreseen beforehand. Secondly, by studying multiple projects and interviewing multiple project managers, the researcher is able to cover more projects than when multiple persons per project are interviewed (and therefore, a smaller number of projects is considered). This will give us a broader overview of the projects that are carried out. By looking for saturation in the data (i.e. if the addition of more data does not introduce any new information), the researcher has the ability to assess whether the information that is gathered is complete. Thirdly, by getting feedback on the worked-out version of the interviews, the chance of misunderstanding or drawing of the wrong conclusions is decreased.
- Internal validity is not that relevant for this research project (Yin, 2003), since it is of descriptive and exploratory nature and it does not aim to establish a causal relationship between independent and dependent research variables. This is because the research variables were not established a priori, but these should be found through this research project.
- External validity is concerned with the generalizability of the study's finding. In this research project, this means that the sample of projects that is to be studied needs to be chosen carefully to represent the category of projects that this research project aims to investigate. Because the research is carried out in one company (NXP), the results will in general not be generalizable to the whole sector. To make this generalization, projects at other companies have to be studied, but this is outside the scope of this research project. To be able to generalize the study's findings to NXP projects in general, the cases that are selected need to be selected carefully to give a general overview of projects or the class of projects that are executed within the company.
- Reliability of the research entails that the results of the research project are reproducible for other researchers. This is ensured by careful reporting of the case studies, so the executed research is reproducible; by recording the interviews, so other researchers can check if the measured data has been properly analyzed; and by getting feedback from the interviewed experts, so it is made sure that the gathered information is correctly understood by the researcher.

There are several limitations associated with this research project. Firstly, the research is done in one company, so the findings of this research are not necessarily generalizable to other firms in the same sector. Second, only a limited number of cases can be investigated, so there is always the possibility that certain complexity factors are overlooked or that other complexity factors are overrepresented. Careful case selection should minimize the latter limitation as much as possible.

Chapter 4

Projects and Project Management at NXP

To gain insight into the way in which projects are managed at NXP, this chapter investigates the current practices. In the framework of this research project, this chapter aims to answer the zeroth and second sub-questions. To answer these questions, this chapter will first address projects in general (using scientific literature), and secondly the current practice at NXP (using internal information from the company).

This chapter also functions as a funnel, delineating the exact subject of our research (e.g. the type of projects that is to be studied), towards the case studies.

4.1 What characterizes NXP projects?

The Project Management Body of Knowledge (PMBOK) defines a project as:

"A project is a temporary endeavor undertaken to create a unique product, service, or result."
(Project Management Institute, 2008)

Two adjectives in this definition are crucial to consider, namely *temporary* and *unique*. The temporary nature of a project means that a project has a definitive beginning and ending. The uniqueness of a project means that a project entails an activity that has never been done before.

Related to this, project management is defined as:

"Project management is the application of knowledge, skills and tools, and techniques to project activities to meet the project requirements."
(Project Management Institute, 2008)

Because of the unique needs (although is has to be noted that the degree of uniqueness differs between different projects) for each new product that is developed at NXP, the project approach is appropriate for product development. As was noted in chapter 2, several types of projects are defined within NXP. The different project types and hierarchy between projects is explained in the next section. This research project will mainly focus on projects that are involved with the development of new products or processes.

Activities that are concerned with the selection and execution of projects that lead to the creation of new products (the so-called Product Creation Process, or PCP) are formalized in a framework, that is called Business Creation and Management. Because this framework plays a central role in activities that are concerned with projects at NXP, the next section explains this framework. Next to this, projects are subjected to a number of constraints. These constraints are discussed in the section on project features and constraints. How these constraints lead to project drive is discussed in the section after this. Which actors are involved in projects and how these actors interact is elaborated in the section on organizational aspects.

4.1.1 Business Creation and Management (BCaM)

The framework that is used at NXP to manage the product creation process is called BCaM (which stands for Business Creation and Management). The BCaM framework is used to make sure that the product creation process is performed consistently throughout the whole company. The product creation process consists of three stages, or core processes. There are four sub-process areas. In figure 4.1, the BCaM framework is shown schematically. In the following part of this section, we will present a simplified summary of the building blocks of the BCaM framework.

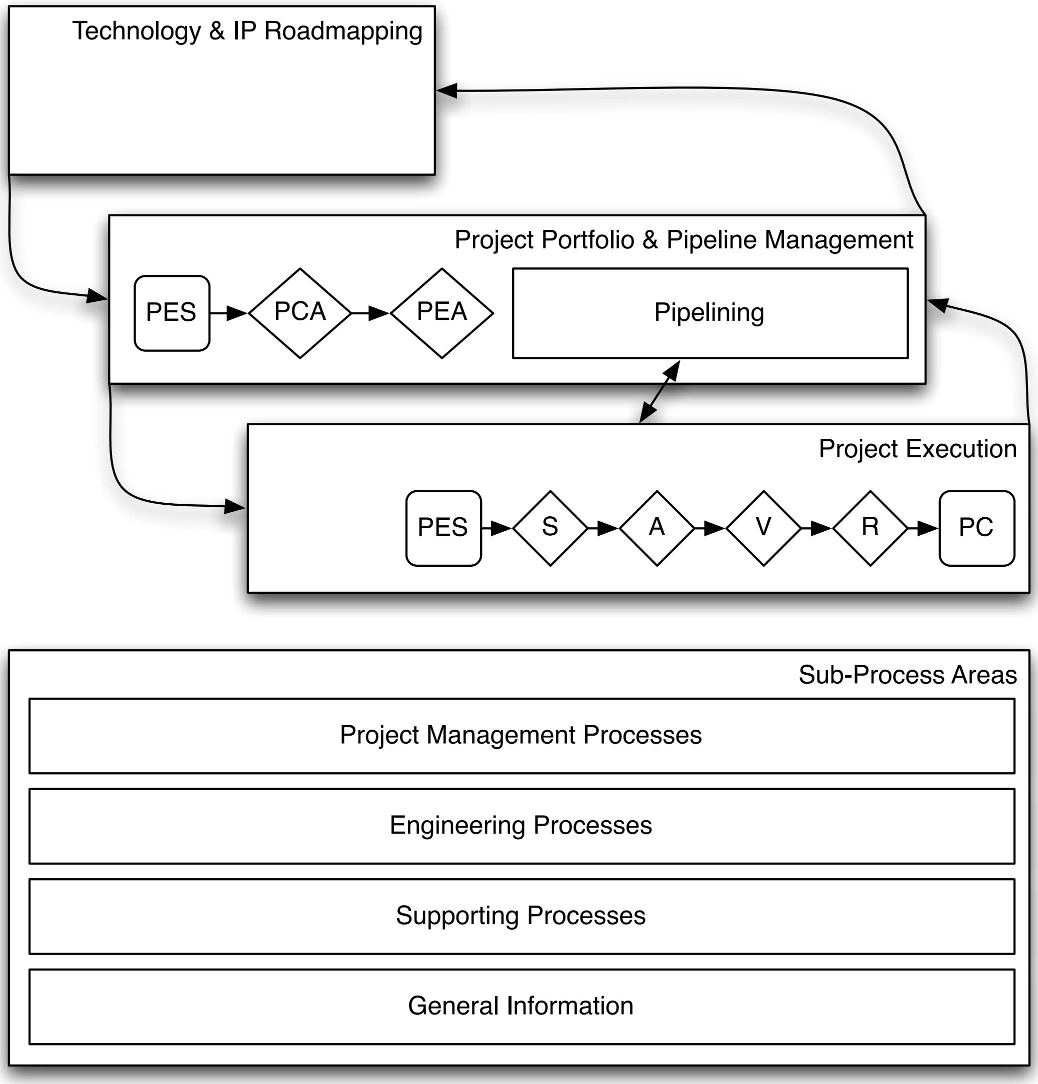

Figure 4.1: A global overview of the BCaM framework.

As can be seen in the figure, the three core processes are: Technology & IP Roadmapping (TIR), Project Portfolio & Pipelining Management (3PM) and Project Execution (PE). Technology & IP Roadmapping takes place at the highest level in the organization. Portfolio & Pipelining Management happens on the Business Unit level. Finally, Project Execution happens on Business Line level. The decisions that are made at a higher level, provide the constraints for the choices that can be made on the lower level.

Technology & IP Roadmapping

The Technology & IP (Intellectual Property) Roadmapping (TIR) stage is the highest level in the BCaM framework. It is concerned with the linkage and constraints of different roadmaps in the organization (NXP, 2010). A roadmap is a high-level description of an eventual outcome of a business activity. Seven different types of roadmaps are distinguished: *function & feature* roadmaps, *competence* roadmaps, *research* roadmaps, *technology* roadmaps, *intellectual property (IP)* roadmaps, *system* roadmaps and *product* roadmaps.

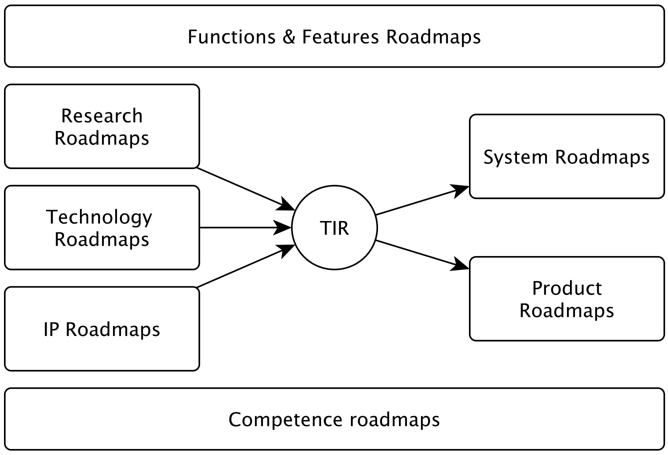

Figure 4.2: A schematic overview of the Technology & IP Roadmapping (TIR) process.

The goal of Technology & IP Roadmapping (schematically shown in figure 4.2) is to make a connection between *research* roadmaps, *technology* roadmaps and *IP* roadmaps on one side, and *system* roadmaps and *product* roadmaps on the other side (ten Have, 2010). In other words, TIR assists in going from concept to a product that can be launched onto the market. The other roadmap types, *function & feature* roadmaps and *competence* roadmaps are requirements on the whole process going from (basic) research to a completed product. These last two roadmap types are also called *underpinnings*, since they are to be taken into account throughout the whole TIR process.

Project Portfolio & Pipeline Management (3PM)

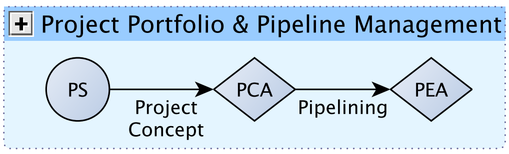

Figure 4.3: A closeup of the Project Portfolio & Pipelining stage.

The second stage in the BCaM framework is Project Portfolio & Pipeline Management (3PM). This stage is concerned with making sure that approved roadmaps are implemented into a portfolio of projects and that this portfolio is managed efficiently and effectively (Gerards and Weeks, 2008). A second aspect of 3PM is the resource pipeline, in which the available capacity is matched to the needs of the different projects in the portfolio. The 3PM stage consists of several sub-stages and milestones (Gerards and Weeks, 2008). Figure 4.3 shows the global structure of this phase and table B.1 elaborates on the different milestones, gates and phases of this stage. Although the above picture indicates that the 3PM stage ends at Project Concept Approval, the project keeps being monitored and controlled (the pipelining process continues to allocate resources to projects, also to projects that are already in the execution phase).

Project Execution

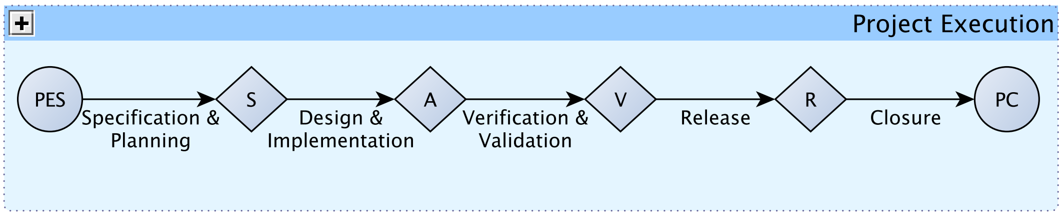

Figure 4.4: A closeup of the Project Execution stage.

The third and final stage in the BCaM framework is the actual execution of the project: the Project Execution (PE) stage. In this stage, the actual project is executed, on the basis on the project concept and resource allocation (Bulsink, 2008a). The main goals of the project execution stage are to fulfil the project goals, to increase the predictability of the project outcome and to achieve consistency in the Time-to-Market of a project. In figure 4.4 and table B.2, the structure of the project execution phase is explained and a short overview is given of each element in the diagram.

During project execution, two processes can be distinguished: project management processes and engineering processes. Tasks that are involved with project management are: project planning, project monitoring and control, risk management, and supplier agreement management. Tasks involved with engineering are: requirements engineering, verification & validation, review & inspection, design engineering, and industrialization.

The PE stage also consists of a number of sub-stages and milestones. The usual milestones, gates and phases of the project execution phase are described in table B.2. Under special circumstances, other phases and gates can be added to the project execution phase, when this is needed (e.g. a gate that determines whether mask-making can start in an IC development project).

An interesting measure that is used in the project execution phase is the *Project Scaling Factor*, which is determined during the project planning phase. In this factor, the *product risk* [1] and *project risk* [2] of the project are assessed. There is a mapping from the risk types that are defined in the PMBOK(Project Management Institute, 2008): technical risks, quality risks and performance risks are mapped onto product risks and project management risks, organizational risks and external risks are mapped onto project risks. For both dimensions, there are three possible levels of risk (low, medium and high) and combining these risks in a matrix gives a value for the project scaling factor. The value of the project scaling factor has for example consequences on certain deliverables that have to be produced at certain gates and milestones.

Sub-Process Areas

The sub-process areas of the BCaM framework (see figure 4.1) are shortly described. In contrary to the three stages in the BCaM framework, these processes are carried out throughout the whole product development process (the particular duration of a sub-process differs between different sub-processes and in general these processes overlap each other in time). Because the final sub-process area (General Information) is not directly related to individual projects, it is not further discussed in this section.

Project Management Processes: Processes that belong to this area are related to the management of the project. The four defined project management processes are discussed in table B.3.

Engineering Processes: Processes that belong to this area are related to the engineering aspects of the project. The three defined engineering processes are discussed in table B.4.

[1] Risks related to the nature of the product.
[2] Risks related to the nature of the project, structure and organization.

Supporting Processes: Supporting processes are processes which are not directly related to project management or engineering activities, but which are important to succesfully execute the project. The four defined supporting processes are discussed in table B.5.

Project types and hierarchy

Within the BCaM framework, several project types and hierarchies are distinguished.

Several types of projects that are distinguished at NXP. These types of projects differ in a number of characteristics, such as the degree in which a project fulfils a particular demand and the type of end product of the project. A short description of these types is given next (from (Kot, 2008b)):

Studies
"A detailed investigation that leads to a report or conclusion, such as architecture proposal, requirements gathering, or feasibility studies. Should resolve large unknowns."

Implementation
"Delivering a sellable product, its components or items that may support the creation, development or sales of a product, such as demo systems, training material, processes and tools to aid the development of products."

Design-in
"Collaboration with a customer to incorporate an existing product into the customer's environment."

Maintenance and Support

Other
Projects that do not fit into the other categories, e.g. improvement projects.

The different hierarchy levels that are distinguished at NXP are (from (Kot, 2008b)):

Program
Highest level, a set of strongly related projects (which do not need to be delivered at the same time). The main purpose of a program is to align projects that are part of the program. Consists of one or more projects.

Project
Characterized by the fact that all deliverables need to be delivered at the same time (e.g. a product). May (but not necessarily) consist of one or more sub-projects or work packages.

Sub-project
Consists of a large part of a product, which is used for further integration into the project. Part of a project

Work package
Delivers a small part of a product or component for further integration. Can be part of a project or a sub-project.

Each hierarchical level has its own level of responsibility, and therefore the principal of each hierarchy level also is of a different level (e.g. a program manager leads a program, and a project manager leads a project).

4.1.2 Project Performance and Constraints

It is a well-known fact from project management literature that a project is subjected to a number of constraints to meet its objectives (see for example (Oisen, 1971)). Typically, these constraints are: *schedule*, *cost* and *specifications* (sometimes quality is added as a fourth, integral constraint or sometimes it is included in the scope). These interrelated concepts are sometimes called *The Iron Triangle* or *The Spring Model*, because in principle, changing one of these constraints influences the others.

In theory, a perfect project is finished on time, within budget and satisfies the requirements that were developed at the start of the project. In practice, controlling these variables all at once is a daunting task. This subsection describes how NXP acts to control these three variables.

Schedule

The schedule relates to the time that is available to execute the project. To create a good schedule, a planning tool is needed. To do this, the BCaM framework provides a project planning mechanism, the so-called Planning & Tracking Cycle (the elements in the cycle are further explained in table 4.1). In figure 4.5, the tool is schematically shown.

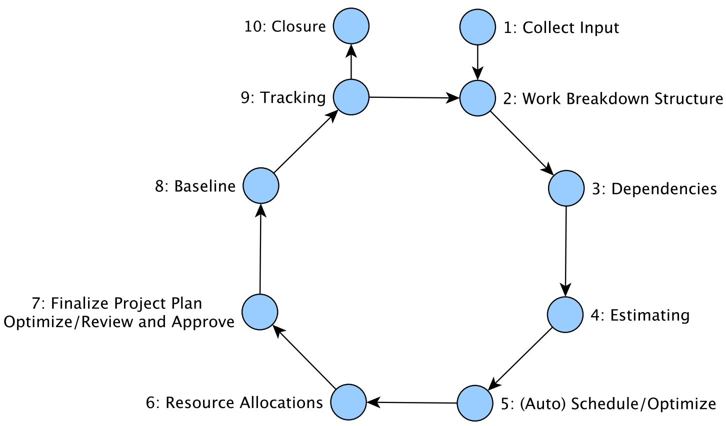

Figure 4.5: A schematic overview of the Planning & Tracking Cycle. From (Bulsink, 2008b).

Element	Description
1. Collect input	Collection of the product requirements, project requirements, assumptions. Creation of the Project Breakdown Structure (e.g. when a project consists of multiple sub-projects, work packages).
2. Work Breakdown Structure	Creation of Work Breakdown Structure (WBS).
3. Dependencies	Creation of dependencies between WBS elements and related projects.
4. Estimating	Estimation of the length and effort of each task in the WBS.
5. (Auto) Schedule/Optimize	Optimization of the plan with respect to boundary conditions.
6. Allocation of resources	Allocation of the needed resources for the project.
7. Finalize Project Plan	Review of the schedule and Project Plan and receive approval.
8. Baseline	Storage of the schedule for future reference.
9. Tracking	Tracking of project's progress, if needed iteration of the cycle.
10. Closure	Closure of the project.

Table 4.1: Overview of the elements in the Planning and Tracking Cycle (shown in figure 4.5).

To get a good estimate for the length and effort of the tasks in the WBS, a number of tools exist. For example, to track a project's progress, a tool called SPaRC (Schedule, Project and Resource Core) is used. A tool that we have encountered before, Numetrics, is used as a tool for planning, by using external benchmarks to compare the tasks with historical data. Next to these, a number of other tools is used, but these tools are not relevant to this research project.

In the Planning & Tracking Cycle, most elements have to do with planning the project. However, it is also important to track the project's progress throughout the execution of the project. During the execution, the following properties of the project are monitored and controlled (Bulsink, 2009):

Schedule → to monitor the progress of the project with respect to the planned milestones and gates and to monitor the timely execution of individual task.

Costs → to monitor the project budget (per cost type).

Resources → to monitor allocated resources, effort (hours or money) that was or is to be spent on project tasks, effort (hours) to go ("ETC") on project tasks.

Deliverables → to monitor the deliverables of the project, per task.

Risk → to monitor the different risks in the risk register.

Business Case → to monitor the benefit and need of the project's result.

An important metric in project planning and tracking is project slip. Slip is defined as the amount of deviation between the actual schedule of a project and the original planning. Ideally, the amount of slip is zero (because then the project is executed according to plan). Project slip is monitored from the S-gate to the R-gate (see figure 4.4).

Cost

Cost is related to the amount of resources that are needed to execute the project. Resource (Allocation) Management is the support process that controls the amount of resources that are dedicated to a project. The amount of resources (i.e. budget, amount of FTEs needed) that is needed for a project is determined from the project plan (c.f. the Planning & Tracking Cycle in figure 4.5). To receive resources for a project, the project manager needs to hand in a request at a resource manager. The manager then allocates the resources on basis of the available resource capacity and the requests from project managers.

Specifications

Project specifications are related to the contents of the project. The exact contents of a project are laid down in the list of requirements. To get to a well-defined set of requirements that cover all the needs of the project, a procedure called Requirements Engineering is used. This procedure consists of several phases: first the right requirements are developed in the Requirements Development phase. The Requirements Development phase manages the requirements of the product and components throughout the product's lifetime and aligns the requirements with the planning and needed resources (based on Kot (2008a)). Requirements can be placed into a number of categories:

Functional requirements
"Describe the features of a product, the functions it should have, and the actions it should perform."

Quality requirements
"Are the properties or qualities of a product, the look-and-feel, the level of security, quality characteristics like Reliability, Usability, Efficiency, Maintainability, Performance and Portability."

Constraints
"Describe the boundary conditions for a product. They refer to a restriction of the degree of freedom that one has in providing a specific solution. The can be technical or environmental. Examples are standards, the production process for an IC or the operating system for software."

Defining requirements carefully in an early stage of the project is important, because changing requirements is easier costs less in an early stage of the project execution. After the requirements have been developed in the Development phase, Requirements Management traces, measures and manages the requirements. To get from stakeholder requirements to an accepted design, a so-called V-model is used (Jacobs and de Vaal, 2008). This model shows how the project team goes from high-level requirements to implementation to testing and verification. Within the V-model (which is shown in figure 4.6), two types of requirements tracing can be distinguished: vertical and horizontal tracing. Vertical tracing of requirements means the coupling of (functional) requirements to higher level requirements (which for example originate from a stakeholder's requirement). Horizontal tracing is the connection of requirements to the verification stage on the same level. Measuring and managing requirements is necessary to make sure that requirements remain under control and that the implementation of certain requirements is monitored. Again, it is important to identify the need for change in requirements in an early stage of the project, since recognizing and implementing these changes in an early stage costs much less than changing a design in an advanced stage.

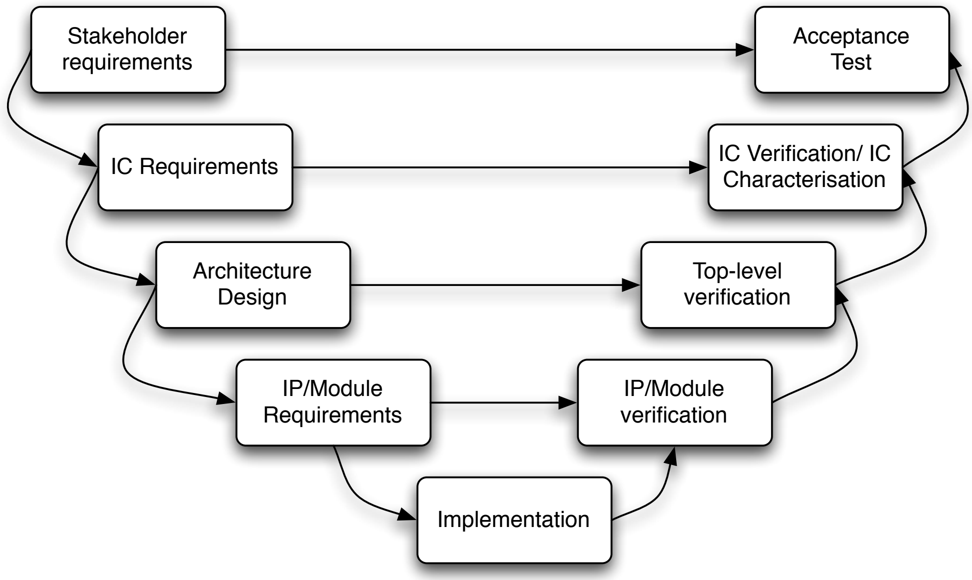

Figure 4.6: A graphical depiction of the V-model, in which vertical and horizontal tracing can be seen. From (Jacobs and de Vaal, 2008).

4.1.3 Project Drivers

In the preceding section the factors that define the performance of a project were described. In this section, we are interested in how these constraints *drive* NXP projects.

There are several factors that determine the way in which projects are executed in the semiconductor industry. In general, these factors can be divided into three categories, that we have encountered in the section before this one: time, cost and specifications. For each of these factors, we will discuss what influence these factors have and how the factors interrelate with each other.

Schedule

Because innovations in the semiconductor industry follow each other so quickly (partly because of Moore's law), it is very important that the project's duration is kept under control. Delivering a product too late may mean that a competitor already introduced a similar or better product. In addition to this, each month of delay in the introduction of a product is a month in which the product does not generate any revenue. The relation between schedule (slip) and (lost) revenue is therefore straight forward.

Cost

Controlling a project's costs in the semiconductor industry is essential for a number of reasons. Firstly, by minimizing the cost of product development, the profit margin on the product that can be achieved increases on the long run. Secondly, because the company's resources are limited, these resources have to managed and allocated efficiently between different projects. An example of efficient use of resources is the use of a single test wafer to test several new products that are under development (since the cost of producing a single wafer is high and only a small amount of test dies is needed for a test run (typically, some tens of thousands of dies can be made out of a single wafer). Therefore, a single test wafer (which is called a *multi project wafer*), can be used by several projects.

However, the consequences of design errors in a integrated circuit project can be very serious[3]. The cost of replacing chips after they have been introduced in the market can be very costly. Therefore,

[3] A famous example is a bug that was found in an Intel Pentium chip in 1994, also known as the Pentium FDIV bug (Williams, 1997). It was found that these chips produced an error in certain floating point operations (in fact, it was estimated that this error occured only in 1 in 9 billion divisions). Although the chance of an error occurring was very small, Intel offered to replace the faulty chips, which cost Intel $ 475 million. More recently, a chip design error is estimated to cost Intel $ 700 million (Intel, 2011).

it very important to thoroughly test the design of the chip, in order minimize the occurrence of these design errors.

Specifications

There are several ways in which the specifications performance of a semiconductor project can be measured. Iansiti and West (1999) state that a good measure for project performance is the density of transistors on a given chip (i.e. the number of transistors per unit of chip area). However, this study focused on memory devices and microprocessors, and not on mixed-signal devices. Therefore, the purpose of a chip design product has a big influence on the correct measure of specification performance. Memory devices and microprocessors are products that are made in very high volumes, and a higher transistor density means that more devices can be made out of a single wafer, which decreases unit costs. Also, adding more complex functionality to a chip often requires the chip to consist of more components. This means that if the chip needs to have the same size as an earlier version, its components need to be smaller still. It has to be noted that the type of products that were studied for this articles are - to a certain extent - commodity products, which means that the functionality of these products is comparable for related products.

There are also other drivers for certain specifications of chips. For example, some chips have to be absolutely defect free (e.g. chips that are for example made for the automotive industry), because of the grave consequences of a malfunction of some devices. To achieve this, NXP has a zero-defect program for their projects, which aims to minimize the amount of customer complaints due to malfunctioning chips and to trace the cause of the found chip defects. The zero defects program mainly focusses on ESD (electrostatic discharge), EOS (electrical overstress) and NTF (no trouble found) defects.

4.1.4 Actors involved in NXP projects

In this subsection the organization of NXP projects is discussed. This involves the way in which project teams are formed and with which actors inside and outside NXP the project team interacts.

In general, we can make a distinction between three different types of actors that are involved with a project: the project team; actors that are outside of the project team, but part of the company; actors that are both outside the project team and the company. In this section, attention is given to who is involved, the roles of the actors and their interactions and interdepencies. In figure 4.7, a global overview is given of how the different actors in the process interact and what the exact interdependencies are.

The different roles and responsibilities that are associated with a project are described in the BCaM framework (Kot et al., 2008). To describe the interactions that the actors have with other actors in the framework, a short description of these interaction is given after the description of an actor. Interactions that go *out of* the actor are symbolised with a right-pointing arrow, interactions that are directed *towards* the actor are represented with a left-pointing arrow. This section is based on information from BCaM documentation (Kot et al., 2008).

The Project Team

The role of the project team is to plan and execute the project, on the basis of the project that was made during the project concept phase. Typical activities that the project team performs are project management (e.g. project planning, project monitoring & control, risk management) and engineering tasks (e.g. requirements engineering, designing, implementing, verification, testing) (Kot et al., 2008).

Typical functions in the project team are: project manager, subproject leader, marketing manager, (lead) designer, test engineer, product engineer and application engineer. Depending on the project, different numbers of people can be needed for these functions. For example, in a big project there can be several subproject leaders and a number of designers and engineers. On the other hand, in a small projects people can be working on the project for a portion of their time For instance, a project manager can manage a project on a part-time basis (for example only one day per week, on average).

These examples show that design errors that are found after a chip has been introduced onto the market can be very costly to replace.

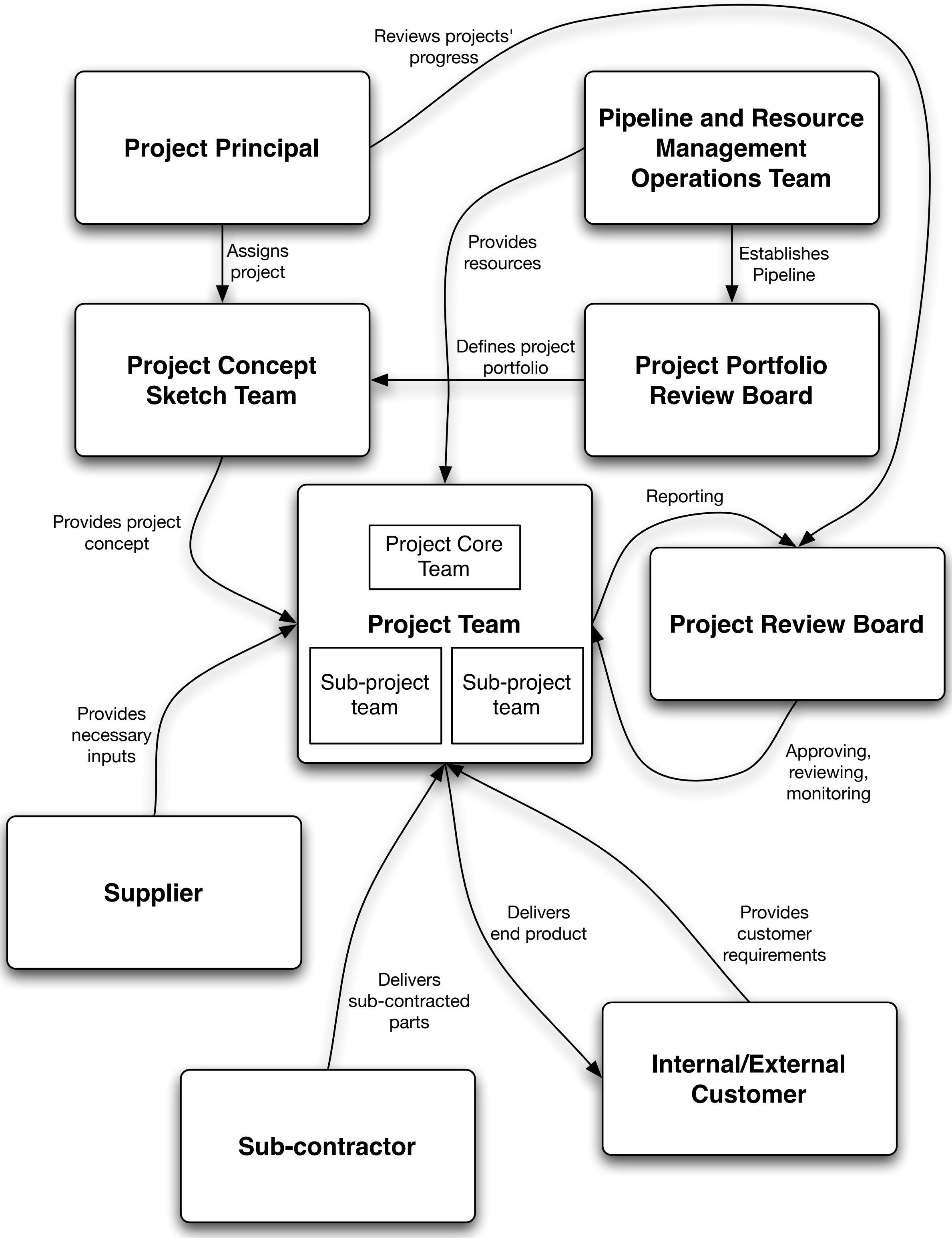

Figure 4.7: An overview of the involved actors in the product creation process and their interdependencies. The elements and interdepencies in this figure are discussed in the main text.

After the product has been developed, the project is also responsible for the market introduction of the product and the ramp up (the first stage of the commercial life cycle of a product, in which sales start to increase).

A few important functions within the project team are:

The Project Manager is responsible for organizing and running the project.

The Designer/design engineer is responsible for creating the product or system design or the design of a sub-product.

The Tester/Integrator is responsible for testing the system or sub-system and for the integration of the different sub-products into a single system (in the *Acceptance Test* and *Integration Test*).

The Architect is responsible for creation of the technical skeleton of the product. The architect determines the technical approach, on basis of the found product requirements. The architect also participates in the project concept sketch team to make a translation from roadmaps and portfolios to project proposals.

The Marketing representative represents the Marketing and Sales department in the team and has to make sure that the end product is linked to the market.

Because of the central role of the project team, all interactions that are either directed towards or from the team are described in the descriptions of the other actors or stakeholders.

The sub-project team

In some projects, sub-projects are defined to execute parts of the project (see the sub-section about project hierarchy). For these sub-projects, sub-project teams are defined that execute these.

→ Delivers sub-project deliverables.

Project Concept Sketch Team (PCST)

Before the actual project can be executed, a concept sketch needs to be made (see section 4.1 for more information about this). The project concept sketch team consists at least of the following members (Kot et al., 2008): a *(system) architect*, a *marketing representative*, *subject specialists* (e.g. production representatives, technical experts) and a *financial representative* (however, a single person in the concept sketch team can represent more than one of these roles). Most of the times, the project concept sketch team is relatively small, consisting of three or four persons.

This team is responsible for establishing the project's objectives, scope and approach. Besides this, the team performs the needed groundwork to see whether there is a valid business case (in the case of a commercial project) and gathers high-level requirements for the project.

← The project portfolio acts as a starting point for the concept sketch.

→ Provides input to the project team with the concept sketch of the project.

Project Core Team

The core team is the group of people that plan and lead the project team. The core team consists of the *project manager*, *subproject leaders* (if there are sub-projects in the project) and a *marketing representative*. In addition to these roles, all functional areas that are involved in the project should be represented in the core team (Kot et al., 2008).

→ Makes project planning.

→ Manages technical and business aspects of the project.

→ Ensures that the customer requirements are fulfilled.

→ Reports projects' progress to project review board.

External Actors from inside the company

A number of actors is not part of the project team itself, but do have a relation to the project. A number of important functions and bodies that are related to projects is described below.

The Project Principal
The project principle is the person or body that commissions the project and project team. Usually, the project principal is in the project review board and monitors the project throughout the project's execution.

→ Assigns and commissions project and project team.

→ Usually reviews the progress of the project (for example by participating in the project review board).

4.2 The Numetrics framework

Numetrics is a tool that is used for planning and benchmarking chip design projects. Central to the analysis of a new chip design is the complexity of the design. By studying the properties of semiconductor industry related projects (which can be programs, IC design projects, software projects and IP projects), Numetrics can be used to compare design projects. Complexity (or to be more exact, *design complexity*) in the Numetrics framework is defined as (Numetrics Management Systems, Inc.):

*"**Design Complexity:** A standardized measure of the intrinsic difficulty of the development of an IC, seen through the eyes of an industry average design team with average tools, methodology, library quality, etc. This metric is calculated by a statistical complexity model based on the Chip Characteristics and Block Complexity values entered, and is reported as Complexity Units (CU)"*

This section will further investigate the possibilities of Numetrics and the intended use of Numetrics at NXP. To assess complexity, the Numetrics framework works with so-called *complexity units*, which expresses the (design) complexity of an IC development project, on the basis of certain project parameters that the project managers enters into the Numetrics system.

Numetrics calculates chip design complexity in a four-step process (Numetrics Management Systems, Inc., 2010). These steps are:

- The first step is the identification of *'major "technology and design attributes"'*, which have an influence on the needed development effort of an IC.
- The second step is determining what impact an attribute has on the the development effort.
- The third step entails finding out how effort and attributes interrelate.
- The fourth and final step is to create weighted factors from the interrelations.

Using this model to calculate the design complexity, which is called the "normalization model" by Numetrics, a quantification for the development complexity of a design project is attained. As an example, Numetrics Management Systems, Inc. (2010) claims that this model describes the relation between IC Design complexity and development effort reasonably. The observation is also made that sometimes two projects can be identical from a technical and design perspective, but that one of these projects requires more effort, due to other reasons (for example due to a lack of relevant experience in one of the project teams). The proposed solution for this by Numetrics is to try to compare these projects to other projects, which are similar in scope and application and other factors that cannot be normalized (but what these exact non-normalizable features are, is not explicated). The existence of interrelations or interdependencies between project attributes is also described by Baccarini (1996), see chapter 1.

Central to the Numetrics system is a number of so-called "Key Performance Indicators" (KPIs) (Numetrics Management Systems, Inc., 2005). These ten indicators are measures that describe development capability of IC products, and cover the dimensions of project performance that were discussed earlier:

time, cost and specifications[4]. In the Numetrics system, measuring these indicators gives the possibility to compare an IC development project to other projects in the semiconductor industry. The key performance indicators are presented in table 4.2. Next to design complexity of a project (which is one of the key performance indicators), the development productivity plays an important role in the Numetrics system. Numetrics defines productivity as:

> *"**Development Productivity:** A calculated metric indicating a team's ability to develop a product over time, expressed in Complexity Units per person-week. Development productivity equals Design Complexity divided by Total Project Effort. Differences in Development Productivity explain why different teams require different amounts of effort to develop ICs of the same Design Complexity."* (Numetrics Management Systems, Inc.).

The development productivity in a project can be calculated by dividing the design complexity by the multiplication of the average project staffing by the scheduled time.

A number of remarks can be made about the above mentioned indicators. Firstly, it is clear that not all measures are independent (in appendix C, the relations between the different indicators are given), but some measures are derivative from other measures. Secondly, some measures are overlapping. For example, the IC Design Complexity and the IC Functional Complexity measure the same aspect of the project, but the first measure takes into account the possible reuse of IC blocks in the IC design. Thirdly, a number of these measures describe the *average* of a certain measure over the course of the project's execution. Therefore, these measures do not show what the peak values are (e.g. when maximum productivity is needed and what the value of this productivity at the peak is).

Indicator	Description
IC Design Complexity	*"1) Level of project difficulty and 2) quantification of development team's output (i.e. what the team designed)."* Measured in Complexity Units (CU).
IC Development Productivity	*"Average rate of output per individual on a development team."* Measured in Complexity Units per person-week.
IC Development Throughput	*"Average rate of output for the entire development team."* Measured in Complexity Units per week.
IC Development Cycle Time	*"Elapsed IC development time, from project start to volume production."* Measured in weeks.
Total IC Project Effort	*"Total laber expended during development time."* Measured in person-weeks.
IC Project Schedule Slip	*"Difference between originally planned cycle time and actual cycle time."* Measured in %.
Total Silicon Spins	Number of mask sets that is made to assess whether the product is ready for mass-production. Measured in numbers
Total IC Development Cost	*"Total cost of IC[project]'s development."* Measured in amount of financial resources.
IC Development Cost per Complexity Unit	*"Development cost per unit of output [complexity]"* Measured in $/CU or euro/CU.
IC Functional Complexity	*"Richness of IC's feature set and its performance"* Note that this value does not take into account the possible reuse of knowledge from earlier projects, so it is a measure for the "total" complexity of a design project. Measured in Functional Complexity Units (FCU).

Table 4.2: The Key Performance Indicators of the Numetrics framework. From (Numetrics Management Systems, Inc., 2005).

[4] The attentive reader might note that using ten indicators for three performance measures is redundant. This is true, because the ten indicators are not independent. In appendix C, the relations between these key performance indicators is given.

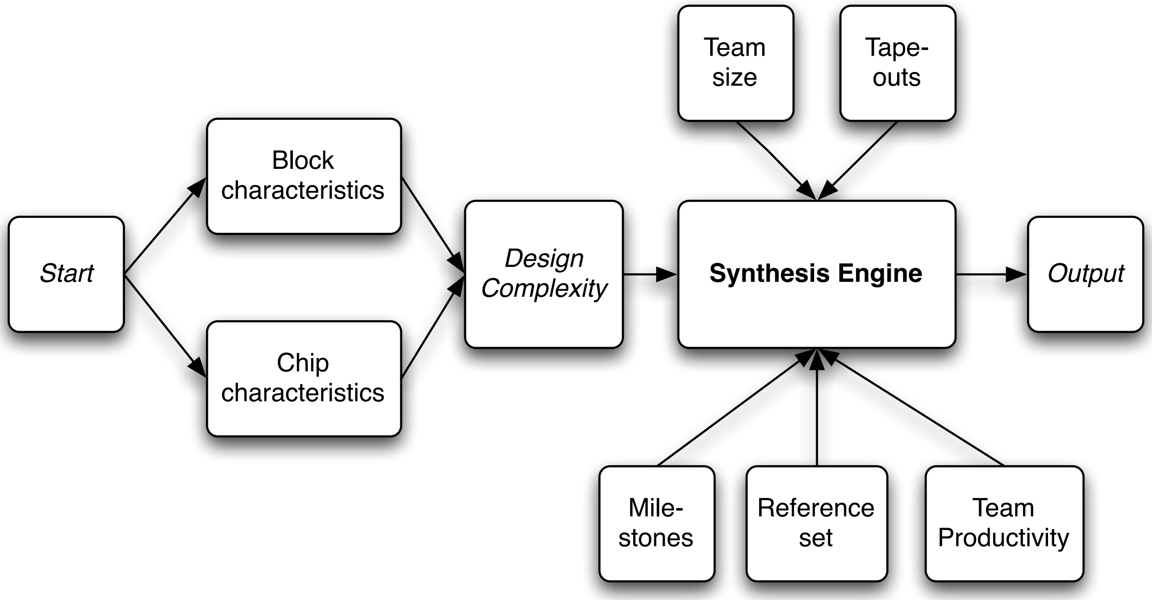

Figure 4.8: A schematic overview of the plan synthesis tool of the Numetrics system. The elements of this tool are discussed in the body text. From (Numetrics Management Systems, Inc.).

4.2.1 Numetrics Project planning

Before the actual execution of a project starts, a project planning has to be made. To be able to make a forecast of the needed time and resources for a certain task, Numetrics uses a database of executed semiconductor products to compare the project that is being planned with historical data. This enables the project manager to see how his project relates to other projects with respect to a number of parameters.

There are two ways in which Numetrics can assist in project scheduling: plan synthesis (top-down planning) and schedule risk analysis. Numetrics can *synthesize* a project plan itself, on the basis of information that was entered into the system. In figure 4.8, the way in which Numetrics synthesizes a project plan is shown schematically (Numetrics Management Systems, Inc.). The process starts with entering chip characteristics and block characteristics (what these entail is explained later in this section). Numetrics calculates the design complexity of the product under planning from these inputs. The design complexity is in turn an input for the *Synthesis Engine*, which generates the synthesized plan. The other inputs for the synthesis engine are: the (peak) team size, tapeouts (number of design iterations that are send to the fab to produce a mask), milestones (the number and types of milestones), the reference set (the set of project to which the project under planning is compared) and team productivity[5]. The synthesis engine then provides its outputs: a synthesized project plan, a staffing table and a staffing chart (these last two outputs show the amount of FTEs that are to be designated to the project at a certain time). In other words, the synthesis engine estimates the amount of FTEs that are needed in the different phases of the project and the length of these phases, on the basis of its inputs.

As was mentioned above, the calculation of a project's design complexity starts with entering characteristics of the chip as a whole and the different blocks on the chip into the Numetrics system.

Chip Characteristics These parameters are concerned with attributes of the chip as a whole and only need to be entered once for the whole product under development. What these characteristics exactly entail is elaborated in appendix C.

[5]On a sidenote: the team productivity can be adjusted for a number of factors: *derivate design* (+), *immature silicon technology* (-), *team continuity* (+), *multi-site team* (-), *new tools or methodology* (neutral), *annual productivity improvement* (+) and user-defined factors. These factors can be selected and can have both an increasing or decreasing influence on the productivity (signified by a +/- sign, the sign of the influences shown above is the default sign in Numetrics).

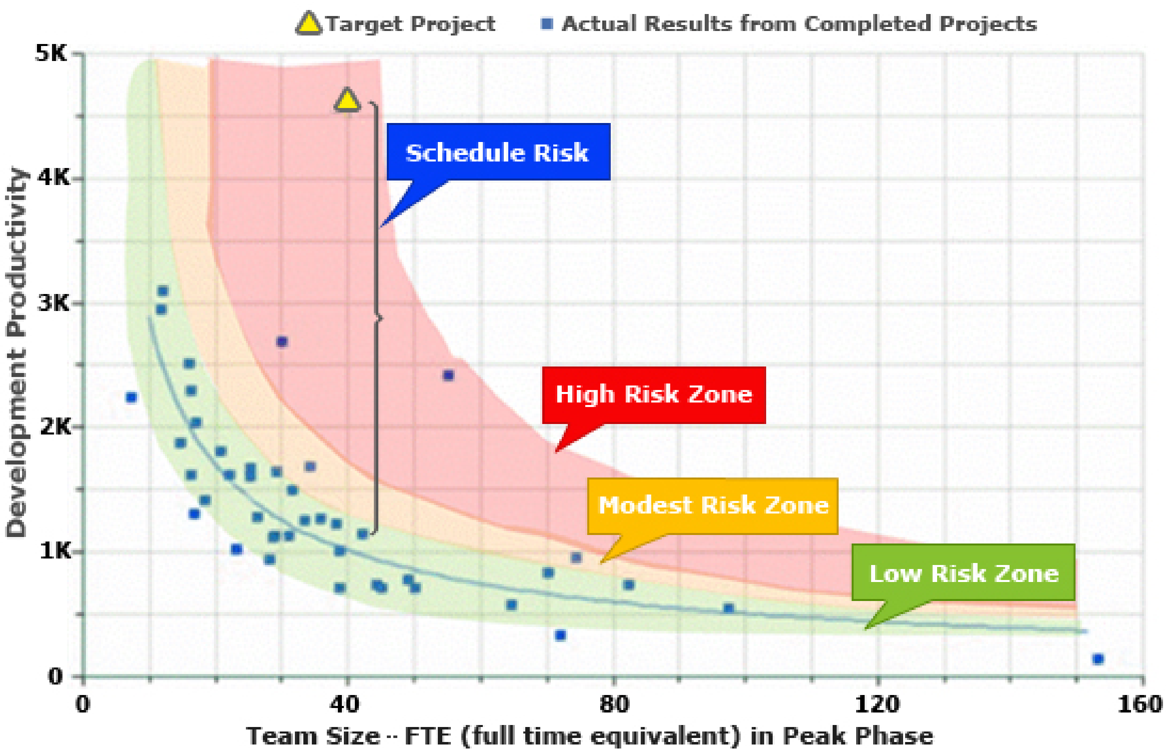

Figure 4.9: A plot of team sizes of different projects versus the development productivity. The projects are related, in the sense that they entail similar products from the same market. Numetrics fits a relationship through the data, although there is no underlying model that predicts this behavior of the data. Therefore, the fit is only phenomenological in nature and does not represent an underlying theoretical model. However, in general one can say that development productivity becomes lower with increasing team size. From (Numetrics Management Systems, Inc.).

Block Complexity Block complexity parameters need to be filled in for each block (an part of a chip with a certain functionality) separately. The parameters are further discussed in appendix C.

Complexity Units

- Functional Complexity
- Reuse Leverage
- Functional Productivity
- Functional Throughput
- Total Silicon Spins/Total IP Deliveries

4.2.2 Numetrics Schedule Risk Analysis

To see whether certain assumptions in an existing project plan are feasible, Numetrics can assist in making a so-called *schedule risk analysis*. By making such an analysis, the Numetrics system shows how the planned project relates to other (finished) projects. By comparing the project under planning with other projects, certain (schedule) risks can be identified and be mitigated. For example, if a project manager plans to use a certain team size in the peak phase of the project[6], he can compare this team size to the needed productivity. In figure 4.9, an example is shown of a graph, in which the relationship between team size and development productivity is shown. This, way the performance of a project can be compared to that of projects of competitors (benchmarking) or the feasibility of estimated performance can be assessed (planning). In the example shown in the picture, the project manager could make a decision on the basis of the analysis, for example by changing the project's schedule such that the necessary development productivity decreases.

[6]The peak phase is the phase in a project when most team members are needed in a project team.

Within the Numetrics system, it is possible to make a large number of graphs that show the relationship between different project variables. Figure 4.9 shows a scatter plot of two variables, but it is also possible to present data in different ways, such as histograms and radar charts, whatever is appropriate for the desired analysis. It is possible to plot 62 dependent variables against 57 dependent variables (in the XY scatter mode), so the possible number of different graphs is quite large (in the order of 3500). Therefore, the person making the analysis needs to have a clear vision on which analysis is appropriate to assess the project.

At NXP, the following targets, that are related with possible schedule slip are evaluated in the schedule risk analysis:

- Expected cycle time
- Expected spin count
- Expected total project effort
- Expected design productivity
- Expected development throughput (in order to finish the project on time)
- Expected project cost efficiency (IC Development Cost per Complexity Unit)
- Comparison with "Best-in-class" projects

4.2.3 Numetrics Project Benchmarking

The Numetrics system can also be used to analyze the performance of a project after it has been executed. This allows the company to compare its performance to other projects, both internally and projects of other companies in the semiconductor industry. Several types of integrated circuits are included in the benchmarking function of Numetrics, allowing companies to compare their products to similar products of other producers. Benchmarking is also used to see whether the estimates of complexity, time and effort that were made before the execution of the project. This way, the planning of future projects can be done more accurately, possible risks for future projects can be identified and it possible ways of improvement can be found.

The benchmarking approach is very similar to the schedule risk analysis approach, in the sense that a project is compared to other projects with the same characteristics. However, where the schedule risk analysis is performed a priori, benchmarking is done a posteriori, i.e. after the project was finished. Doing a benchmark allows the company to assess the project's performance and to draw lessons for the future.

4.2.4 Factors outside the Numetrics scope

Next to the inputs and outputs that the Numetrics system takes into account to assess complexity, it is also important to see which factors are *not* taken into account by Numetrics. The attentive reader already noticed that Numetrics is concerned with the *design* complexity of a product creation project. Therefore, other factors that might contribute to the total complexity of the project are not taken into account in the calculation of design complexity. Some complexity-inducing factors, such as the use of new technology and the project team operating from different locations is taken into account in other factors (in this particular case the development productivity).

Analyzing the Numetrics framework from the TOE point-of-view, one can conclude that mainly the technical aspects of the design project are taken into account by the Numetrics framework. The organizational and environmental aspects are sometimes used, but these aspects do not play a role in the assessment of the project's complexities.

4.2.5 Numetrics use at NXP

Within NXP, Numetrics is linked with BCaM. The use of Numetrics for comparing project plans and benchmarking is mandatory for an IC development project (NXP, 2010). Several Numetrics deliverables are coupled with BCaM stages, to assist in decision making related with the project. Related to the different BCaM stages of a project, the following actions in the Numetrics system need to be taken at the particular stages:

- **Pre PCA (project concept approval):**
  - The project needs to be registered in the Numetrics database
  - A complexity analysis needs to be made
  - A bottom up plan needs to be made
  - A diagnostics analysis needs to be done
  - An initial schedule risk analysis of bottom up plan need to be done
  - The project data needs to be 'PCA certified' by Numetrics
- **Pre S (specified gate):**
  - The data entered at PCA needs to be updated (if no PCA was held, initial data entry)
  - A schedule risk analysis of bottom up plan needs to be made
  - The project data needs to be 'S certified' by Numetrics
- **Post MRA (mask request approval):**
  - The complexity analysis needs to be updated
  - Project data needs to be 'MRA certified' by Numetrics
- **Post R/SRA (released gate/supply release approval):**
  - All sections above need to be completed with actual project data
  - A project benchmark report needs to be made
  - The project data needs to be 'Certified' by Numetrics.

These measures are put in place to be able to monitor the performance of projects. In practice however, Numetrics is not always used as it is described in the official documentation. To further study the discrepancies between the theoretical use Numetrics and the actual use, the case studies will also focus on the use of Numetrics in NXP projects.

4.3 Towards the case study

This chapter showed how product creation projects are carried out in general at NXP and how the design complexity of a product is assessed by Numetrics. This section shows how we can use this information in the case studies, which are described in the next chapter.

The case studies mainly concentrate on product and process development projects. The types of projects that are be studied are: *studies*, *implementations*, *design-ins* and *an improvement project*. Concerning hierarchy, projects and sub-projects are investigated. Chapter 5 presents an overview of the different projects that are investigated in this research project.

We can make a number of observations regarding the way that projects are executed at NXP: A framework is used at NXP in the product creation process: BCaM (Business Creation and Management). Each business unit, business line and product line has to use this framework, but it should be adapted to meet the needs of the organization, as long as the adaptations are documented. BCaM consists of three main processes: technology & IP roadmapping; project portfolio & pipeline management; project execution. Each stage looks at the creation of new products at a different level and is done at a different level in the organization. Several types of projects and hierarchies of projects are distinguished within the BCaM framework.

A tool is specified that assists in making a project plan and to monitor and control the progress of a project throughout its execution. To make sure that (high-level) requirements are implemented correctly into the final product, a so-called V-model is used. This model serves to connect high-level requirements with corresponding low-level requirements and implementations with verification (testing) procedures.

To assess the complexity of a chip design, a tool called Numetrics can be used in product development projects. Numetrics translates design features into a normalized value of the design complexity. This design complexity value is subsequently used to compare the chip design to other (comparable) designs from the semiconductor industry. Numetrics can be used in three ways: to make a project planning, to benchmark a project planning (before the project is executed) and to benchmark a project's outcome (after the project is executed). Numetrics only takes into account the (technical) design properties and no organizationally-related properties of the project. Numetrics is implemented into the BCaM framework.

The information that was gathered during the literature study is used as a starting point for the case studies: building on this information, part of the interview questions were formulated (for the actual design of the case study, see chapter 5). This way, one can see how the formally formulated product development process and use of Numetrics, and the actual practice at NXP relate to each other.

Chapter 5

Exploring Project Complexity at NXP

5.1 Case study design

Case studies were performed to answer the first and third sub-questions that were defined in chapter 2. From the knowledge gathered from the case studies, a potential adaptation of the TOE framework is going to be made in chapter 6. This case study consists of multiple cases, where the unit of analysis is an NXP product or process development project. Since there is only one unit of analysis per case, the case study design is holistic in nature (Yin, 2003). For each case, one interview was held. Since this research project is based on the TOE framework, this framework acts as the starting point for the answer to the first sub-question.

5.1.1 Case selection

Projects will be selected from the following organizations within NXP (figure 5.1 shows which parts of NXP are subject to research):

- BU High Performance Mixed Signal
  - BL RF Power (3 cases)
  - BL RF Small Signal (3 cases)
  - BL Power and Lighting Solutions (1 case)
  - PL Mobile audio (2 cases)
- BU Automotive
  - BL Car Entertainment Solutions (2 cases)
  - BL Sensors (1 case)
- BU Standard Products
  - Logic (1 case)
- Central R&D
  - Design Services - IC Lab (1 case)
- Operations
  - Wafer Technology and Foundry Optimization (1 case)
  - Operations Backend Innovation (1 case)

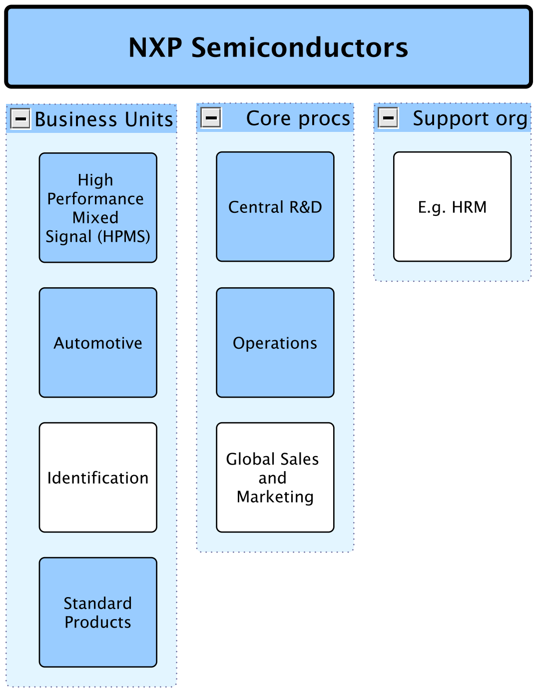

Figure 5.1: An overview of the business lines and organizations within NXP that were investigated in this research project. The parts of NXP that were subject to this research are highlighted in blue.

A choice was made for these parts of NXP for both theoretical and practical reasons: these parts of NXP give a broad overview of the different activities that are carried out with respect to the development of new products and processes and the parts are located in the Netherlands (in Nijmegen and Eindhoven), which meant that the interviews could be held on location. A number of departments are not considered in this research project, since the activities that these departments carry out fall outside the scope of this research project.

Different project types (studies, implementations, design-ins, other projects, these are described in chapter 4) are investigated within NXP. Furthermore, several project variables were taken into account in the selection of cases:

- Project nature (product/process development)
- Product design characteristics, if available (e.g. high reuse or new developments, mainly discrete/analog components or mixed signal)
- If available: the use of Numetrics

By observing these variables in different projects, and making sure that these variables are different between different projects, one can make sure that a broad selection of projects is made.

Next to project variables (which need to be *different* between different cases), there are also a number of project criteria to which the studied projects need to comply:

- The project needs to involve the *development* of a new product or process at NXP.
- The project needs to be finished or nearly finished.
- The project needs to be completed in 2008 or later.
- It has to be known in which phases of the project the interviewee was involved in the project.

These criteria were mainly chosen to be able to compare the different cases afterwards (e.g. to compare product development projects between different business units). The products need to be executed recently, so one can make sure that the current practice at NXP is investigated in this research.

In total, 16 projects are investigated. This number of cases was chosen to strike a balance between the available time for this research project and the possibilities to draw general conclusions from the study's findings.

Case study procedures

The case studies will be performed by conducting semi-structured interviews with project managers. The interview protocol that was used is shown in appendix D. Before the interview was held, a letter of intent was sent to the intended interviewee, to ask whether this person is willing to participate, to inform this person about the research and the purpose of the research. The interviews were planned to have a duration of approximately 60 minutes.

5.1.2 Data treatment

Data collection

The interviews have been recorded (using a digital audio recorder) and notes have been taken. The results of the interviews were given back to the interviewees for feedback. The notes and audio files were stored in different directories for each interview/project. After the interview is conducted, a written summary of the interview was made. This interview was sent to the interviewee, so there was the possibility of giving feedback on the worked-out interview. For each case, a directory was made in which all raw and worked-out data concerning the case is stored. This way, information can be traced back conveniently.

Data analysis

After the interview has been finished and feedback from the interviewee has been received, the cases were analyzed. Two types of analysis can be distinguished: intra-case analysis (concerning a single case) and inter-case analysis (concerning multiple cases).

In the intra-case analysis, the researcher looks for different aspects of the project that contribute to the project's complexity. This type of analysis is done for each case separately. This part of the analysis concerns level 2 questions (questions asked of the individual case) (Yin, 2003, pp. 74). Questions that were answered in this part of the analysis are:

- What project complexities are mentioned?
- Which aspect of project complexity has the largest influence on the total complexity of the project?
- How was Numetrics used in this project?

These questions are answered for each case in section **??**, at the end of each separate case.

In the inter-case analysis, we look for patterns (similarities or differences) in project complexities that were found in the intra-case analysis. This analysis is only done once for all the cases. This part of the analysis is concerned with level 3 questions (questions asked of the pattern of findings across multiple cases) (Yin, 2003, pp. 74). Questions that were answered in this part of the analysis are:

- What is the background and work experience of the interviewees?
- What kind of projects have been studied in the cases?
- What are the main drivers behind the studied cases?
- What causes projects at NXP to be complex, according to the interviewees?
- Which project complexities are mentioned in the cases?
- Are certain complexities linked to projects with particular properties?
- Can a hierarchy in complexities be established? (E.g. through the number of times that a certain complexity is mentioned in the different interviews)

- Which encountered complexities are missing in the TOE framework?
- How is Numetrics used in the projects and what is the view on Numetrics by the interviewees?

Combining the findings of both analyses, an image should be formed of the different complexities that are encountered in NXP (IC) development projects, the use of Numetrics and the way in which the TOE framework could be adapted to fit the findings of the research project. Finally, the analysis should provide the first indications to policy recommendations to cope with complexity in projects. The cross-case analyses can be found in section 5.3.

5.2 Cases

– Company confidential information –

	HPMS	Automotive	Standard Products	Central R&D	Operations	Total
Total per organization:	9	3	1	1	2	16
Project status:						
Terminated	1	0	0	0	0	1
Not finished	6	2	0	1	0	9
Success	2	1	1	0	2	6
Numetrics:						
Used	3	2	0	0	0	5
Not used	6	1	1	1	2	11
Project type:						
Product dev.	7	3	1	1	0	12
Process dev. & inn. study	2	0	0	0	2	4

Table 5.1: Overview table of the cases treated in this research project.

5.3 Cross-case analyses

In this section, the different cases under study are compared along a number of dimensions. First, an overview is given of the interviewees, in particular on their background, experience and project-management related training. After this, the different project types that were encountered in this research project are discussed, with common characteristics and highlights. Next, the drivers behind the project will be elucidated upon, by using a statistical analysis on the data that was gathered during the interviews. The use of and views on Numetrics is discussed subsequently, to see how the actual use of Numetrics relates to the prescribed use of the framework. The complexities that were mentioned during the interviews are discussed, to get an image of the views of the interviewees on complexity in their projects (before the interviewees were informed about the TOE framework). The application of the TOE framework to the cases is discussed hereafter, with the scores of the different elements. Finally, we will discuss the views of the interviewees on what makes projects in the semiconductor industry different from projects in other industries.

Table 5.1 gives an overview of the distribution of cases from the different organizations within NXP, with respect to a number of variables treated in this section.

In relation to the research questions, this section is dedicated to shed light on sub-questions 0, 1 and 3: we look for characteristics that define NXP projects and project management, for the factors that play a role in the complexity of NXP projects and how Numetrics is used at NXP.

5.3.1 Overview of interviewees

To get an overview of the persons that were interviewed for this research project, this section provides information about the interviewees: their background, work experience and project management-related training.

In total, 16 interviews were held with 16 project managers from NXP. Out of the 16 interviewees, 12 interviewees had a background in electrical engineering or a related field, 3 interviewees had a background in physics (both fundamental and applied physics) and one interviewee has a chemical engineering degree. Hence, all interviewees have a background in engineering or natural sciences. This coincides with the fact that all interviewees started in an engineering function before becoming project managers. The interviewees have an average working experience at Philips/NXP of 17.9 years (lowest: 7 years, highest: 28 years). 11 of the interviewees are PMP certified, two interviewees are working to attain a certification and three do not have a PMP certification.

We will come back to this result in chapter 6: since all interviewees have an technical background, this has implications for the way the TOE framework could be applied to NXP projects.

5.3.2 Different project types encountered

The cases in this research project can be placed into three categories: product developments (12 cases), process developments (3 cases) and one innovation study. Since only one innovation study was studied in this research project, we have included this project in the subsection on process developments (the innovation study in question is related to process developments, so this combination is justified). The remainder of this subsection will compare the cases in each category in a number of ways: the activities that were performed during the project execution and common actors that are involved in the projects.

Product developments Twelve cases that entailed the development of a new product were studied in this research project.

An important distinction between the different types of product development projects is the type of design effort: analog design, digital design (and sometimes, software design is also a part of the total design). Most design projects do not involve only one type of design, often the design types are mixed (within NXP, devices that process different types of signals are called *mixed-signal devices*). The different design types ask for different approaches to the design and for different expertises. Bringing together designers with different expertises is seen as an important source of complexity by the interviewees (see for example cases 7 and 9).

Although designing the chip is an important phase in the development of the chip, there are a number of other activities that also have to be done to deliver a successful product: because the device needs to be tested before it is delivered, test engineers develop industrial test procedures that determine if the chips works correctly. Secondly, in order to be able to mass-produce the chips (sometimes hundreds of millions of units of a single chip type are produced), an industrial manufacturing method needs to be developed. The different expertises that are involved in the development sometimes have conflicting requirements related to the product (for example, often a trade-off has to be made between an efficient design and good testing properties of the device). Satisfying the needs (and determining comprises between the needs) of these groups of experts (designers, test engineers, etc.) at the same time can prove to be a challenge for the project manager.

A particular activity that seems to have a large influence on the projects is the availability of computer simulation models that simulate the behaviour of the device. Because making a prototype devices is expensive and takes a long time, it is important to have tools to assess whether the design operates as desired. When a device is developed that has certain properties that are hard to simulate (some examples that were encountered in this research project: using high frequencies or using very small components). For examples of projects in which this played a role, see cases 2, 5, 6, 7 and 8.

The interviewees were asked to make a list of the stakeholders (outside of the project team) that were involved in the project. An overview of the mentioned stakeholders (with the amount of times that the stakeholders is mentioned) follows next, where a distinction is made between internal stakeholders (which are a part of NXP) and external stakeholders.

Internal stakeholders:

- Project review board (10 times)
- Project core team (when the case is a sub-project) (twice)
- Principal (once)
- Functional management (development, resources, quality, systems architect, project officers) (mentioned 5 times)
- Marketing department (7 times)
- Supporting teams (testing, assembly) (3 times)
- Internal subcontractors (5 times)
- Wafer fab (5 times, can also be an external stakeholder)

External stakeholders:

- Suppliers (4 times)

- External customer (12 times)

In all studied projects external customers were involved. Several interviewees mentioned that this is not always the case, although one interviewee mentioned that there is a tendency that products are increasingly developed in cooperation with a customer (before, products were developed in series of products with different properties and customers chose the product from the available series).

Because of the specialized (and often complex nature) of the product, the requirements of the customer play an important role in product developments. Roughly three situation types can be distinguished: no direct customer, one key customer and more than one key customers (with different perspectives). We will treat these situations separately, together with the influence on the project's complexity that these situations have:

- When no key customers are involved in the development of the product, the product is developed as a generic product. This means that the possible customers will have to adapt their own systems to the system that was developed by the chip manufacturer. This means that the product can be developed by the company in such a way that the product only has to attain the requirements that were developed by the company itself. On the other hand, there is no direct feedback from the customer about possible shortcomings of the product.

- When only one key customer is present during the development of the product, the product can be developed exactly according to the needs of the customer. There is a possibility for feedback during the development process, which enhances the possibility for the project team to develop a product that exactly fits the need of the customer. Since the product has to fulfil the need of the customer, the company is less flexible in choosing for certain solutions (the developed product needs to "fit" inside the system that the customer uses).

- When more than one key customers are present during the development, the company has to make a choice between making a comprise between the needs of several key customers (if such comprise is necessary) and choosing for a single dominant customer demand. In general, the project becomes more complex when more than one key customers are involved during the development of the product.

Concluding this part about the influence of the customer, one can see that there is not a simple one-to-one relation between the number of customers and the complexity of the development. Having no clear customer during the development increases the uncertainty about whether the right product is under development, and having a number of customers involved increases the complexity by having to fulfil the needs of multiple customers.

Process developments and innovation study This section treats the process development projects and the innovation study that were treated in this research. The cases that belong to this category are: (confidential information) Due to the complex nature of the production of ICs, not only new products need to be developed, but the processes (these are also called "technologies") that are used to manufacture the ICs need to be improved continuously, too.

The interviewees from these cases were also asked to make a list of the internal and external stakeholders, an overview of the mentioned stakeholders (with the amount of times that each stakeholder was mentioned) is given next.

Company internal stakeholders:

- Project Review Board (twice)
- Sponsor (twice)
- Technical management (once)
- Marketing (once)
- Extra teams outside of the project team (can be both internal and external to the company, provided additional knowledge) (4 times)

- Internal subcontractors (once)
- Wafer fab (internal and external) (3 times)

External stakeholders:

- External expertise (once)
- Customers (twice)

Although the sample of projects in this category is much smaller than the sample of product development projects, we can try to distill information from this list of stakeholders. What catches the attention first is that in all projects in this sample, external expertise was involved in the project (note that external in this sense means that this expertise does not come from within the project team itself, but can be part of the company, e.g. a business line that is involved in the development of a technology which will later be used for their projects). Also, in two cases, a customer was involved in the development of a technology. Although a technology development does not directly result in a product, customers are sometimes involved in these projects, to provide input about their requirements for the technology.

5.3.3 Project drivers

During the interviews, each interviewee was asked to rank the drivers in the project triangle (specifications, schedule, project cost) (Oisen, 1971) in order of importance (in which 1 signified the most important driver and 3 the least important). In this section, the rankings from each case are brought together to see whether a pattern can be found in these rankings. To assess whether a statistical significant pattern is present in the data, a statistical test is used. This test, the *Friedman rank correlation test* (Friedman, 1937), measures whether the data significantly differs from a uniform distribution of rankings (i.e. each driver has the same mean rank over the whole data set). We shall call the hypothesis that the ranking is uniformly distributed H_0. The alternative hypothesis, that the ranking of the data is not uniformly distributed (and therefore, there is a preference for a certain driver) will be called H_1.

Project #	**Specifications**	**Schedule**	**Cost**
1	1	2	3
2	1	2	3
3	1	2	3
4	2	1	3
5	1	2	3
6	1	2	3
7	2	1	3
8	1	2	3
9	2	1	3
10	2	1	3
11	1	2	3
12	2	1	3
13	1	2	3
14	1	2	3
15	1	2	3
16	2	1	3
Mean	1.375	1.675	3
Std Dev.	0.5	0.5	0

Table 5.2: An overview of the project triangle ranking data that was collected during the interviews.

Although one could see by eye that the data is not uniformly distributed, a statistical analysis was made to support this observation. The data results in a sum-of-squares of $SS_{bg} = 24.5$ and 2 degrees of freedom (since there are 3 possible values for the ranking), which results in a χ^2-value of $\chi^2 = 24.5$[1]. Therefore, the null-hypothesis can be rejected at the 0.000005 level (assuming a χ^2-distribution with two degrees of freedom). We can therefore conclude that the ranking is not uniformly distributed.

The statistical analysis (and direct observation) shows that the data significantly differs from a uniform distribution of rankings. It is interesting to reflect on why this is the case. As was said in an earlier part of this thesis, time is a very important driver in the semiconductor industry. Therefore, it is important that projects are finished as quickly as possible and this can be seen in the ranking of schedule as a driver (the average ranking is 1.675, standard deviation: 0.5). Because the project deliverables need to attain the required specifications in order to have a well-functioning product, specifications are also a very important driver (average ranking: 1.375, standard deviation: 0.5). Since the costs that are associated with executing the project are only minimal in comparison to the manufacturing costs and revenues associated with the project, project costs play a much smaller role in the execution of the project.

A note has to be made that a number of employees regarded *product* costs as an important variable, but since this is a property of the project's deliverables, product costs are regarded as a part of the specifications of the project. A second note has to be made is that the research was executed in a time in which the company was growing in an economically favourable time period. It could very well be that during an economic downturn, project costs are more important (since the semiconductor industry can be regarded as an industry that is sensitive to the economic situation), but further research should be done to provide more clarity on this subject.

5.3.4 The use of Numetrics

In total, Numetrics was used in 5 out of the 16 projects (one case is a sub-project of a larger project, where Numetrics is not used in the particular sub-project, but it is used in the total project, the interviewee was however not involved in the use of Numetrics). However, several interviewees that did not use Numetrics in their projects did give an opinion about the system and these opinions are also added to this analysis.

During the interviews, the interviewees that answered a number of questions related to the way of using Numetrics (project plan synthesis, schedule risk analysis, post-project benchmarking), about the advantages that Numetrics brought to the project, concerning the performance of the system (if Numetrics correctly described the complexity of the product's design), and about the improvements that could be made in the system and the use of the system. The following sections will summarize the outcomes of the interviews.

The use of Numetrics Out of the five cases, the project plan synthesis was used in one instance, the existing project plans were benchmarked to the Numetrics database in four cases and in one case, the project will be benchmarked after the project is finished, according to the interviewees. Note that since all project that use Numetrics are not yet finished, the post-project benchmark could not be made for all projects.

In a number of cases, the Numetrics analysis showed that the original planning of the project was not in accordance with the outcome of the Numetrics system (in practice this often meant that more spins were necessary than that were originally planned to be carried out). Interestingly, the Numetrics estimation was often closer to the actual way the project was executed than the planning made by the project manager independently from Numetrics.

Perceived advantages of Numetrics An advantage of Numetrics that was often mentioned is that it can be used as a rationale for the choices that are made in the planning and for requesting more resources or time for the project (e.g. when a project turns out to be complex than was expected in a first estimation of the complexity), towards the stakeholders to which the project team has to report to.

Performance Most interviewees mention that complexities are described "reasonably" well by Numetrics, but a number of remarks were made.

[1]The χ^2-value is calculated by: $\chi^2 = \frac{SS_{bg}}{k(k-1)/12}$, where $k = df + 1$ is the number of possible values of the ranking.

- Firstly, the population of projects to which the project under study is compared to is critical: when the wrong group of projects is chosen, the outcome of the system is not very useful. Therefore, a lot of care has to be taken when choosing for a group of projects to compare to.
- Secondly, some interviewees opine that the system is sensitive to the subjective input of the user and the complexity value of a design can vary if different persons would enter data into the system. Some interviewees believe that the person that enters data into the system can influence the outcome towards the desire of that person.
- Thirdly, interviewees noticed that the complexity of digital design is described better by the system than the complexity of analog design (because in general, the behaviour of digital components is easier to describe than the behaviour of analog components). The description of the combination of digital and analog design in a single design is also perceived as difficult by the interviewees.
- Fourthly, the development of software is not included in the Numetrics system scope. When a development project includes the development of new software, Numetrics cannot calculate the total complexity of the project.

Suggested improvements by the interviewees to the system and the use of the system A number of improvements for the Numetrics system itself were suggested by the interviewees:

- Including software development in the system would increase the accuracy of the complexity calculation, in case of a project that includes the development of new software. On top of this, the interaction between hardware design and software design should be captured by the system.
- At this moment, analog design is not described well enough according to the interviewees. Numetrics could be improved by making describing the complexity of analog design better, but interviewees did not elaborate on how this should be done in practice.
- When a new process is developed together with a new project, it should be possible to include this in the complexity calculation.
- A number of interviewees regard the system itself to be very complex to use and filling in the system is seen as a large amount of effort (some interviewees mentioned that often, the added value of Numetrics, compared to complexity estimation based on experience is not seen). Therefore, the usability of the the system could be enhanced.
- The input into the system should be done more systematically and objectively: it should not matter who enters data into the system.
- Not all interviewees agree about the use of Numetrics as a basis for justification of a project's planning. While some interviewees indicated that higher management accepts the outcome of Numetrics as a valid backing, other interviewees believe that higher management does not take the outcomes of Numetrics seriously.
- Since projects receive their resources from a single pool, the outcome of a Numetrics complexity calculation also influences other projects (more or less resources are allocated to a project on the basis of its complexity) and the total project portfolio of a business entity within NXP.
- Interviewees mentioned that the use of Numetrics could be improved by using Numetrics for decreasing a project's complexity, because the complexity calculation should show where (design) complexity comes from in a project and suitable attention should then be given to these complex parts of the design.
- Numetrics only treats the complexity of the product's design. When novel technology or concepts are used in a project, Numetrics cannot accurately describe the complexity of this (the discrepancy between design complexity and technological complexity).

- When only a small number of market players are present, the amount of projects to which a project under study can be compared to is small: therefore, the value of the comparison might be considered as minimal. Since not enough data is available to draw useful conclusions from, the benefits of Numetrics are small in this case.

5.3.5 Complexities mentioned in the cases

Before the interviewees were introduced to the TOE framework, they were asked to mention characteristics of complex projects (that is, projects in general, in which the interviewees were involved or projects from the business line of the interviewee). This section brings together the views of the interviewees, tries to distill commonly encountered complexities in the cases and compares these complexities to the TOE framework (for example by showing where the encountered complexities are described by the framework and if certain complexities are not sufficiently described by the framework). The mentioned complexities are presented in table 5.3. Note that these complexities are *possible* project complexities that could occur in projects in which the interviewees were involved in and do not reflect the complexities that were encountered in the cases that are studied. This approach was chosen to get the broadest possible overview of complexities in projects at NXP.

Out of the 38 mentioned complexities, 17 complexities can be directly related to a complexity in the TOE framework, 3 complexities are roughly described by the TOE framework, and 18 complexities are not described by the TOE framework.

The complexity that is mentioned most often is the dispersion of the project team on *multiple locations*. Interviewees indicated that this is a source of complexity because of the increased complexity of communication between team members. *New technology* and *new combinations of technologies* rank second.

An interesting addition is that the customer is mentioned a number of times explicitly as an important stakeholder (*undetailed customer requirements*, *different customers*). Because products are often developed on the basis of a direct request from a customer, getting the right requirements from these customers is crucial to the success of the project.

A number of mentioned complexities is especially concerned with the particular circumstances in the semiconductor industry: *modelling uncertainties* (which are needed for the simulations that are done before a physical test chip is made); *combination of digital and analog design and verification*; *availability of key IP*; *combination of product and process innovation*; *multiple system architects*. Although these complexities are probably not of very much value to a more general, poly-industrial TOE framework, they would be interesting in an application of TOE to NXP.

5.3.6 TOE scores

During the interviews, each interviewee was asked to fill out a scoring list that contained the TOE framework, on the basis of complexities that were encountered in the project in question. The interviewee could give a score between 1 (complexity did not have an influence on the total complexity of the project) and 5 (complexity had a very large influence on the total complexity of the project). The interviewee could also indicate that a certain complexity was not applicable to the project under study. In this section, we will discuss the scores that were given during the interviews.

The interviewees could give a rank to complexities between 1 and 5. We have made a distinction between three groups of scores: low scores ($1 \leq score \leq 2.25$), intermediate scores ($2.25 < score \leq 3.75$) and high scores ($3.75 < score \leq 5$). Note that a low score on an element does *not* mean that a complexity is not applicable to the project, but that this factor did not have a big influence on the project. Figure 5.2 shows the distribution of TOE scores in a histogram. One can see how the scores fall into the categories that were chosen for this analysis.

In this section we will discuss three categories of elements: the elements that scored high, elements that scored low and elements that had a large number of "not applicable" characterisations. In appendix E, the complete scoring table for all elements in all cases is given.

High scores The elements that scored higher than 3.75 on the score list are shown in table 5.4. In total, four elements from the TOE framework scored a score that was higher than 3.75. Therefore, these

Complexity	Times mentioned	Category	In TOE?
Multiple locations	11	T	Yes
New technology	4	T	Yes
New combinations of technologies	4	T	No
Multiple companies/departments in a single team	3	O	No
Different disciplines	3	O	Yes
Team size	3	O	Yes
Resource availability	3	O	Yes
New market	3	E	No
Undetailed customer requirements	2	E	No
Interactions with other projects	2	E	Yes
Modelling uncertainties	2	T	*
Project approach uncertainties	2	O	No
Risks	2	TOE	Yes
Large number of involved parties	2	O	Yes
Combination of digital and analog design and verification	2	T	No
Number of interactions	2	O	No
Distance between locations	1	O	No
Cultural differences	1	O	No
Influence of higher management decisions	1	E	Yes
Uncertainty due to technology	1	T	Yes
Complex physical details	1	T	Yes
Multiple teams	1	O	*
Different customers	1	E	*
Availability of key IP	1	T	No
Lack of configuration management	1	O	No
Lack of project structure	1	O	No
Dynamics in team composition	1	O	No
Budget size	1	T	Yes
Combination of product innovation and process innovation	1	T	No
Product complexity	1	T	No
Alignment of different development parts	1	TO	No
Complexity of project transfers	1	O	No
Lack of experience in project team	1	O	Yes
Multiple system architects	1	O	No
Number of tasks	1	T	Yes
Lack of knowledge about a technology	1	T	Yes
High time pressure	1	O	Yes
Differences of interests between stakeholders	1	E	Yes

Table 5.3: The complexities that were mentioned by the interviewees, together with a (proposed) category in the TOE framework and the possible presence of the complexity in the TOE framework. * *this complexity is described by a complexity in the TOE framework, but the TOE complexity is more general than this complexity.*

elements contributed most to the projects' complexities.

The first element that scores a high complexity score is the involvement of different technical disciplines (TT5). As was said before, the development of a new chip or process requires the cooperation of a lot of different disciplines. The interviewees declared that the main reason why this element has an influence on complexity is the communication between the different disciplines. The fact that (failing) communication between team members because of different backgrounds can have an influence on team performance is described by Jackson (1996) and van der Vegt and Stuart Bunderson (2005).

The second element that has a high complexity score are the technical risks (TR1). Technical risks can be high in semiconductor projects, according to a number of interviewees (for example, the uncertainty

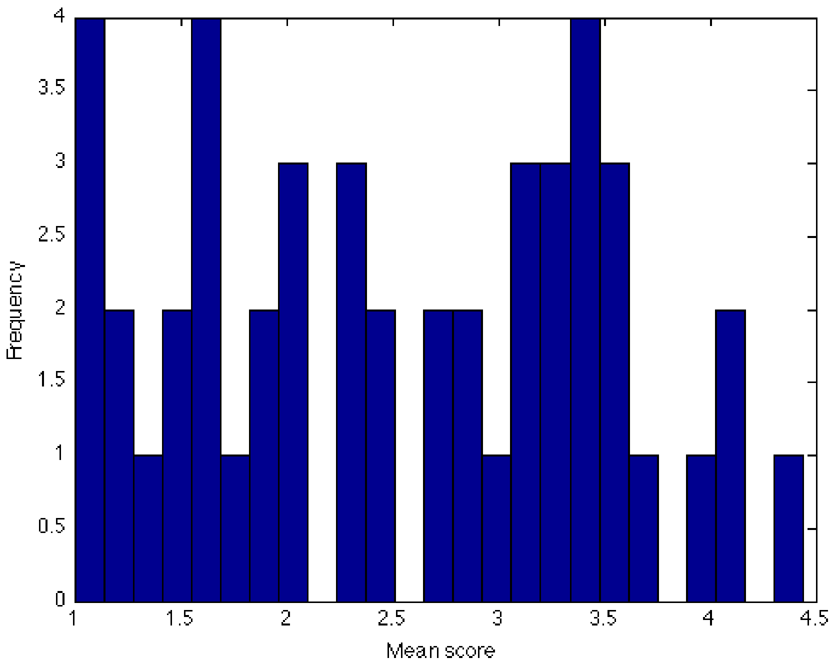

Figure 5.2: A histogram of the average TOE scores in the case studies. Note that three groups of element scores can be distinguished, coinciding with the groups of scores that we have chosen in our analysis

Element code	Element	$\overline{x}$	σ	N
TT5	Involvement of different technical disciplines	4.06	0.68	16
TR1	Technical risks	4.00	1.15	16
ORE1	High project schedule drive	4.44	0.63	16
EM3	Level of competition	4.07	0.59	15

Table 5.4: An overview of the high-scoring elements (scoring more than 3.75) in the TOE framework. The average scores are shown in the column $\overline{x}$, the standard deviation in the score is shown in the column σ and the number of data points (i.e. cases in which a score was given to the element) is shown in the column N.

that is introduced by not having the correct modelling tools has a large influence on the development of products that need these models for simulation of their behaviour).

The third element, high project schedule drive (ORE1), is the highest scoring element. As was shown in the section on the project drivers in the cases, the main drivers in the studied cases are the project's schedule and specifications. Because competition can be fierce (see the fourth high-scoring element), there is a large drive to realize the project's deliverables within schedule and specifications, which has a large influence on the project's complexity.

The fourth high scoring element is the level of competition in the market (EM3). The market in which NXP operates is often highly competitive. This directly influences the complexity of the project, because the market competition pressure directly influences development projects. Because of market pressure, a higher strain is put onto project teams to finish the development within less time.

Low scores The elements that scored less than 2.25 on the score list are shown in table 5.5. The complexities that scored low did not have a large influence on the total complexity of the projects, but are by no means not relevant.

We will not discuss all low-scoring complexities separately, but some general remarks are made about these complexities. Two distinct themes can be seen in the data: the influence of a centralized framework for product development and the fact that most projects are carried out as "internal" projects.

Element code	Element	$\overline{x}$	σ	N
TG2	Non-alignment of project goals	1.87	1.06	15
TG3	Unclarity of project goals	1.81	1.17	16
TS1	Uncertainties in scope	2.00	1.26	16
TT6	Conflicting norms and standards	1.58	0.90	12
ORE6	Number of financial sources	1.17	0.58	12
ORE7	Number of contracts	1.90	1.20	10
OP2	Number of different languages	2.00	1.00	15
OM1	Incompatibility between different project management methods/tools	1.67	1.11	15
OT1	Trust in the project team	1.50	0.97	16
OT2	Trust in contractor	1.22	0.44	9
ES2	Variety of stakeholders' perspectives	2.00	1.00	15
ES5	Lack of company internal support	1.56	1.09	16
EL4	Lack of experience in the country	1.57	1.13	7
EM2	Instability of externalities	1.54	0.97	13

Table 5.5: Low-scoring elements (scoring less than 1.25). The average scores are shown in the column $\overline{x}$, the standard deviation in the score is shown in the column σ and the number of data points (i.e. cases in which a score was given to the element) is shown in the column N.

The framework that is used for the development of new products influences the unclarities about the projects' goals and scope (elements TG2, TG3 and TS1). Therefore, the internal support that is provided from within the company is also regarded as having an influence on the complexity (to be precise, the project's complexity is lowered by having a framework that streamlines the product creation process, according to an interviewee). The complexities that are associated with this are OM1 and ES5.

In the cases that were studied, most project teams only consisted of NXP employees. Although sometimes activities are contracted out to other parties (such as the development of specialized IP), most tasks are carried out by internal teams. This means that often, the number of external contracts (ORE7) that are used is low and only a single financial resource is used for the project (ORE6). Trust within the project team (OT2) and trust in the contractor (OT1) are therefore also not a big issue in the cases. The fact that most projects are carried out within the company itself also means that there is no lack of experience in the country (EL4) where the project is executed (since the projects are carried out on the existing sites of the company) and the externalities are mostly stable (EM2).

Non-applicable elements The interviewees also had the possibility to mark certain complexities as ”not applicable” to their project. These complexities did not only have a low influence on the project's complexity, they are also considered not to be relevant to the project by the interviewees.

Element code	Element	$\overline{x}$	σ	N	% NA
ORE4	Lack of HSSE awareness	1.00	0.00	4	75
OP3	Presence of a JV partner	3.50	0.71	2	88
ES4	Political influence	1.00	0.00	3	81
ES6	Required local content	1.33	0.58	3	81
EL2	Weather conditions	1.00	0.00	2	88
EL3	Remoteness of location	1.00	0.00	3	81

Table 5.6: Elements in the TOE framework that received a ”Not-applicable”-mark in more than or equal to 75% of the cases.

HSSE (health, safety, security and environment) awareness (ORE4) is not considered as a big issue by the interviewees. Although these factors are taken into account in the normal way of working, the awareness is not explicitly brought forward in the project's execution.

Since the project is normally carried out on the existing sites of the company, political influence (ES4), required local content (ES6), weather conditions (EL2) and remoteness of location (EL3) do not have an influence on the project's complexity.

Special interest has to be given to element OP3: Presence of a JV partner. In 14 out of 16 cases, no JV (joint venture) partner was present. However, in the two remaining projects in which a JV partners was present, this presence contributed to the total complexity of the project (the element scored 3 and 4 out of 5 in these projects). Therefore, we cannot dismiss the presence of a JV partner from the list of complexities related to NXP projects.

5.3.7 Missing elements in the TOE framework

After the interviewees were introduced with the TOE framework, they were asked if there were any complexities that occurred in their projects, but which are not sufficiently covered by the TOE framework. For each T, O, E category these complexities are listed below (the elements that were already mentioned by the interviewees before the interviewees were introduced to the TOE framework [section 5.3.5] are highlighted and the amount of times that a complexity was mentioned when the interviewees were asked to extend TOE are shown in parentheses):

Technical complexities

- The influence of the complexity of the design on technical complexity (1)
- The availability of modelling tools (3)
- First of a kind design (1)
- Availability of necessary technology (1)
- The amount of reuse (3)
- Are the architectures of all key deliverables at the moment of project base lining known and feasible? (1)
- The development of a main building block instead of redesign of an existing block (1)
- Inhouse development of blocks or development by third party (1)
- Use of new design tools (1)
- Amount of change in requirements (1)
- Number of spins (1)
- Trust in the expected number of spins (1)
- New application (for the company) (1)

Organizational complexities

- The soundness of the business case (2)
- Type of organization: functional/matrix (2)
- Presence of marketing department inside or outside project team (1)
- Differences in responsibility with respect to the organization (1)
- Clearness of achievements (requirements management), availability of tools to track requirements (1)
- Project subdefinitions (subdivision into sub-projects, etc.) (1)
- Availability of non-technical skill within the project team (1)

External complexities

- Differences in stakeholder interests (1)
- Influence of customers (2)
- Change of customer requirements/relation (3)
- Clarity of roadmaps and strategy (clear direction, priorities) (1)
- Inconsistent governance policy (1)
- Influence of NXP OPEX (1)
- Availability of support organizations to support complex projects (1)
- Changes in IT environments/migrations (1)
- Presence of a single key customer (1)
- Insight in market development (1)

One can observe that the complexities that were mentioned before and after the introduction of the TOE framework, do not fully match. Furthermore, not all complexities that were mentioned are complexities per se, but can also be seen as comments on the TOE framework.

5.3.8 Views on projects in the semiconductor industry

As a closing question in the interview, the interviewees were asked to explain what makes projects in semiconductor projects different from projects in other industries. In general, interviewees regarded this question as a hard question, because most interviewees only have had working experience within the semiconductor industry. Nonetheless, the main characteristics that were mentioned by the interviewees are shown next:

- With time, the products that are being developed in the semiconductor industry are becoming increasingly complex. This means that on average, product development projects also become more complex and higher demands are put onto the processes that are used. Also, there is a "law-like" tendence that on average, the costs of a product go down with time. These characteristics combined mean that there is a large pressure from the market onto companies in the industry to produce their products at lower costs and with better specifications in time.
- The semiconductor industry is seen as a cyclical industry[2] by the interviewees (since companies in the industry produce parts of complete products, intermediate goods, they are dependent on the production of end products, such as consumer electronics, cars or other devices). As a consequence, the revenues of companies in this industry are dependent on the economic situation. Because intermediate goods are produced, projects sometimes have to follow the annual cycle of other markets, such as the Christmas sales peak for televisions. This directly influences the time pressure that is put on projects that develop products for these markets.
- Cooperation of teams in different places: since a large part of the production of a chip is done in the far east, it is not unusual that project teams are dispersed over the world. This means that team members often cannot interact tłte--tłte, but need to communicate using other tools, such as conference calls or e-mail. This makes communication within the project team more complex than direct communication.
- According to a number of interviewees, risks are treated differently than in other industries. In the semiconductor industry, the risks are often mitigated by accepting the risks, since the impact of these is regarded as being low. However, some interviewees note that risks in fact can have a large impact on the project (for example with respect to project slip) and risk mitigation should have a more prominent role.

[2]An industry that is strongly influenced by the economic cycle.

- Technology plays an important role in semiconductor industry projects. Therefore, the person that leads the project should have extensive knowledge about and experience with semiconductor projects. Combined with the fact that semiconductor projects are often not large (in comparison to other industries), the project manager is closely involved with the development with the project. Therefore, the project manager is directly involved with the work on the project and has a role that is less a governing type of role than in other industries.
- An important characteristic of the development of semiconductor products is the complicated nature of the fabrication process. Therefore, it takes a long time and it is expensive to produce prototypes/test chips. This means that one already has to be quite certain about the correct functioning of a product before a prototype design can be send to the fab. It is therefore essential that good simulation tools exist that correctly predict the behaviour of a chip. The long duration of producing a test chip therefore has a large influence on the schedule of a project, when extra spins need to take place in the development phase of the product.
- Although the products that are developed can be quite different, the flow of product development projects is fairly uniform, going from design to testing, etc.
- Relative small size of projects (project leader close to work being done). In comparison to projects in other industries (e.g. the oil industry), projects are relatively small.

5.4 Discussion

In the preceding section we have seen a number of analyses applied to the cases: on the background of the interviewees, about common characteristics in the different types of projects that were encountered in this research project, concerning the drivers of the studied projects, about the use of Numetrics, an overview of complexities that were encountered in the project, how the TOE framework fits the projects and finally how the interviewees perceive their industry. Next to understanding the cases that were studied in this research project, a goal of these analyses is to provide a starting point to the application of the TOE framework to the company, which will be the subject of the following chapter.

Before we go on to the application, a short comparison is made between the findings of the case studies and the literature that was described in chapter 1:

- Iansiti and West (1999) and West (2000) note that there is a significant difference between research (R) and development (D) activities in the semiconductor industry. This was also observed in the cases, where in some cases the cooperation of both disciplines created extra complexity in the project.
- West (2000) observes that new semiconductor products often operate at the frontier of what is technically or physically possible. We have also observed this in the cases, in particular in the way in which existing simulation models can describe the behaviour of these devices.
- Considering the article by Hobday (1998), we can recognize a number of characteristics of complex products and systems (CoPS) in a number of cases, such as:
  - *"Complex component interfaces"*, such as cases 2 and 8.
  - *"Multi-functional"*, such as cases 11 and 12.
  - *"Many skill/knowledge inputs"*, such as cases 3 and 11.
  - *"Hierarchical/systemic"*, such as cases 11 and 12.
  - *"User-producer driven"*, such as cases 13 and 16, see also the section in the cross case analysis on the influence of the customer on the development of a new product.
  - *"Business to business"*, in all product development projects, products were developed for use in products of the (business) customer.
- Looking at the marks that were given to the different types of complex by the interviewees, one can see that technical complexity is the dominant source of complexity in the studied projects. This can also be seen in the mean scores of the TOE elements: the weighted averages of the scores are (out of 5): T-scores: 3.03; O-scores: 2.52; E-scores: 2.38.

Chapter 6

Adapting and Applying the TOE Framework

On the basis of the gathered data, a start is made with the synthesis of this data towards an adaptation of the TOE framework. We make a distinction between two versions of the TOE framework: an adapted version of the framework that would be suitable for use at NXP, to assess the possible presence of certain complex characteristics in development projects, and a general version of the framework, that could find its application in a larger number of industries.

This chapter consists of three sections: in the first section, the results of the case studies are put to use, on the basis of the existing TOE framework and the empirical data that was gathered in this research project; in the second section, a proposal is made for a possible practical application of the framework for use at NXP, by removing elements that are not applicable for NXP and adding elements that were missing in the original framework, but came forward during the case studies; in the third section, the general TOE framework is extended on basis of the findings in the empirical part of this research project.

6.1 Results from the empirical research

This section summarizes the results of this research project concerning the elements of the TOE framework. First, a number of elements that received high ″not-applicable″ scores during the interviews are discussed. Next, a number of complexities that were mentioned during the interviews, but which are not yet part of the existing TOE framework are considered.

6.1.1 Unapplicable elements

During the interviews, six elements from the existing TOE framework scored notably higher ″not-applicable″-scores than other elements (these elements were marked ″not-applicable″ in more than 75% of the cases, whereas the next element in this ranking scored ″not-applicable″ in 56% of the case). Out of these six elements, there is one element that stands out: OP3 (Presence of a JV partner). Although this element scored a ″not-applicable″-score in 88% of the cases, it did score reasonably high scores in the cases in which it did play a role. Sometimes projects are executed together with JV partners at NXP. Therefore, we cannot conclude that the presence of a JV partner is not applicable to NXP projects in general and we opine that it should be present in the adapted NXP version of the TOE framework.

The other elements that scored high ″not-applicable″-scores also had low scores in the projects in which a score was given to these elements. We therefore believe that these elements are not applicable for the use of the TOE framework at NXP and suggest that these elements be excluded from the adapted TOE framework. An overview of the elements which are suggested to be removed is given in table 6.1.

Element	Description
ORE4	Lack of HSSE awareness
ES4	Political influence
ES6	Required local content
EL2	Weather conditions
EL3	Remoteness of location

Table 6.1: Overview of the elements which are suggested to be taken out of the TOE framework in adapted form.

6.1.2 New elements

The interviewees were also asked to which elements could contribute to a form of the TOE framework that would suit NXP. To find out which elements would contribute to this, the interviewees were first asked to share their views on what characterizes complex projects in their experience and their business line or product line, before they were introduced to the TOE framework. This way, we were able to receive information from the interviewees, where the interviewees were not influenced by knowledge about the TOE framework. Secondly, the interviewees were asked which elements were missing in the TOE framework. The answers to these questions could then lead to new elements, which correctly describe the situation in NXP projects.

Since finding out which elements are missing is quite different from finding out which existing elements are obsolete - the former question requires *exploratory* research, whereas the latter question requires *descriptive* research - another approach is necessary to answer this question. What we therefore do is to look at the mentioned elements and try to find common characteristics and patterns between these elements in the different cases, in order to get to an extra set of complexities that is both not too general and not too specific.

To allocate categories to the new complexities, we have used the following definitions (from the existing TOE framework): technical (T) elements are those elements that directly involve the technical characteristics of the project or project deliverables; organizational (O) elements are those elements that are not directly technical in nature, but which are directly related to the project team and the organization thereof; external (E) elements are those elements that have an influence on the project, but which are not directly related to or controlled by the project team.

The following complexities, which are not a part of the existing TOE framework, were mentioned more than once by the interviewees before they were introduced to the TOE framework (between parentheses, the number of times the complexity is mentioned and a proposed category is shown):

- New combinations of technologies (4, T)
- Multiple companies/departments in a single team (3, O)
- New market (for the company) (3, E)
- Undetailed customer requirements (2, E)
- Project approach uncertainties (2, O)
- Combination of digital and analog design & verification (2, T)
- Number of interactions between team members and stakeholders (2, O)

There is also a complexity that could be allocated to an existing complexity in the TOE framework, but the existing description of the complexity is defined much more general than the description that is given by the interviewees: the presence of correct modelling tools for simulations. The existing TOE framework describes this complexity as ”Uncertainty in methods” (TT4), but the (lack of) availability of modelling tools is a complexity that has such a big influence on projects, that it might be defended that this complexity should be in an extended version of TOE.

The following complexities were mentioned during the question about which complexities are missing from the TOE framework. The complexities that are shown were mentioned more than twice (again, the number of times the complexity is mentioned and the proposed category of the complexity is shown between parentheses):

- Availability of modelling tools (3, T)
- Amount of (design) reuse (3, T)
- Soundness of the business case (2, O)
- Type of organization: functional/matrix (2, O)
- Influence of customers (2, E)
- Change of customer requirements/relation (3, E)

In the next sections, we will present the decision criteria that are chosen for the two versions of the TOE framework and the changes that are made to the framework in these two versions.

6.2 Towards the application of TOE at NXP

Two steps are taken to adapt the existing TOE framework for application at NXP: removing the elements which are not applicable to the company and by adding extra elements which are not yet present in the existing TOE framework.

Removing elements As we have seen in the case studies, a number of elements in the existing TOE framework can be considered ”not-applicable”, therefore, these elements are removed in the adapted version of the framework:

- Lack of HSSE awareness (ORE4)
- Political influence (ES4)
- Required local content (ES6)
- Weather conditions (EL2)
- Remoteness of location (EL3)

Adding new elements As a decision criterion for choosing elements that are added to the applied TOE framework, elements must have been mentioned at least twice before *or* after the interview was introduced to the TOE framework (in the questions C1 and C2.1 until C2.3, see the interview protocol in appendix D). Using this decision criterion, we end up with 13 new elements (4 technical, 5 organizational and 4 external), which are presented in tables 6.2, 6.3 and 6.4.

About the elements that have been marked by a star, it can be argued that these elements are already described in general terms by existing elements in the framework. However, we have chosen to include these elements, since they describe complexities that are encountered often in the activities of NXP. Therefore we believe that it is justified to include these elements in the TOE version that is tailored to NXP.

Complexity	Proposed sub-category
New combinations of technologies	Experience
*Combination of digital and analog design & verification	Tasks
*Availability of modelling tools	Tasks
*Amount of (design) reuse	Tasks

Table 6.2: Overview of the elements which are suggested to be added to the technical complexities in the applied framework.

Complexity	Proposed sub-category
Soundness of the business case	Resources
Multiple companies/departments in a single team	Project team
Number of interactions between team members and stakeholders	Project team
Type of organization (functional/matrix)	Project team
Project approach uncertainties	Methods

Table 6.3: Overview of the elements which are suggested to be added to the organizational complexities in the applied framework.

Complexity	Proposed sub-category
Undetailed customer requirements	Customer
Influence of customers	Customer
Change of customer requirements/relation	Customer
New market	Market conditions

Table 6.4: Overview of the elements which are suggested to be added to the external complexities in the applied framework

Suggestions for application In her PhD thesis, Bosch-Rekveldt (2011) proposed a possible way of implementing the TOE framework. We will follow a comparable approach that was taken in this thesis, with the adapted TOE framework. A parallel with the Numetrics approach is also drawn.

In the future, a first application of the framework could transform into a series of protocols, in which procedures are laid out that can be followed when certain complexities are present in a project. However, developing these procedures in detail would involve a significant amount of work and are outside the scope of this research project.

Analogously to the Numetrics approach, the TOE framework could be applied to projects at NXP. However, since the TOE approach would be more general than the Numetrics approach, it would be suitable for a larger group of projects than Numetrics. By plotting complexity characteristics from the TOE framework to variables such as project execution time and work effort (which to a large degree determines the amount of resources that is needed for a project), one could get an image of how different projects relate to each other in terms of performance and what can be expected for project that are being planned. To achieve this, a clear and unambiguous definition of the elements is needed (probably with examples that treat worst and best case scenarios). As we have seen in the cross case analysis, all interviewees have a technical background (see section 5.3). Because the project managers often have a good understanding of the technical challenges that are present in their projects, this should be taken to our advantage in the implementation: the question that can be asked to the interviewee can be technically advanced. This should improve the precision with which complexity can be assessed. The next step in the application of the framework is to get the necessary data from a larger group of projects and to how this data is distributed (in an analogous way to how this is done in Numetrics, c.f. figure 4.9). The historical data on projects that is present in the company should provide a valuable starting point to understand how complexity influenced these projects.

The outcome of an analysis that uses the adapted TOE framework could for example yield an advice to the approach that should be taken for a project: if many uncertainties exist about the outcome of the project, a "study" approach might be best (and consequently, a certain type of project team member would be needed who is suited for the type of tasks that are related to this type of projects). On the other hand, if the type of activities that is needed for the development of a new product is fairly straight forward, the "implementation" type of project might be better suited, together with a particular team composition. Also, the application of the TOE framework should shed light on the amount of effort that would be needed to successfully execute the project under analysis (both in terms of the amount of work effort that is needed, as well as the expected number of iterations that would be necessary). One of the outputs of the Numetrics systems is a "complexity value" that gives an indication of the complexity of the product that is being designed. Although it would be a useful measure to communicate the complexity of a project to other parties, it remains to be seen if a similar approach to the TOE

Code	Complexity	Applicable?
TG1	Number of project goals	☐
TG2	Non-alignment of project goals	☐
TG3	Unclarity of project goals	☐
TS1	Uncertainties in scope	☐
TS2	Strict quality requirements	☐
TS3	Project duration	☐
TS4	Size in CAPEX	☐
TS5	Number of locations	☐
TE1	Newness of technology (world-wide)	☐
TE2	Experience with technology	☐
TE3	New combinations of technologies	☐
TT1	Number of tasks	☐
TT2	Variety of tasks	☐
TT3	Dependencies between tasks	☐
TT4	Uncertainty in methods	☐
TT5	Involvement of different technical disciplines	☐
TT6	Conflicting norms and standards	☐
TT7	Combination of digital and analog design & verification	☐
TT8	Availability of modelling tools	☐
TT9	Amount of (design) reuse	☐
TR1	Technical risks	☐

Table 6.5: Example of a possible TOE form (T-complexities), based on the adapted TOE framework

Code	Complexity	Applicable?
ORE1	High project schedule drive	☐
ORE2	Lack of resource & skills availability	☐
ORE3	Lack of experience with parties involved	☐
ORE4	Interface between different disciplines	☐
ORE5	Number of financial sources	☐
ORE6	Number of contracts	☐
ORE7	Soundness of the business case	☐
OP1	Number of different nationalities	☐
OP2	Number of different languages	☐
OP3	Presence of a JV partner	☐
OP4	Involvement of different time zones	☐
OP5	Size of the project team	☐
OP6	Multiple companies/departments in a single project team	☐
OP7	Number of interactions between team members and stakeholders	☐
OP8	Type of organization (functional/matrix)	☐
OM1	Incompatibility between different project management methods/tools	☐
OM2	Uncertainties in project approach	☐
OT1	Trust in project team	☐
OT2	Trust in contractor	☐
OR1	Organizational risks	☐

Table 6.6: Example of a possible TOE form (O-complexities), based on the adapted TOE framework

Code	Complexity	Applicable?
ES1	Number of external stakeholders	□
ES2	Variety of external stakeholder's perspectives	□
ES3	Dependencies on external stakeholders	□
ES4	Lack of company internal support	□
EC1	Undetailed customer requirements	□
EC2	Influence of customer	□
EC3	Change of customer requirements/relation	□
EL1	Interference with existing site	□
EL2	Lack of experience in the country	□
EM1	Company internal strategic pressure	□
EM2	Instability of the environment	□
EM3	Level of competition	□
EM4	New market	□
ER1	External risks	□

Table 6.7: Example of a possible TOE form (E-complexities), based on the adapted TOE framework

implementation would be a valuable addition. Namely, reducing the complexity of a project to a single factor might be too much of a simplification to draw useful conclusions from. The minimal description of complexity would be to assign three complexity values to a project, for each category in the framework. Therefore, the implementation of TOE would have more use in assessing the *type* of complexities that can be encountered during a project, than in assessing the amount of complexity. TOE is more qualitative in nature than Numetrics. This means that a translation from TOE to numbers such as the necessary *amount* of effort or productivity would be quite a large challenge.

A number of articles were published that link certain properties of project managers to properties of projects (such as project complexities) (Müller et al., 2007; Lewis et al., 2002; Turner and Müller, 2005; Bosch-Rekveldt et al., 2009). This literature could provide a valuable starting point for choosing the right team composition for projects with certain characteristics (which follow from filling out the TOE framework). Of course, existing knowledge within the organization should also be taken into account in choosing the right team composition.

As we can see, the application of the framework is far from finished. However, a complete worked-out version of the framework that would be available for practical use in the company would require an effort that is outside the scope of this research project. In a future implementation of TOE at the company, one should take into account a number of things. The amount of time it would take to fill in the framework and the possibilities of the outcome should be assessed, to see if the application of the framework would have use to the company. To be able to compare different projects or project types, a database could be made that would enable the user to make comparisons between these projects (in a fashion comparable to Numetrics, but more focussed on the type of complexities that are encountered in stead of the amount of complexity). In principle, TOE would be applicable to a more general sample of projects than Numetrics. That being said, Numetrics and TOE should not be seen as competitors, but as complementary tools.

6.3 The general TOE framework

Concerning the general TOE framework (a framework that would be suitable for more than just one company and even for more than one industry), the approach that we utilize is different from the applied version of the TOE framework. In the general version, no existing elements are removed from the framework. Also, the decision criterion that is used to include new elements to the framework is more strict: the elements have to be mentioned at least three times in the question before *or* after exposure to the TOE framework and the elements have to be independent from other elements in the existing TOE framework. Combining this, we end up with 4 new elements (one technical, one organizational and two external). These new elements are presented in table 6.8.

It would be interesting to see how the framework would change if more industries would be investigated. In addition, by extending the research effort to other companies in the semiconductor industry, the results from this research project can be validated or extended (if more or other elements would be added to the general framework).

Type	Complexity	Proposed sub-category
Technical	New combinations of technologies	Experience
Organizational	Multiple companies/departments in a single team	Project team
External	Change of customer requirements/relation	Customer
External	New market	Market conditions

Table 6.8: Overview of the elements which are suggested to be added to the external complexities in the general framework

We will shortly discuss why these elements can have an influence on the total complexity of a project.

Not only new technologies themselves can have an influence on the complexity of a project, new combinations (interrelations) of technologies can also have an influence on complexity (c.f. Baccarini (1996)). Since from these new combinations unforeseen problems can occur (emergent problems), the existence of these combinations have to be taken into account in the assessment of complexity of a project.

When multiple companies or departments work together in a single project team, this can lead to communication problems between team members (this is related to having multiple technical disciplines in a single project team). These communication problems can result from the difference in cultures or jargon that can exist between different companies or departments. Therefore, this complexity can have an influence on project performance.

Uncertainty about the exact requirements of a customer or the relation between the customer and the project team can lead to more complexity in the project. This is because this can lead to scope uncertainties. The customer can play an important role in the execution of the project and we therefore believe that this complexity should be mentioned separately.

A new market will have an influence on the complexity of a project because the company and project team will need to go through a learning curve on what the dynamics of the new market are. In a way, this complexity is related to the complexity that describes unfamiliarity with a technology in the project team, because it describes a lack of experience within the project team. However, this element can be considered an external complexity, since it is not only concerned with the technical aspects of the project.

Chapter 7

Conclusions and Discussion

In this final chapter, the conclusions are presented, the results are discussed and suggestions for future research are given.

7.1 Conclusions

To answer the main research question, the answers to the sub-questions are discussed in this section.

Research question 0: What characteristics define projects and project management at NXP?

The main purpose of this question was to get an overview of how projects are executed and managed at NXP. Central in the development process of new products and new technologies is the BCaM framework. Section 4.1.1 describes this framework in more detail. The framework provides a structure on which project execution is based. The framework itself is not completely rigid in the sense that all projects have to be executed in the same manner. However, if necessary it can be adapted to meet the needs of a particular project. The well-defined structure of the project makes it easier to compare the maturity of different development projects. Especially the "gate structure" makes it clear in which phase a project is, which deliverables have been produced and are going to be produced. However, a number of interviewees have indicated that in some cases, the gates are quite far apart in time. This situation can have a negative influence on the focus in the project team. To cope with this situation, some project managers choose to include extra gates in the project schedule, to maintain focus in the team.

In addition, the case studies gave a number of pointers to the characteristics of projects at NXP. As several interviewees mentioned, projects are almost always executed by multidisciplinary teams. The reason for this is the wide variety of expertises that are necessary to develop a new product or process in the semiconductor industry. Moreover, teams are often dispersed over different locations, sometimes even over different continents. This dispersion has profound implications on the way different team members can communicate with each other. Since there is a constant market pressure on the company, the company needs to develop innovative products constantly. This research project has shown that the main drivers behind the project are the specifications of the project and the schedule (see section 5.3.3). Several interviewees indicated that a good support structure is present in the company to assist the project teams to achieve their goals. The BCaM framework is one of the ways in which this is brought forward.

Research question 1: Which factors play a role in the degree of complexity of typical projects at NXP?

To answer this question, a number of steps have been taken. During the interviews, the interviewees were asked to explain what characterizes complex projects. Next, the TOE framework was introduced to the interviewees and they were asked to give rankings to the different complexities in the framework, with respect to the project about which they were interviewed. Finally, the interviewees were asked to indicate which complexities were still missing in the framework, according to their own experience.

Emerging from these research steps, a number of complexities have come forward that play a role in the total complexity of the projects studied. The complexities from the existing TOE framework that scored the highest scores were: "Involvement of different technical disciplines" (TT5), "Technical risks" (TR1), "High project schedule drive" (ORE1) and "Level of competition" (EM3).

Next to the complexities from the existing TOE framework, several other complexities were mentioned by the interviewees (see the conclusions related to research question 4). In general, one can say that the main sources of complexity encountered in NXP projects are the technical complexity of the product itself (e.g. the ability to model the behaviour of a product under development before a test product is made) and the influence of the market. A complete overview of the analysis of project complexities can be found in section 5.3.

Research question 2: What possibilities does Numetrics provide to model and manage complexity?

The Numetrics framework was developed for assessing the complexity of a semiconductor product design. Section 4.2 discusses the way in which Numetrics can be used to determine the complexity of a new product.

The basis of the Numetrics approach is the comparison between a new development and other (comparable) products on the market. These products can be both from the same company as well as market competitors. This comparison can be done in a number of ways: firstly, by filling in the characteristics of a new product design, Numetrics can generate a "bottom-up" project plan. Secondly, an existing project plan can be "benchmarked" to other projects in the database, to see whether certain assumptions which are done in the planning match with the execution of other projects in the database. Thirdly, after a project is finished, the project can be compared to other projects in the database, to see how the performance of the project team relates to other projects in the database.

Numetrics is mainly concerned with the complexity of the product design, and does not take into account a number of factors that could contribute to the total complexity of the project. Therefore, the complexity value given by the system only reflects a *part* of the total complexity of a project. Moreover, the system is dependent on the existing database of projects. When a certain product is developed that is developed by a small number of market players only, the database will also be small and comparisons of a newly developed product with other products on the market will be hard to do. In this sense, this is a difficult situation, since companies will not be willing to enter more data into the system if not enough data to compare to is present. Another improvement that could be made to the system is the inclusion of software development into the system. At this moment, it is not possible to include software development into the complexity calculation.

Research question 3: How is Numetrics currently being used at NXP?

As became clear in the case studies, not all product development projects use or have used Numetrics. This is due to a number of reasons: firstly, Numetrics is not suitable for all projects. Especially when chips with a large number of analog components are developed, the complexity of that design is not captured well enough by Numetrics, according to the interviewees. Secondly, a number of interviewees criticizes the system because of its complexity. Numetrics is perceived as a complex system, which does not provide much benefits to the user, if one compares it to an experience-based approach to assess the complexity of the project. Besides, the interviewees also believe that there is (too) much room for a subjective input of data into the system. Some interviewees opine that the user has a large influence on the complexity value that the system calculates. These interviewees therefore perceive the added value of the system to be minimal. Thirdly, not all project managers knew the system exists.

On the other hand, some interviewees noted that the outcome of Numetrics was closer to the actual execution of the project than the prediction the project managers made themselves. In one case, the number of spins had to be adjusted, where the final number of spins was correctly predicted by Numetrics.

Although the reuse of existing parts is included in the system, one interviewee noted that the interaction between different reused components (which in theory could come from different designs) is not described sufficiently by Numetrics. This situation has an influence on the reliability of the complexity calculation.

Not all interviewees agree on the degree that Numetrics provides benefits to provide a rationale for the choices that are made with respect to planning and staffing. While some interviewees indicated that higher management takes the outcomes of the system serious and accept the outcome of the system as a good motivation to the choices that the system makes, other interviewees indicate that the outcome of the system is not taken seriously by the management.

In the projects that were studied during this research project, Numetrics was mainly used for benchmarking of the project plan (schedule risk analysis) and to benchmark the project after the finish of the project. For these analyses to provide benefits, it is important that a large enough set of projects exist in the database, to compare the project to. Interviewees that have used the system often mention that the design complexity of the product is described well by the system and that the outcome (prediction) of the system often agrees with the actual execution of the project. However, it is critical that the project is compared to a set of similar projects, otherwise the comparison does not have much added value.

Research question 4: How does the TOE framework potentially need to be adapted to meet the needs of NXP?

To see whether the existing TOE framework fits the current situation at NXP, a number of steps have been taken: firstly, the interviewees were asked which complexities are encountered in projects in which they or their department are involved. Secondly, they were asked to give scores to the elements of the existing TOE framework, related to the degree of applicability of these elements to the project which was discussed during the interview. Thirdly, the interviewees were asked to indicate which encountered complexities were missing in the existing TOE framework.

For the next step, a distinction is made between an adapted version that would be useful for application at NXP and the general TOE framework.

From the data gathered during the interviews, the elements that had high "not-applicable"-scores were identified and elements that were not yet part of the TOE framework, which were mentioned multiple times, were discerned. In total, five elements that were not applicable are removed from the framework. These elements are shown in table 6.1. 13 new elements (four technical, five organizational and four external elements) are added to the TOE framework to capture the complexities that are encountered in NXP projects. The new elements are concerned with: new combinations of technologies, availability of models and design reuse (technical elements); multiple companies or departments in a single project team, project approach uncertainties, interaction intensity with stakeholders, soundness of the business case and type of organization (functional/matrix) (organizational elements); new market and interactions with customers (external elements). The new elements are presented in more detail in section 6.2. Together, these elements make up a TOE framework that could be used at NXP to assess the complexities of (new) projects.

For the general TOE framework, which would be suitable for use in multiple industries, we propose to add four new elements to the framework, no elements are removed from the original framework. The new elements are concerned with: new *combinations* of technologies; multiple companies or departments in a single project team; change in customer requirements/relation; a new market.

Research question 5: How can the TOE framework be applied at NXP to help managing project complexity?

Based on the adapted TOE framework, a score chart was made that could be used by project managers to get an impression of where complexity can come from in development projects which are executed at NXP. However, this chart is only a first step towards the application of a framework such as the TOE framework. A possible way of applying TOE is by using a similar approach as is used by Numetrics: by making clear definitions of the elements of the TOE framework, information about the project's scores could be entered into a system and different projects could be compared to each other. This comparison would not only be limited to product development project, but also process developments could be benchmarked this way. In addition, this type of implementation would allow the user to assess the credibility of the project's planning and estimate the type of effort that is expected to be necessary for the project.

Main question: What benefits does the application of the TOE framework provide for projects at NXP?

Combining the conclusions that can be drawn from the sub-questions, we can formulate an answer to the main research question:

Applying the TOE framework would certainly provide benefits for projects at NXP. As we have seen in the case studies, complexities can have a large influence on the project's execution and success. Therefore, a tool that can assess the complexity and sources of complexity of a project would be valuable. At this moment, such a tool already exists (i.e. Numetrics), but the application span of this tool is limited to certain product development projects. Therefore, it would be useful if a tool would exist that could also assess the complexity of a more general class of (development) projects. The adapted version of the TOE framework could fulfil this role.

The TOE framework could also help choosing the right approach to a project (e.g. the project type) and the type of project team that could bring the project to a successful end.

7.2 Discussion

The main goal of this research project was to find out if the TOE framework matches the practice at NXP, in which way the TOE framework (potentially) should be adapted to match this practice and to make the first step in the application of the TOE framework at NXP. To find out which complexities play a role in NXP projects, we have conducted case studies, in which 16 NXP projects were studied by means of interviews with project managers.

Validity, generalizability and applicability to NXP The approach taken has a number of limitations, as was discussed in chapter 3. Since a limited number of cases has been studied in this research project, one could ask the question whether this number of cases is sufficient to draw general conclusions out of the data that was gathered. We ensured this by making a selection of cases that covers a broad number of subjects in which the company is active. To be able to cover this number of subjects, we have chosen to limit the number of interviewees per case to one.

To ensure the construct validity and reliability of the findings, all interviews have been recorded and the worked out interviews have been sent back to the interviewees (reference check method). Therefore, we could make sure that we have written down what the interviewees thought to have said.

The case studies that have been performed have yielded results about the ways in which way complexities influenced these cases and to which degree each complexity had an influence on the projects. Since 16 projects have been investigated in this research project, research should be done on more cases (both within the company as well as within other companies in the semiconductor industry). This would allow the researcher to see if the results that were found in this research project are also more generally applicable.

Application A first step has been made towards a possible application of the TOE framework to the current practice at NXP. However, more (research) effort would be needed to successfully implement the TOE framework as a usable tool. The way in which Numetrics assesses complexity could be used as a starting point to apply the TOE framework as a complexity assessment tool.

7.3 Suggestions for further research and application at NXP

Within this research project, a first step is made towards the possible application of TOE at NXP. However, the proposed application of TOE would first need to be further (validated) before it could be applied. For example, a survey could be set up that tests the relevance and usefulness of the framework, which would provide the researcher with a larger population of projects that can be compared. In this way, a larger number of projects could be reached. Next to the score card that has been made, protocols could be developed on the basis of this list of complexities that would help the project manager when certain complexities are present in a project and to provide the project manager with support to cope with these complexities.

For further application of TOE, the amount of effort that is needed from a project manager to fill in the framework would need to be assessed. This would have to be compared to the possible benefits of using the framework. The main benefit of the use of the framework would probably be the estimation of the *type* complexities that are encountered during a project. Therefore, the combination of Numetrics and TOE would give a combined overview of the expected amount and type of complexities. On top of this, TOE can be applied to a more general class of projects, i.e. not only to product development projects, for example also to process development projects or maintenance projects.

Not all business units are represented in the selection of cases. This is because not all business units are based in the Netherlands. Therefore, it would be interesting for a future research project to also study projects from the parts of NXP that were not covered by this research project.

One of the of the goals of the complete effort that is made to do research on the TOE framework is the way in which the framework can be applied to different industries, such as the semiconductor industry. Since this research project only focussed on a single company in this industry, a logical extension of this effort would be to carry out research projects in other companies in the semiconductor industry. This way, it would become clear if the findings of this study only apply to the company in which this research project was carried out or that these findings can be generalized to the total industry (to some degree).

As was brought forward in the introductory chapter, interesting parallels can be drawn between the semiconductor industry and the pharmaceutical industry. Therefore, it would be very interesting to perform the same research exercise in that industry, too. This way, one could see whether parallels can also be found in project complexities that are encountered in these industries.

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Nijmegen, 15 september 2011

As with any research project, this project is the result of the combined work of a number of people. Therefore, I would like to take the opportunity to thank the people who helped realising this work.

After finishing my first master's research project, I started looking for a project to do to finish my Management of Technology degree. During this master, the project management course was one of the courses that I enjoyed most in the program. Therefore, I went to this section to be informed about the possibilities to do my graduation on a project management-related subjected. It turned out that this was possible and that it was even possible to do this project inside a company, which was one of my preferences for the project. Incidentally, it turned out that this company – NXP – operated in an industry that was closely related to my other master: the semiconductor industry.

The first person I would like to thank is Marian, my main supervisor from the university, for supporting me throughout my project and always being there for advise. Frank, thank you for showing me around in the company and for interesting discussions that helped my thesis go forward. Cor, thank you for giving me the opportunity to do the research project at NXP and the discussions we had were very interesting and inspiring. Herman, as chair of my graduation committee, you addressed a number of very interesting points that have certainly helped improving my work. Scott, as my second supervisor, you made sure that the scientific content of my thesis was on par and your suggestions have been very helpful.

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Concluding, the past half year has been a very interesting time and experience for me. I have had the opportunity to take a look inside a very interesting company and meet inspiring people. I hope that the work that I have done will be of use to the company.

Finally, I would like to thank my parents who have helped me a lot by being a big support to me during my studies and by always giving me freedom to make the choices that I wanted to make.

Bibliography

P.W. Anderson. More is different. *Science*, 177(4047):393–396, 1972.

T. Arita and P. McCann. The spatial and hierarchical organization of Japanese and US multinational semiconductor firms. *Journal of International Management*, 8:121–139, 2002.

D. Baccarini. The concept of project complexity - a review. *International Journal of Project Management*, 14(4):201–204, 1996.

M. Bosch-Rekveldt. *Managing project complexity*. PhD thesis, Delft University of Technology, 2011.

M. Bosch-Rekveldt, C. Gulden, B. Wolsing, H. Mooi, A. Verbraeck, and E. Sjoer. Mapping project manager's competences to project complexity. *23th IPMA 2009 World Congress*, 2009.

M. Bosch-Rekveldt, S. Hermanides, H. Mooi, Bakker H., and A. Verbraeck. The influence of project front end management and project complexity on project success. *PMI Research and Education Conference 2010*, 2010a.

M. Bosch-Rekveldt, Y. Jongkind, H. Mooi, H. Bakker, and A. Verbraeck. Grasping project complexity in large engineering projects: The TOE (Technical, Organizational and Environmental) framework. *International Journal of Project Management*, 2010b.

H. Bulsink. Foundation of Project Execution. Internal document, 2008a.

H. Bulsink. Foundation of Project Planning. Internal document, 2008b.

H. Bulsink. Foundation of Project Monitoring and Control. Internal document, 2009.

T.D. Cook and D.T. Campbell. *Quasi-experimentation: design & analysis issues for field settings*. Rand McNally College Publications co., 1979.

T.J. Cooke-Davies, S.J.K. Cicmil, L.H. Crawford, and K. Richardson. We're not in Kansas anymore, Toto: Mapping the strange landscape of complexity theory, and it relationship to project management. *Project management journal*, 38(2):50–61, 2007.

J. Diamond and J.A. Robinson, editors. *Natural Experiments of History*. Belknap Harvard University Press, 2010.

P. Erdi. *Complexity Explained*. Springer-Verlag, 2008.

D. Ford. Semiconductor revenue expands by record margin in 2010. 2010.

M. Friedman. The use of ranks to avoid the assumption of normality implicit in the analysis of variance. *Journal of the American Statistical Association*, 32:675–701, 1937.

S. Gerards and C. Weeks. Foundation of Project Portfolio and Pipeline Management (3PM) v1.9. Internal document, 2008.

R.M. Henderson and K.B. Clark. Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms. *Administrative Science Quarterly*, 35(1):9–30, 1990.

D.K. Hitchins. *Systems Engineering: a 21st century systems methodology*. John Wiley and Sons, Inc., 2007.

M. Hobday. Product complexity, innovation and industrial organisation. *Research Policy*, 26:689–710, 1998.

M. Hobday, A. Davies, and A. Prencipe. Systems integration: a core capability of the modern corporation. *Industrial and corporate change*, 14(6):1109–1143, 2005.

M. Iansiti and J. West. From physics to function: an empirical study of research and development performance in the semiconductor industry. *Journal of Product Innovation Management*, 16:385–399, 1999.

Intel, 2011. URL `newsroom.intel.com/community/intel_newsroom/blog/2011/01/31/intel-identifies-chipset-design-error-implementing-solution`.

S.E. Jackson. The consequenses of diversity in multidisciplinary work teams. In *Handbook of work group psychology*, chapter 3. John Wiley & Sons, Ltd., 1996.

J. Jacobs and K. de Vaal. Foundation of Verification & Validation. Internal document, 2008.

T. Jenkins. A brief history of ... semiconductors. *Physics Education*, 40(5):430–439, 2005.

S.B. Johnson. Three approaches to big technology: operations research, systems engineering, and project management. *Technology and Culture*, 38:891–919, 1997.

K. Kot. Foundation of Requirements Engineering. Internal document, 2008a.

K. Kot. Foundation of Life cycle construction. Internal document, 2008b.

K. Kot, S. Gerards, and C. Weeks. Roles and responsibilities. Internal document, 2008.

M.W. Lewis, M.A. Welsh, G.E. Dehler, and S.G. Green. Product development tensions: exploring contrasting styles of project management. *Academy of Management Journal*, 45(3):546–564, 2002.

K. Lim. The relation between research and innovation in the semiconductor and pharmaceutical industries (1981-1997). *Research Policy*, 33:287–321, 2004.

G.E. Moore. Cramming more components onto integrated circuits. *Electronics*, 38(8), 1965.

R. Müller, J.G. Geraldi, and J.R. Turner. Linking complexity and leadership competences of project managers. *IRNOP VIII Conference (International Research Network for Organizing by Projects)*, 2007.

Numetrics Management Systems, Inc. `http://www.numetrics.com`.

Numetrics Management Systems, Inc. Key performance indicators of IC development capability - a framework. White Paper, 2005.

Numetrics Management Systems, Inc. Ic development capability - what to measure? White Paper, 2010.

NXP. BCaM 6.0 Documentation. NXP Intranet, 2010.

R.P. Oisen. Can project management be defined? *Project management quarterly*, 2(1):12–14, 1971.

Project Management Institute. *A guide to the Project Management Body of Knowledge (PMBOK®)*. Project Management Institute, Inc., 4th edition, 2008.

K. Remington, R. Zolin, and J.R. Turner. A model of project complexity: distinguishing dimensions of complexity from severity. *Proceedings of the 9th International Research Network of Project Management*, 2009.

A.J. Shenhar. One size does not fit all projects: exploring classical contingency domains. *Management Science*, 47(3):394–414, 2001.

A.J. Shenhar and D. Dvir. Toward a typological theory of project management. *Research Policy*, 25: 607–632, 1996.

H.A. Simon. The architecture of complexity. *Proceedings of the American Philosophical Society*, 106:467–482, 1962.

S. Solomon and B. Shir. Complexity; a science at 30. *Europhysics News*, 34(2):54–57, 2003.

R.D. Stacey. The science of complexity: an alternative perspective for strategic change processes. *Strategic Management Journal*, 16(6):477–495, 1995.

M. ten Have. Foundation of Technology and IP Roadmapping (TIR) v0.3. Internal document, 2010.

N. Tredennick. Technology and business: forces driving microprocessor evolution. *Proceedings of the IEEE*, 83(12):1641–1652, 1995.

J.R. Turner and R. Müller. The project manager's leadership style as a success factor on projects: a literature review. *Project management journal*, 36(2):49–62, 2005.

G.S. van der Vegt and J. Stuart Bunderson. Learning and performance in multidisciplinary teams: the importance of collective team identification. *Academy of Management Journal*, 48(3):532–547, 2005.

M. van der Velde, P. Jansen, and N. Anderson. *Guide to management research methods*. Blackwell Publishing Ltd, 2004.

J. van Helvoort. Complexity in IT projects. Master thesis, Delft University of Technology, 2011.

P. Verschuren and H. Doorewaard. *Het ontwerpen van een onderzoek*. Lemma, 1995.

S.T. Walsh, R.L. Boylan, C. McDermott, and A. Paulson. The semiconductor silicon industry roadmap: Epochs driven by the dynamics between disruptive technologies and core competencies. *Technological Forecasting & Social Change*, 72:213–236, 2005.

J. Wentink. Project complexities in maintenance projects. Master thesis, Delft University of Technology, 2010.

J. West. Institutions, information processing, and organization structure in research and development: evidence from the semiconductor industry. *Research Policy*, 29:349–373, 2000.

J. West and M. Iansiti. Experience, experimentation, and the accumulation of knowledge: the evolution of r& d in the semiconductor industry. *Research Policy*, 32:809–825, 2003.

C. Williams. Intel's Pentium chip crisis: an ethical analysis. *IEEE Transactions on Professional Communication*, 40(1):13–19, 1997.

T. Williams. *Modelling Complex Projects*. John Wiley & Sons, Ltd., 2002.

R.K. Yin. *Case study research: design and methods*. Sage Publications, Inc, 2003.

Appendix A

The TOE framework

In this appendix, an overview is given of the existing TOE framework, that was developed by Bosch-Rekveldt et al. (2010b).

Sub-ordering	ID	Elements defined	Explanation
Goals	TG1	Number of project goals	What is the number of strategic project goals?
Goals	TG2	Non-alignment of project goals	Are the project goals aligned?
Goals	TG3	Unclarity of project goals	Are the project goals clear amongst the project team?
Scope	TS1	Uncertainties in scope	Are there uncertainties in the scope?
Scope	TS2	Strict quality requirements	Are there strict quality requirements regarding the project deliverables?
Scope	TS3	Project duration	What is the planned duration of the project
Scope	TS4	Size in CAPEX	What is the estimated CAPEX of the project?
Scope	TS5	Number of locations	How many site location are involved in the project, including contractor sites?
Experience	TE1	Newness of technology (world-wide)	Did the project make use of new technology, e.g. non-proven technology?
Experience	TE2	Experience with technology	Do the involved parties have experience with the technology involved?
Tasks	TT1	Number of tasks	What is the number of tasks involved?
Tasks	TT2	Variety of tasks	Does the project have a variety of tasks (e.g. different types of tasks)?
Tasks	TT3	Dependencies between tasks	What is the number and nature of dependencies between the tasks?
Tasks	TT4	Uncertainty in methods	Are there uncertainties in the technical methods to be applied?
Tasks	TT5	Involvement of different technical disciplines	To what extent do technical processes in this project have interrelations with existing processes?
Tasks	TT6	Conflicting norms and standards	Are there conflicting design standards and country specific norms involved in the project?
Risk	TR1	Technical risks	Do you consider the project being high risk (number, probability and/or impact of) in terms of technical risks?

Table A.1: Technical complexities in the TOE framework.

Sub-ordering	ID	Elements defined	Explanation
Resources	ORE1	High project schedule drive	Is there strong project drive (cost, quality, schedule)?
Resources	ORE2	Lack of resource& skills availability	Are the resources and skills required in the project available?
Resources	ORE3	Lack of experience with parties involved	Do you have experience with the parties involved in the project (JV partner, contractor, supplier, etc.)?
Resources	ORE4	Lack of HSSE awareness	Are involved parties aware of health, safety, security and environment (HSSE) importance?
Resources	ORE5	Interfaces between different disciplines	Are there interface between different disciplines involved in the project that could lead to interface problems?
Resources	ORE6	Number of financial sources	How many financial resources does the project have (e.g. own investment, bank investment, JV-parties, subsidies, etc.)?
Resources	ORE7	Number of contracts	
Project team	OP1	Number of different nationalities	What is the number of different nationalities involved in the project team?
Project team	OP2	Number of different languages	How many different languages were used in the project for work or work related communication?
Project team	OP3	Presence of JV partner	Do you cooperate with a JV partner in the project?
Project team	OP4	Involvement of different time zones	How many overlapping office hours does the project have because of different time zones involved?
Project team	OP5	Size of the project team	How many persons are within the project team?
Methods	OM1	Incompatibility between different project management methods/tools	Are there incompatible project management methods or tools used?
Trust	OT1	Trust in project team	Do you trust the project team members (incl JV partner if applicable)?
Trust	OT2	Trust in contractor	Do you trust the contractor(s)?
Risk	OR1	Organizational risks	Do you consider the project being high risk (number, probability and/or impact of in terms of organizational risk?

Table A.2: Organizational complexities in the TOE framework.

Sub-ordering	ID	Elements defined	Explanation
Stakeholders	ES1	Number of external stakeholders	What is the number of stakeholders (all parties (external) around the table, NGOs, suppliers, contractors, governments)?
Stakeholders	ES2	Variety of external stakeholders' perspectives	Do different external stakeholders have different perspectives?
Stakeholders	ES3	Dependencies on external stakeholders	What is the number and nature of dependencies on external stakeholders?
Stakeholders	ES4	Political influence	Does the political situation influence the project?
Stakeholders	ES5	Lack of company internal support	Is there internal support (management support) for the project?
Stakeholders	ES6	Required local content (forced cooperation with local parties)	What is the required local content?
Location	EL1	Interference with existing site	Do you expect interference with the current site or the current use of the (foreseen) project location?
Location	EL2	Weather conditions	Do you expect unstable and/or extreme weather conditions; could they potentially influence the project progress?
Location	EL3	Remoteness of location	How remote is the location?
Location	EL4	Lack of experience in the country	Do the involved parties have experience in that country?
Market conditions	EM1	Company internal strategic pressure	Is there internal strategic pressure from the business?
Market conditions	EM2	Instability of the environment	Is the project environment stable (e.g. exchange rates, oil price, raw material price, etc.)?
Market conditions	EM3	Level of competition	What is the level of competition (e.g. related to market conditions)?
Risk	ER1	Risks from environment	Do you consider the project being high risk (number, probability and/or impact of) in terms of risk from the environment?

Table A.3: External complexities in the TOE framework

Appendix B

Elements of the BCaM framework

This appendix gives further information on the elements of the BCaM framework, which were described in section 4.1.

B.1 Project Portfolio and Project Management (3PM)

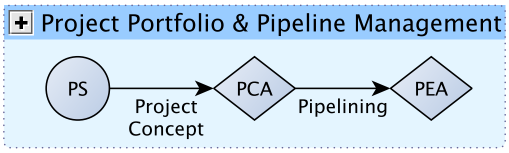

Figure B.1: A closeup of the Project Portfolio & Pipelining stage.

Element	Description
Project Start(PS)	*Start of the project.*
Project concept sketch	*"A quick, initial assessment of a new concept."*
Project Concept Approval (PCA)	*"Check whether project concept fits within strategy, satisfies the roadmap and required deliverables are available."*
Pipelining	*"Balancing of resource capacity and demand."*
Project Execution Approval (PEA)	*"Execution is approved when the resource pipeline scenario meets demands."*

Table B.1: Overview of the elements in the Project Portfolio & Pipelining Management phase.

B.2 Project Execution

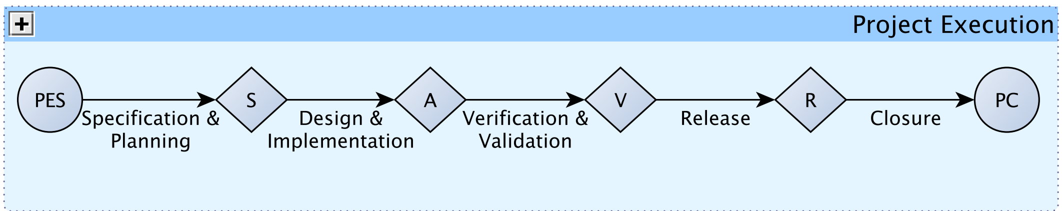

Figure B.2: A closeup of the Project Execution stage.

Element	Description
Project Execution Start (PES)	*Start of project execution*
Specification & Planning phase	*"Establishing scope and specifications of the project, developing the project plan and mitigate project risks."*
"Specified" (S) gate	*"Agreement on project end goal requirements and specifications, and project approach."*
Design & Implementation phase	*"Designing, implementing and verifying component parts and agreeing on customer acceptance plan."*
"Available" (A) gate	*"Check on availability of product components and readiness for testing."*
Verification & Validation phase	*"Integrating and verifying the product and validating against requirements."*
"Validated" (V) gate	*"Check on match with specifications and fulfillment of requirements at S-gate."*
Release Preparation phase	*"Obtain external approvals and prepare for release."*
"Released"(R) gate	*"Agreement that the product can be released to the customer and post-release care has been set up."*
Project Closure phase	*"Capturing best practices and improvement (lessons learned), archiving and disbanding project team."*
Project Closure (PC) milestone	*End of the project, when all project deliverables have been produced.*

Table B.2: Overview of the elements in the Project Execution phase.

B.3 Sub-Process Areas

Project Management Processes

Process	Description
Project Planning (PP)	*"Establishing and maintaining plans that define project activities."*
Project Monitoring & Control (PMC)	*"Providing methods to monitor the project's progress and planning appropriate corrective actions."*
Risk Management (RSKM)	*"Managing risks from project start to project closure."*
Supplier Agreement Management (SAM)	*Activities related to managing the project's suppliers.*

Table B.3: Overview of Project Management Processes

Engineering Processes

Process	Description
Requirements Engineering	*"All the activities required to create and maintain a set of requirements."*
Verification & Validation	*"Providing appropriate visibility into, and feedback on, verification and validation activities and associated work products."*
Review & Inspection	*"Detecting and repairing defects in work products as early as possible."*

Table B.4: Overview of Engineering Processes

Supporting Processes

Process	Description
Resource (Allocation) Management (RAM)	*"Planning and managing the resource pool in an effective and efficient way."*
Data Management (DM)	*"Controlling and preserving data generated by the activities of the various BCaM processes."*
Quality Assurance (QA)	*"an independent, planned and systematic approach to the verification of compliance to processes, associated procedures and standards."*
Measurement & Analysis	*"Developing and sustaining a measurement capability that is used to support management information needs."*

Table B.5: Overview of Supporting Processes

B.4 Actor descriptions

In this sections, the actors are discussed that are involved in the BCaM framework, but which are not essential to this research project. The way these actors interact with the other actors in the BCaM framework is shown in figure 4.7.

External actors from inside the company

Project Portfolio Review Board (PPRB)
The role of the project portfolio review board is to make sure that the project portfolio follows the integral roadmaps. From these portfolios, projects will be defined, according to the available resources. The project portfolio review board consists of a number of senior managers (among them is the business unit/business line manager) and it operates at the business unit/business line level.

→ Defines the project portfolio on basis of the resource pipeline that was established by the pipeline and resource management operations team.

← Sees to it that the project portfolio is aligned with the integral roadmaps.

Project Review Board (PRB)
The project review board is responsible for approving projects, monitoring projects during gate reviews and milestones (and make go/no-go decisions), checking the business situation for a project, determining cross-project priorities. The project review board usually consists of senior managers, from different disciplines. At which level the project review board operates, depends on the importance of the project.

→ Approves, reviews and monitors the project.

← Receives reports from the project (core) team.

Pipeline and Resource Management Operations Team (PRMOT)
Because a project needs resources to be executed, a pipeline and resources management operations team makes sure that resources are available to the project, on the basis of optimization of the resource pipeline. This ensures that a balance exists between the needed staffing of projects and the available staff. The pipeline and resource management operations team consists of the resource managers of the groups that are involved with projects in the pipeline.

→ Allocates resources to the project.

→ Establishes the resource pipeline that is used by the project portfolio review board.

External Actors from outside the company

Not all actors that are related to a project are part of the company. Who these actors are and what relation they have with the project and project team is elaborated next (Kot et al., 2008).

The Customer
Officially, the customer can be both internal and external. It is also possible that a project has several customers. Customer requirements are taken into account by adding these to the project requirements.

→ Receives the end product that was delivered by the project team.

← Provides the project team with customer requirements.

Suppliers
Some projects need additional inputs from external suppliers.

→ Provides necessary inputs to the project team.

Sub-contractors
For some projects, parts of the project are outsourced to external parties.

→ Delivers the parts of the project that were sub-contracted.

Appendix C

Numetrics Complexity Factors

This appendix gives a more extensive overview of the inputs and outputs of the Numetrics that were introduced in section 4.2. The information in this appendix was extracted from the Numetrics system website. Numetrics divides the inputs of the system into two categories: properties of the chip design as a whole and properties of the different blocks that make up the chip.

C.1 Chip characteristics

The following characteristics only have be filled in once for the whole chip design:

Process Parameters:
Parameters in this category describe process-related properties of the design, such as: the minimum process geometry (smallest feature size), the average metal pitch (distance between metal layers) and the number of metal layers.

Digital Logic (Excluding Processor Cores):
The number of logic gates that is used in the design.

Power:
The minimum and maximum internal operating voltage, the number of supply voltages and the minimum, average and maximum amount of power that is used.

Power Management:
Properties related to the way power is managed on the chip, such as the presence of multiple independent power islands and the number of power modes.

Processor Cores:
The properties of processor cores that are used in the design (for instance in an microprocessor design project).

Timing and clocking:
Timing and clocking properties of the design, such as the clock frequency and the number of independent clock domains.

Memory (Excluding Processor SRAM):
The amount of memory (measured in KBytes or MBytes), type of memory and number of memory blocks.

IO Pads:
The number of signal input/output pads on the die.

Analog/Mixed-signal:
Amount of analog transistors that is used and the amount of circuit reuse.

Design Highlights:
Properties of the chip design, such as the design style, the way the chip is bonded to the substrate, the operating temperature range of the chip, the size of the die, the area that is occupied by analog or mixed-signal circuits and the number of input/output signals.

Design for Test:
Properties of the test procedures that are used.

Additional Lifecycle Management Data:
Miscellaneous other properties of the design, such as the potential use of new IC packaging, the maximum operating temperature and the thermal resistance of the package.

C.2 Block complexity

The following properties have to be filled in for each block that is a part of the chip design:

Number of Blocks:
The amount of independent blocks on the chip.

Type of Block:
The type of block (analog/mixed signal or logic).

Function of Block:
The function of a certain block.

Design Style:
The way in which the physical layout of the block is implemented on the chip. Ranging from pre-defined styles to completely custom design.

Instance Count:
Number of instances of a certain block on the chip.

Transistors per Instance:
Amount of transistors used on the block.

Frequency Maximum:
Maximum operating frequency in the block in MHz.

Voltage Operating Min:
Minimum operating voltage on the block.

Data Path Bits:
Number of data path bits used in a block (cf. a 64-bit processor).

% Logic Transistors:
Percentage of transistors on the block that is used in digital circuits.

% Memory Transistors:
Percentage of transistors that is used for data storage on the block.

% Analog Transistors:
Percentage of transistors that is used in analog circuitry in the block.

% Specification Reuse:
The percentage of the specification of a block that was not made by the design team, but taken from an earlier design.

% Verification Reuse:
The percentage of testing activities of a block that was not developed by the design team, but taken from an earlier design.

% RTL/Circuit Reuse:
The percentage of RTL (register transfer level) or circuit design that was not developed by the design team, but taken from an earlier design.

% Layout Reuse:
The percentage of the block's layout that was not designed by the design team, but taken from an earlier design.

% New Design:
The percentage of new design of the block (equal to 100% - the sum of reuse percentages).

% Chip Verification Reuse:
The percentage of testing activities on a chip level that was not developed by the design team.

Voltage Operating Max:
Maximum operating voltage of the block.

Capacitors per Instance:
Number of capacitors in a given block.

Resistor Ratio Tolerance:
The amount of variance in resistance value that is allowed in a given block.

% CMOS Transistors:
Percentage of CMOS (complementary metal oxide semiconductor)-type transistors in the block.

% Bipolar Transistors:
Percentage of bipolar transistor in the block.

% DMOS Transistors:
Percentage of DMOS (double-diffused metal oxide semiconductor)-type transistors in the block.

% HBT Transistors:
Percentage of HBT (heterojunction bipolar transistor)-type transistors in the block.

Maximum Current Consumption:
The maximum current that a block is allowed to consume.

Minimum Rating:
Minimum rating of the block.

Maximum Rating:
Maximum rating of the block.

Minimum Block Operating Voltage:
Minimum voltage the block needs to operate.

C.3 Complexity measures and performance indicators

Numetrics defines so-called "Key Performance Indicators" (Numetrics Management Systems, Inc., 2005), which give an overview of the design complexity of a design project. These key performance indicators are discussed in table 4.2. Next to the key indicators, there are a number of other indicators that are part of the system's output.

Reuse Leverage:
Percentage of project effort that is avoided by reusing existing knowledge (a measure for the amount of reuse in a project).

Functional Productivity:
The average rate of output per individual of a design project, in which reuse is not taken into account.

Functional Throughput:
The average rate of output of a design project, in which reuse is not taken into account.

Total Silicon Spins/Total IP Deliveries:
The amount of mask sets that was produced, to test the functionality of an almost-finished chip design.

Indicator	Description
IC Design Complexity	*"1) Level of project difficulty and 2) quantification of development team's output (i.e. what the team designed)."* Measured in Complexity Units (CU).
IC Development Productivity	*"Average rate of output per individual on a development team."* Measured in Complexity Units per person-week.
IC Development Throughput	*"Average rate of output for the entire development team."* Measured in Complexity Units per week.
IC Development Cycle Time	*"Elapsed IC development time, from project start to volume production."* Measured in weeks.
Total IC Project Effort	*"Total laber expended during development time."* Measured in person-weeks.
IC Project Schedule Slip	*"Difference between originally planned cycle time and actual cycle time."* Measured in %.
Total Silicon Spins	Number of mask sets that is made to assess whether the product is ready for mass-production. Measured in numbers
Total IC Development Cost	*"Total cost of IC[project]'s development."* Measured in amount of financial resources.
IC Development Cost per Complexity Unit	*"Development cost per unit of output [complexity]"* Measured in \$/CU or euro/CU.
IC Functional Complexity	*"Richness of IC's feature set and its performance"* Note that this value does not take into account the possible reuse of knowledge from earlier projects, so it is a measure for the "total" complexity of a design project. Measured in Functional Complexity Units (FCU).

Table C.1: The Key Performance Indicators of the Numetrics framework. From (Numetrics Management Systems, Inc., 2005).

The performance indicators in the table above are not independent. The relations between indicators are:

- $IC\_Development\_Productivity = \frac{Design\_Complexity}{Average\_Staffing * Time} = \frac{Design\_Complexity}{Total\_IC\_Project\_Effort}$
- $IC\_Development\_Throughput = \frac{Design\_Complexity}{Time}$
- $Total\_IC\_Project\_Effort = Average\_Staffing * Time$
- $IC\_Project\_Schedule\_Slip = \frac{Actual\_Time - Planned\_Time}{Planned\_Time}$
- $IC\_Development\_Cost\_per\_Complexity\_Unit = \frac{Cost}{Design\_Complexity}$
- $IC\_Functional\_Complexity = \frac{Design\_Complexity}{1 - Reuse}, 0 \leq Reuse \leq 1$

Appendix D

Interview Questions and TOE Score List

Code	Question Type	Question
General questions		
A1	Information	Name
A2	Information	Nationality
A3	Information	Background (education, etc)
A4	Information	At which Business Unit/Business Line do you work?
A5	Information	What PM training did you follow?
A6	Information	Working experience in years, type of business, responsibilities
A7	Information	Role in project under study?
A8	Information	During which phases were you involved in the project?
General question about the project		
B1	Information	What was the project objective?
B2	Information	What was the main project driver (specs, cost, time)?
B3	Information	Which internal/external stakeholders were involved in the project?
B4	Information	What stakeholder roles can you identify?
B5	Perspective	What made this project different from other projects in which you were involved?
B6	Perspective	Do you consider this project to be a success? In what way?
Project Complexities		
C1	Perspective	What characteristics does a complex project have in your opinion?
C2	Perspective	Can you identify and scale complexities from the TOE framework in relation to this project?
C2.1	Perspective	Can you identify more technical complexities in this project?
C2.2	Perspective	Can you identify more organizational complexities in this project?
C2.3	Perspective	Can you identify more external complexities in this project?
C3.1	Perspective	Do you think this was a technically complex project? (Scale 1-10)
C3.2	Perspective	Do you think this was an organizationally complex project? (Scale 1-10)
C3.3	Perspective	Do you think this was an environmentally complex project? (Scale 1-10)
C4	Perspective	Which complexities had the biggest influence on this project?
Project Management		
D1	Perspective	How did project complexities influence the project?
D2	Perspective	How did you manage/mitigate these complexities?
D3	Perspective	Did any project complexities change during the course of the project?
D4	Information	How was the BCaM framework used in this project?
Numetrics		
E1	Information	Was Numetrics used in this project?
E2	Information	For what purpose was Numetrics used? (project plan synthesis, schedule risk analysis, benchmarking)
E3	Perspective	Did the use of Numetrics provide benefits to the project? If yes, which benefits and how? If no, why?
E4	Perspective	Do you think that Numetrics accurately describes complexities that were encountered in the project?
E5	Perspective	Do you think that the Numetrics system could be improved? If yes, how?
E6	Perspective	Do you think that the use of Numetrics at NXP could be improved? If yes, how?
Semiconductor projects		
F1	Perspective	In your opinion, what makes semiconductor industry projects different from projects in other industries?
F2	Perspective	What are typical complexities in semiconductor projects, in your view?
Closing		
G1	Perspective	Do you have any questions or other things you would like to discuss?
G2	Information	Thank you for the interview. Would you be willing to review the interview report?

ID	Elements defined	Explanation	Not Appl.	1	2	3	4	5	Applicable
TG1	Number of project goals	What is the number of strategic project goals?							
TG2	Non-alignment of project goals	Are the project goals aligned?							
TG3	Unclarity of project goals	Are the project goals clear amongst the project team?							
TS1	Uncertainties in scope	Are there uncertainties in the scope?							
TS2	Strict quality requirements	Are there strict quality requirements regarding the project deliverables?							
TS3	Project duration	What is the planned duration of the project?							
TS4	Size in CAPEX	What is the estimated CAPEX of the project?							
TS5	Number of locations	How many site locations are involved in the project, including contractor sites?							
TE1	Newness of technology (world-wide)	Did the project make use of new technology, e.g. non-proven technology?							
TE2	Experience with technology	Do the involved parties have experience with the technology involved?							
TT1	Number of tasks	What is the number of tasks involved?							
TT2	Variety of tasks	Does the project have a variety of tasks (e.g. different types of tasks)?							
TT3	Dependencies between tasks	What is the number and nature of dependencies between the tasks?							
TT4	Uncertainty in methods	Are there uncertainties in the technical methods to be applied?							
TT5	Involvement of different technical disciplines	To what extent do technical processes in this project have interrelations with existing processes?							
TT6	Conflicting norms and standards	Are there conflicting design standards and country specific norms involved in the project?							
TR1	Technical risks	Do you consider the project being high risk (number, probability and/or impact of) in terms of technical risks?							
ORE1	High project schedule drive	Is there strong project drive (cost, quality, schedule)?							
ORE2	Lack of resource & skills availability	Are the resources and skills required in the project available?							
ORE3	Lack of experience with parties involved	Do you have experience with the parties involved in the project (JV partner, contractor, supplier, etc.)?							
ORE4	Lack of HSSE awareness	Are involved parties aware of health, safety, security and environment (HSSE) importance?							
ORE5	Interfaces between different disciplines	Are there interface between different disciplines involved in the project that could lead to interface problems?							
ORE6	Number of financial sources	How many financial resources does the project have (e.g. own investment, bank investment, JV-parties, subsidies, etc.)?							
ORE7	Number of contracts	How many different contracts were used in the project?							
OP1	Number of different nationalities	What is the number of different nationalities involved in the project team?							
OP2	Number of different languages	How many different languages were used in the project for work related communication?							
OP3	Presence of JV partner	Do you cooperate with a JV partner in the project?							
OP4	Involvement of different time zones	How many overlapping office hours does the project have because of different time zones involved?							
OP5	Size of the project team	How many persons are in the project team?							
OM1	Incompatibility between different project management methods/tools	Are there incompatible project management methods or tools used?							
OT1	Trust in the project team	Do you trust the project team members (incl JV partner if applicable)?							
OT2	Trust in contractor	Do you trust the contractor(s)?							
OR1	Organizational risks	Do you consider the project being high risk (number, probability and/or impact of) in terms of organizational risk?							
ES1	Number of external stakeholders	What is the number of stakeholders (all parties (external) around the table, NGOs, suppliers, contractors, governments)?							
ES2	Variety of external stakeholders' perspectives	Do different external stakeholders have different perspectives?							
ES3	Dependencies on external stakeholders	What is the number and nature of dependencies on external stakeholders?							
ES4	Political influence	Does the political situation influence the project?							
ES5	Lack of company internal support	Is there internal support (management support) for the project?							
ES6	Required local content (forced cooperation with local parties)	What is the required local content?							
EL1	Interference with existing site	Do you expect interference with the current site or the current use of the (foreseen) project location?							
EL2	Weather conditions	Do you expect unstable and/or extreme weather conditions; could the potentially influence the project progress?							
EL3	Remoteness of location	How remote is the location?							
EL4	Lack of experience in the country	Do the involved parties have experience in that country?							
EM1	Company internal strategic pressure	Is there internal strategic pressure from the business?							
EM2	Instability of the environment	Is the project environment stable (e.g. exchange rates, oil price, raw material price, etc.)?							
EM3	Level of competition	What is the level of competition (e.g. related to market conditions)?							
ER1	Risks from environment	Do you consider the project being high risk (number, probability and/or impact of) in terms of risk from the environment?							

Appendix E

TOE Scores

In this appendix, the scores that were given to the complexities of the TOE framework are shown per TOE category (tables E.1, E.2 and E.3). To save space, numbers were given to the different cases.

TOE	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	Mean	S.D.	N	NA	% NA
TG1	3	4	1	1	4	2	2	3	1	3	3	4	3	2	5	2	2.69	1.20	16	0	0 %
TG2	1	2	1	1	1	2	1	2	1	2	1	3	4	*	4	2	1.87	1.06	15	1	6 %
TG3	1	1	1	1	1	2	2	2	1	4	4	4	1	1	1	2	1.81	1.17	16	0	0 %
TS1	2	1	1	1	4	2	2	2	2	2	4	5	1	1	1	1	2.00	1.26	16	0	0 %
TS2	4	5	1	1	4	5	3	2	4	5	5	4	2	1	5	2	3.31	1.58	16	0	0 %
TS3	2	4	3	4	4	4	4	3	4	4	2	4	5	3	2	2	3.38	0.96	16	0	0 %
TS4	2	5	4	3	5	3	3	5	3	4	5	3	4	5	2	1	3.56	1.26	16	0	0 %
TS5	2	5	2	5	3	1	1	5	3	2	5	1	4	3	3	2	2.94	1.48	16	0	0 %
TE1	1	4	3	5	4	5	1	5	2	1	2	3	5	4	4	2	3.19	1.52	16	0	0 %
TE2	1	1	2	4	4	5	2	4	4	1	4	4	3	2	2	2	2.81	1.33	16	0	0 %
TT1	2	5	3	5	5	4	1	4	4	4	3	3	5	4	3	2	3.56	1.21	16	0	0 %
TT2	3	4	3	5	5	4	2	4	3	4	2	4	5	3	3	4	3.63	0.96	16	0	0 %
TT3	3	4	2	5	4	3	3	3	1	1	4	5	4	4	4	3	3.31	1.20	16	0	0 %
TT4	2	4	4	4	4	4	3	4	5	4	4	2	4	1	3	1	3.31	1.20	16	0	0 %
TT5	3	5	4	4	5	4	3	4	4	4	5	5	4	4	4	3	4.06	0.68	16	0	0 %
TT6	1	1	1	1	1	2	*	2	1	1	*	*	2	*	4	2	1.58	0.90	12	4	25 %
TR1	3	4	4	4	4	5	5	4	2	5	5	5	5	4	4	1	4.00	1.15	16	0	0 %

Table E.1: An overview of the T-element scores in the TOE scoring list. **Not applicable.*

TOE	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	Mean	S.D.	N	NA	% NA
ORE1	4	5	4	5	4	5	4	5	5	4	5	4	4	5	5	3	4.44	0.63	16	0	0 %
ORE2	1	2	3	2	5	3	3	4	4	4	4	4	5	4	2	4	3.38	1.15	16	0	0 %
ORE3	1	1	2	1	2	3	*	4	4	4	4	4	4	2	2	2	2.67	1.23	15	1	6 %
ORE4	1	*	*	1	*	*	*	*	*	1	*	*	*	1	*	*	1.00	0.00	4	12	75 %
ORE5	1	3	3	1	3	3	1	4	4	2	4	1	1	3	2	1	2.31	1.20	16	0	0 %
ORE6	1	1	*	1	1	1	*	1	1	1	*	1	3	1	1	*	1.17	0.58	12	4	25 %
ORE7	1	*	*	1	1	1	*	3	*	*	4	1	3	3	1	*	1.90	1.20	10	6	38 %
OP1	3	4	3	5	1	4	*	4	3	4	5	2	5	3	3	3	3.47	1.13	15	1	6 %
OP2	3	4	3	1	1	2	*	3	2	1	1	1	2	3	1	2	2.00	1.00	15	1	6 %
OP3	*	*	*	*	*	3	*	*	*	*	*	4	*	*	*	*	3.50	0.71	2	14	88 %
OP4	2	3	3	3	1	3	*	1	3	2	5	1	1	3	3	2	2.40	1.12	15	1	6 %
OP5	2	4	2	5	5	3	2	5	3	4	4	3	4	4	3	2	3.44	1.09	16	0	0 %
OM1	3	*	1	1	1	2	1	1	1	1	4	1	1	4	2	1	1.67	1.11	15	1	6 %
OT1	1	1	1	1	1	1	1	3	1	2	4	1	1	3	1	1	1.50	0.97	16	0	0 %
OT2	*	*	1	*	1	1	*	2	*	1	2	*	1	1	1	*	1.22	0.44	9	7	44 %
OR1	1	3	3	5	4	5	1	3	1	2	4	3	3	4	2	1	2.81	1.38	16	0	0 %

Table E.2: An overview of the O-element scores in the TOE scoring list. **Not applicable.*

TOE	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	Mean	S.D.	N	NA	% NA
ES1	1	3	1	*	4	2	1	5	1	2	3	2	2	3	4	1	2.33	1.29	15	1	6 %
ES2	1	3	2	*	3	1	1	4	1	2	2	1	3	1	3	2	2.00	1.00	15	1	6 %
ES3	1	4	3	*	4	5	1	3	1	1	2	4	1	2	2	*	2.43	1.40	14	2	13 %
ES4	*	1	1	*	1	*	*	*	*	*	*	*	*	*	*	*	1.00	0.00	3	13	81 %
ES5	1	1	2	1	1	1	1	3	1	1	4	1	4	1	1	1	1.56	1.09	16	0	0 %
ES6	*	*	*	1	*	*	*	*	*	1	*	*	*	*	2	*	1.33	0.58	3	13	81 %
EL1	3	3	4	3	3	1	1	4	2	5	4	4	4	4	3	3	3.19	1.11	16	0	0 %
EL2	*	1	*	1	*	*	*	*	*	*	*	*	*	*	*	*	1.00	0.00	2	14	88 %
EL3	1	1	*	1	*	*	*	*	*	*	*	*	*	*	*	*	1.00	0.00	3	13	81 %
EL4	1	1	*	1	*	1	*	2	*	*	4	*	*	*	1	*	1.57	1.13	7	9	56 %
EM1	2	1	2	5	4	5	3	5	4	4	4	1	4	1	5	1	3.19	1.60	16	0	0 %
EM2	1	*	*	1	1	2	2	1	1	1	4	1	1	1	3	*	1.54	0.97	13	3	19 %
EM3	4	5	3	*	4	4	4	4	5	4	4	3	5	4	4	4	4.07	0.59	15	1	6 %
ER1	3	1	4	1	3	5	1	1	1	2	4	3	3	1	3	1	2.31	1.35	16	0	0 %

Table E.3: An overview of the E-element scores in the TOE scoring list. **Not applicable.*