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TAMPERE UNIVERSITY OF TECHNOLOGY

MOHAMMADHOSSEIN KHADJEHALI  
ROLE OF MID-FIDELITY PROTOTYPES IN FACILITATING OPEN-  
BOOK ACCOUNTING

Master of Science thesis

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## ABSTRACT

**MOHAMMADHOSSEIN KHADJEHALI:** Role of Mid-Fidelity Prototypes in Facilitating Open Book Accounting

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One of the key success factors in today's global and highly competitive markets is to develop new products. On the other hand, new product developments have exponentially increasing as the development project proceeds. Thus, more and more the need for evaluating ideas inexpensively and rapidly is rising. The problem with current prototyping methods is that they come late in the development stages. This problem becomes more important in lean companies which have strong relationships with their strategic allies. The current development tools and methods suggested from scholars for development of physical products do not offer flexibility and iterative development. However, this approach limits developers from testing and comparing several ideas.

The objective of this report is firstly to challenge the common categorization and application of prototypes by introducing mid-fidelity prototypes to merge the two main product development models, agile and stage wise, and secondly to demonstrate the impact of these prototypes on cost estimations and how the information generated from studying them helps to facilitate open book accounting. Mid-fidelity prototypes can reduce costs of development projects by testing functionality of ideas cheaply. They are also an effective communication tool internally and also with supply network firms. The purpose of this approach is to complement the current existing literature on product development models and prototyping. To provide a deeper understanding of the implications of what such a model could offer, it was implemented and analyzed in a case of developing cleanliness of hydraulic hose assemblies. The project was done with a hydraulic hose assembly manufacturer in Finland.

This research shows that first, fully functional mock-ups are effective communication tools among the development team and externally with customers or suppliers. Second, they provide hands on experience of the product for the project stakeholders. Third, they can be used to estimate associated cost impacts of the product. Fourth, the generated data could be used as factual information to be shared with strategic allies and facilitating open book accounting. However, it is noteworthy that this method is not effective applicable in high-tech and complex products due to nature of them.

## PREFACE

During my studies in Tampere University of Technology, I was privileged to work with a small but highly innovative company which had open arms for fresh ideas from young students. It was an amazing opportunity to work there and combine the theories I was learning in the university with practice. Once my compulsory student project was over with the company I felt the crave to work more on the case and see how it proceeds. Thus, I took the initiative and kept working on the case even though it was an unpaid job. However, if I go back I would definitely do the same or even work harder on the project.

While working on the case closely with the managers and workers, I learnt much about work atmosphere in Finland which was totally different from my home country. Of course, it was not all happy days and both in work and personal life there were obstacles occurring time to time, mistakes were made by me or other co-workers, and in general things were not always perfect. However, I learnt that is life and the winners learn from mistakes and carry on.

I would like to deeply thank Dr. Jouni Lyly-yrjänäinen for his supervision on the project, the thesis, and always being available for students. Also, I would like to express my deep gratitude to all managers and employees of the case company whom I have learnt a lot from. I would like to express my deepest gratitude to my family especially my father who has supported me in the most difficult stages of my life. Finally, I would like to thank my beautiful fiancée without whom I would not have been able to complete my Master's degree.

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Mohammadhossein Khadjehali

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## LIST OF SYMBOLS AND ABBREVIATIONS

ABC	Activity Based Costing
ANSI	American National Standards Institute
B2B	Business to Business
BPMN	Business Process Modeling Notation
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
DMU	Digital Mock-up
EVO	Evolutionary Model
ISO	International Organization for Standardization
LM	Lean Manufacturing
NPD	New Product Development
OBA	Open-book Accounting
PDP	Product Development Process
QFD	Quality Function Deployment
RUP	Rational Unified Process
SCM	Supply Chain Management
SIPOC	Supplier–Input–Process–Output–Customer
VoC	Voice of Customer
UML	Unified Modeling Language
WIP	Work in Process

# 1. INTRODUCTION

## 1.1. Background

The changing and highly competitive business atmosphere has dictated innovation as a key success factor, alongside performance and quality improvement (Trkman, 2010). It means not only companies have to be innovative and offer new products to their customers, but also improve their performance to reduce the costs and increase their profit margin consequently. In other words, one of the most significant tactics to compete and survive in a dynamic international environment is new product development (NPD). Nonetheless, NPD is quite challenging since there are high risks associated with it (Kachouie & Sedighadeli, 2015). One of the highest risks is that NPD projects' costs increase exponentially as the project proceeds (Belz, 2011). Therefore, to reduce the NPD risks, managers and scholars have developed different NPD models. These models give a general structure to the project to increase its success chance.

Through an NPD project different prototypes are built to test the product from various points of view. One of the reasons is to provide customers the hand on experience to collect their ideas before the product is released and launched in the market. Just few decades ago this valuable customer experience of the new product occurred in late stages of the NPD (Cooper, 1990). Nowadays however, NPD managers pay more attention to customer involvement in the development project (Cooper, 2008). Yang and el-Haik (2009) have introduced different types of prototypes which either match low-fidelity or high-fidelity prototypes introduced by Rudd et al. (1996). However, the jump from low-fidelity prototypes to high-fidelity prototypes in the development process can increase the development costs significantly.

Moreover, mere a new product cannot win the customers, attention. The target market and customers might like the product but if it is too expensive for them in comparison to value the product offers them, it is unlikely that the product succeeds. On the other hand, engineers have serious limitations to increase the accuracy of their estimation on the cost of production the new product. If the product is aimed for mass production even few seconds extra in the production process of each unit will cost significantly to the company. Thus, there is a tool missing to help calculating the production cost before costs of NPD sums up to the late stages of development.

On the other hand, another way to reduce the risks of NPD projects, especially for business to business (B2B) environment, is customer/supplier integration (Das & Teng,

1998). Close relationship with the key customers and suppliers to reduce costs and increase efficiently is the common goal of lean manufacturing and supply chain management. One of the key success factors of a supply network is close and meaningful relationships with strategic allies. Sharing relevant information is crucial for a constructive cooperation and cost data is one of the challenging information to share. Open book accounting is a concept to share cost data systematically to increase the efficiency (Hoffjan & Kurse, 2006). Cost data is sensitive. When it comes to share information about NPD, it is even more difficult since there is no actual product yet, and there are assumptions involved. The lack of communication tool during a process development with key allies, was visible.

## 1.2. Objective

This thesis introduces a new category of prototypes, “mid-fidelity” prototypes to offer a strong communication tool during a product or process management. Mid-fidelity prototypes share some of the characteristics of both low and high-fidelity prototypes. They represent the key features and functionality of the final product and at the same time they are inexpensive since they are built from easy-to-work and cheap material, such as plywood or plastic. Mid-fidelity prototypes help developers to test the functionality and effectiveness of a product idea before the company spends a fortune on the product development. Besides, when the functionality is approved the development could proceed further with mid-fidelity prototypes to make sure other issues such as ergonomic design and production process are also well thought of.

Furthermore, if the product is designed to be placed in a bigger production line or cell, mid-fidelity prototypes can be installed and tested to study the process. The study process provides valuable information about costs associated with the new product. Thus, if there are various ideas for the same functionality but different qualities, they can be tested and studied to gain the cost data. Now, given all valuable information about each idea from their functionality, ergonomic design, production process, and cost data, a company can prepare material to discuss with its key customers and see which idea is supported by them. Thus, the objective of this thesis is ...

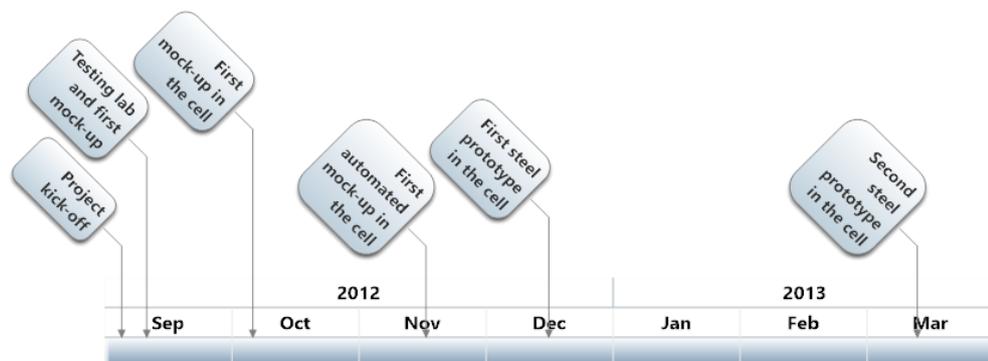
*... to introduce the concept of mid-fidelity prototypes and discuss the role they play in providing factual information regarding different development ideas which can facilitate open book accounting and smoothen customer integration in NPD projects.*

To address this objective, this thesis reviews the literature with regard to product development. Then, a framework is designed to demonstrate the application of mid-fidelity prototypes to simulate and study a business processes to estimate the costs related to the product. Next, it illustrates how the acquired data can be used to facilitate open book

accounting and smoothen customer/supplier integration with facts about the product. Finally, this framework was tested in a quality development project which included an important sub project, developing a new machine to improve the quality.

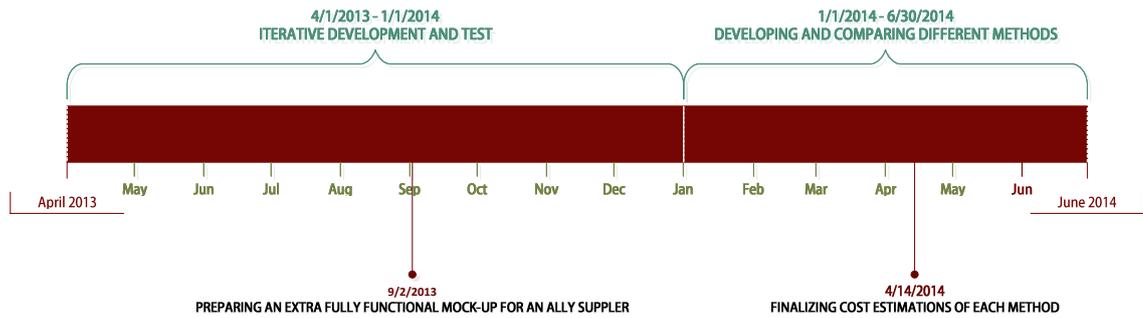
### 1.3. Research Method

The project kicked off in September 2012 as a student project for the author to earn experience in business research and learn how to document empirical studies. The project was to develop a washing machine for a hydraulic hose assembly company in Finland. At the same time with developing the washing machine the author had to test the results and adjust the design accordingly. The first phase of the project ended in March 2013 when preliminary mock-ups had evolved to mid-fidelity fully functional prototypes and the results were presented in the “Finnish quality association seminar”. Figure 1 shows the time line of the first phase of the project.



*Figure 1. First phase of the project process timeline.*

The quality improving project turned its attention to other quality improving areas such as protecting hose assemblies from contaminations during the shipment, and more tests and small improvements were done to the washing machine as well. Eventually, the author received a temporary position in the case company to proceed with the washing machine project further in January 2014. The data presented in this thesis were gathered during both intervals of the project. Figure 2 illustrates the second phase of the project. During this time the development team used iterative development to study all possible ideas which could improve the cleanliness level.



*Figure 2. The second phase of the project timeline.*

The latest particle counting results came from a professional lab in July 2014 which clearly showed the impact of the washing machine. However, from then it was up to the customer to choose a cleaning method based on the quality measures and costs of implementing each method.

#### 1.4. Data Gathering Methods

The scientific revolution in 16<sup>th</sup> century changed the concept of research with introducing scientific methodology (Wootton, 2015). Scientific method refers to the procedures and framework in which modern science is practiced (Bell, 2012). Research methods are systematic tools used to find, collect, analyze and interpret information.

Gummesson (2000) sees academic researchers and management consultants as groups of knowledge workers who each place a different emphasis on theory and practice. Backed by bits and pieces of theory, a consultant contributes to practice, whereas the scholar contributes to theory supported by splinters of practice, but fundamentally he sees their roles as closely related. Gummesson sees researchers and consultants as involved in addressing problems that concern management, thereby supporting the view that the value of both groups is determined by their ability to convince the business community that their findings are relevant and useful. Gummesson (1993) has divided data gathering and analyzing methods in management science in five categories:

- Using existing material
- Questionnaires and surveys
- Interviews
- Observation
- Action research

The first category refers to digging into anything that has been published. It can be any type of existing material from literature review to analysis of existing available data. Second, questionnaires and surveys are research tools consisting of series of questions and other prompts for the purpose of gathering information from respondents. Third, interviewing, when considered as a method for conducting qualitative research, is a technique

used to understand the experiences of others. Fourth, observation is a method for systematically observing the behavior of individuals in terms of a schedule of categories. It is a technique in which the researcher employs explicitly formulated rules for the observation and recording of behavior. Observing can be carried out either in non-participant or participant way. Non-participant observation means the observer does not interact with the subjects whereas for participant observation there is engagement. Finally, action research which was introduced the first time by Lewin (1946), is a way of conducting social science that linked the generation of theory to changing a social system through action.

Researchers choose the research methodology according to the needs the problem generates and the limitations they have. Since the author of this paper was engaged in the whole process, this study's method is basically based on action research. As a matter of fact, it was impossible to use methods such as questionnaires and surveys since there are not many companies using cheap mock-ups and mid-fidelity prototypes in early stages of their NPD process. Although some parts of the research process could match with observation or interviews, they are just part of a whole which makes the action research method the main method.

## **1.5. Structure of the Thesis**

This thesis is logically divided into eight chapters. The content and objectives of each chapter are as follow:

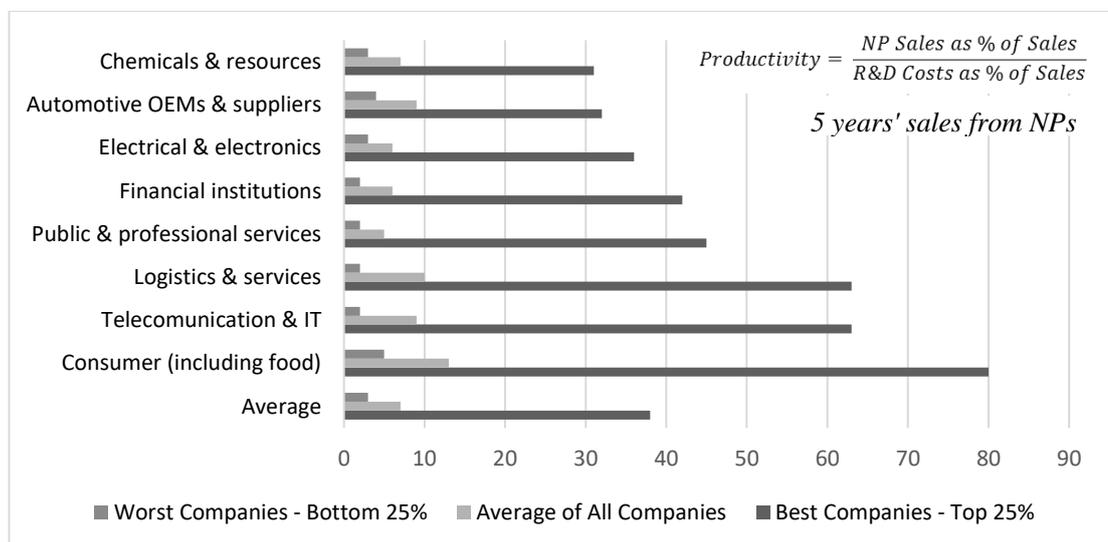
1. Chapter 1 introduced the background and the main objective of the thesis. It also explains the research process and data gathering methods applied during the research activity.
2. Chapter 2 discusses the product development and different development models. It also introduces different types of prototypes and their benefits and suggest a new type of prototype: fully functional mock-up or mid-fidelity prototypes.
3. Chapter 3 provides an introductory to costing and cost management. Then, it explains how business models can be studied from costing point of view. It suggests that mid-fidelity prototypes are useful to estimate costs.
4. Chapter 4 explains the importance of customer/supplier in NPD projects specially for the companies which have implemented LM. Then it explains how the data generated form studying mid-fidelity prototypes can be used as tool for open book accounting.
5. Chapter 5 describes the case company and hydraulic hose assembly industry. It briefly demonstrates the mindset of the owners of the company and how the situation of the company is.

6. Chapter 6 explains the quality problem and how the case company treated the case. It demonstrates the key steps of quality improvement project and how developing washing machine influenced the quality issue.
7. Chapter 7 reviews the research steps and theoretical framework of the thesis. Then, it looks at the case through the theoretical framework eyes and analyzes the results. Finally, it states the findings of the research and points out the limitations of this study.
8. Chapter 8 concludes the thesis.

## 2. ROLE OF MOCK-UPS IN PRODUCT DEVELOPMENT

### 2.1. Definition

The need for new product development has increased rapidly with the improvement in technology and globalization of the market and also the rapid pace of technology development has led to shorter product life cycles for many product categories (Minderhoud & Fraser 2004). Therefore, the challenges for manufacturers include shortened product life cycle, high quality product, highly diversified and global markets with unexpected changes of technologies and customer needs. Thus, for such a dynamic market, product development requires the involvement of customers and business partners during the development process (Kamrani 2010). According to Arthur (2005), huge differences in product development productivities exist between the best and worst firms, according to a major global study (Figure 3), productivity was measured as five years' sales from new products, versus R&D spending by the company. Both metrics are taken as a percentage of company annual sales to adjust for company size. The interesting outcome of this study is that the best firms (defined as the top 25 percent) have twelve times the productivity in new-product development of the worst. It clearly shows the importance of new product development for success.



**Figure 3.** New-Product Sales to R&D Spending (Source of data Arthur, 2005)

Developing new products that will succeed in the marketplace goes way beyond simply coming up with a great new idea, a great new invention, or a great new design. Product development projects start with new ideas. The ideas come from a customer's need to solve a particular problem, a marketing need to counter a competitive product, a new

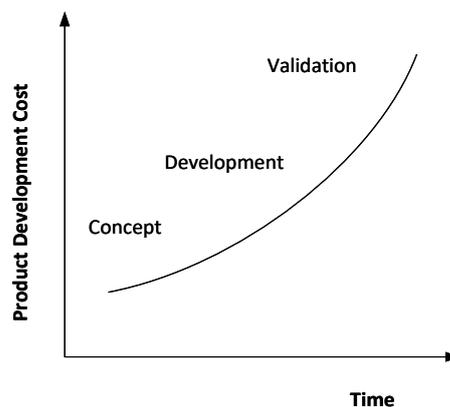
technology that might disrupt the marketplace, a cost reduction of a current product, or a whim of a great idea (Dinsmore, 2006).

Product development is the creation of products with new, different or innovative characteristics that offer new or additional benefits to the customer where product itself means a good or service that meant to meet the requirements of a particular market (Business Dictionary, 2014). Product development may involve modification of an existing product or its presentation, or formulation of an entirely new product that satisfies a newly defined customer want or market niche. Rainey (2005) proposes that the main objectives of product innovation are to create value, to gain a competitive advantage, and to have long-term success through the development and commercialization of new products and services.

In this age of fast and continual change, businesses are at the point where the corporate world is slowly but surely realizing that innovation is the only way to survive and sustain growth. Innovation involves changes and improvements to technologies, products, processes, and services that result in positive contributions for customers and other stakeholders of business organizations (Rainey 2005). An innovation is a creative new solution to the current conditions and trends, and fulfills the expressed and unclear needs of customers and stakeholders in general (Loch & Kavadias, 2008).

## 2.2. Product Development Models

Belz (2011) states that during a new product development process, the more the product matures and approaches to readiness, the more expensive the development gets. Figure 4 shows a typical new product development cost profile which shows how costs change over time. In other words, product development usually becomes more expensive as the product gets closer to the market release.



*Figure 4. A typical cost profile (Adapted from Belz, 2011)*

Usually the first stage of NPD is inexpensive since it is merely concept approval go/kill decision before much investment. Even though it is not common among firms, it is rec-

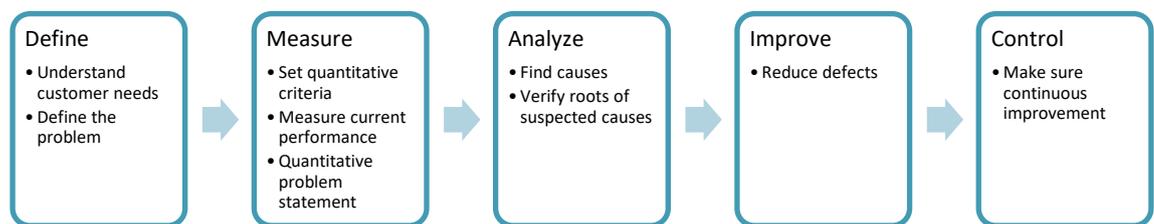
ommended to invest in marketing research at this early stage, since the outcomes are crucial for the decision making; whether to proceed further or stop (Belz, 2011). Many companies invest too much in product development before assessing the market and customers' need; this lesson has cost companies uncountable millions. It is recommended to carry out risk assessment before and during the product development process to avoid increasing development costs (Cooper, 2000). Sometimes individuals or companies make poor investment decisions and fall into sunk cost fallacy trap which leads them to keep investing in a project despite the fact that the further investment is larger than the investment a new project would require to complete (Sofis et al., 2015). Oxford of Finance and Banking (2014) defines sunk costs as "expenditure that has already been incurred and that cannot be recovered." Sunk cost fallacy is a maladaptive form of the investment strategy which scholars mostly studied in decision-making research under the header of escalation (Staw & Ross, 1989). Escalation is defined as a propensity to invest more resources notwithstanding negative consequences (Staw, 1976).

Besides the increasing development costs of product development and the sunk costs fallacy, there are other difficulties on the way of a new product development. According to Unger et al. (2009), an idea does not evolve by itself from void. There must be a background knowledge as a base for an idea. When an idea is generated, there is a long way for it to become a product if it ends up as a product at all. In development of a new idea there are many steps and, in each step, there are many aspects that must be taken in to consideration. Moreover, there are many players whose decisions and feedback are important and effective on the process. All these issues make new product development projects complex. Therefore, academics and researchers have studied different aspects of new product development to tackle these complexities and avoid as many mistakes as possible. Thus, they have introduced and suggested different models for new product development. The most famous ones are DMADV, DMAIC, Stage-gate model and many models focused on software development such as waterfall, V-model, incremental and spiral. As this section discusses, all the new product development methods start with idea generation.

Annacchino (2007) discusses the idea generation pathways in his book lists several venues for new product idea generation. First, customer-defined needs which are collected through either direct customer surveys, focused group discussions, suggestion systems and communication from customers, or customer complaints. Second, scientific research sometimes lead to a breakthrough technology which could be implemented in new products. Third, studying competitors and their product design failure and success is another source of inspiration. Fourth, company dealers and representatives could bring new ideas on the table since they are directly in contact with customers. Fifth, brainstorming sessions on solving current problems. When the issues are not precisely identified, iterative brainstorming sessions could be applied to clear the problems first and then tackle them.

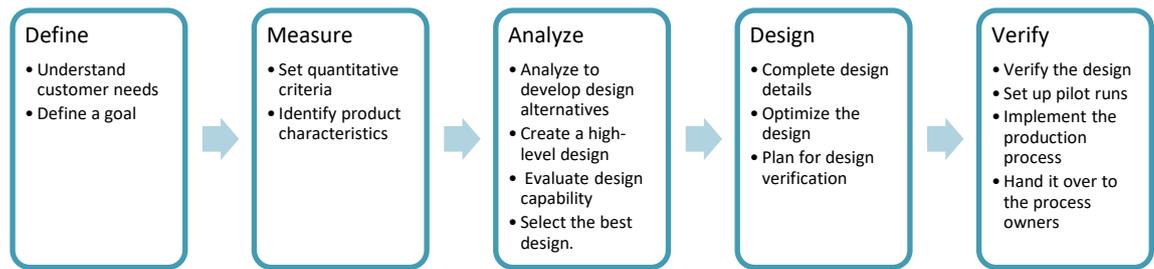
According to Keller & Pyzdek (2009), both DMAIC and DMADV are based on systematic quantitative approaches and the goals are process improvement and process design, respectively. The basic structure and goals of these approaches is focused on identification and elimination of variation and waste both in process design and in process improvement. DMADV is a process defined as part of Six Sigma management and DMAIC is defined as part of lean production philosophy. Nonetheless, Stage-gate model is introduced by product development academics not as part of a particular strategy. DMAIC and DMADV methodologies are briefly explained below.

Define, Measure, Analyze, Improve, and Control or DMAIC model is a simple performance improvement tool used when a project's goals can be achieved by improving existing processes, products and services. According to Voehl et al (2014) step one or define refers to selecting an appropriate project and defining the problem by understanding customers' demands. The next step is to measure the current performance by setting quantitative criteria and then develop a quantitative problem statement. The third step is to analyze the problem to find causes and verify roots of suspected causes. Next step is to improve the product or process by reducing defects and variation instigated by origin causes. The final step is to control the process or product to make sure continuous improvement in the performance (Figure 5).



**Figure 5.** DMAIC process development model.

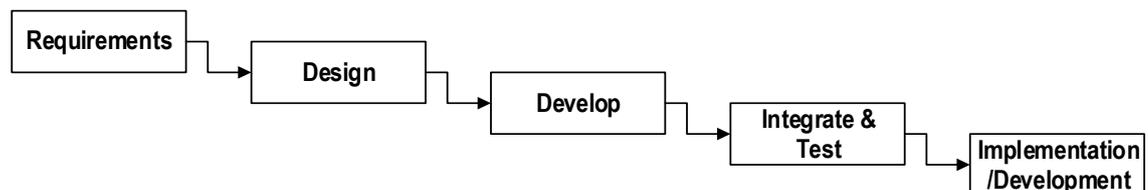
DMADV or define, measure, analyze, design and verify is similar to DMAIC. The first step is to define a goal based on customer demands. Next, measure and identify product characteristics that are critical to quality which means translating customer needs to product characteristics. The third step is to analyze alternative solutions and evaluate them and then the fourth step is to complete the design and optimize it and develop plans for design verification. The final step is to run pilots of the best designs and verify them and when it is ready hand it to process owners (Figure 6).



**Figure 6.** DMADV model (summarized from Charron, 2014).

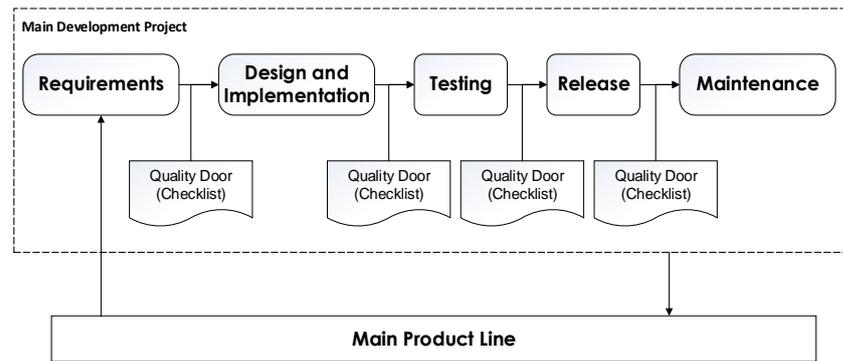
There are many product development models used by software developers such as V-model (Forsberg & Mooz, 1991), incremental model (Pressman, 2010), waterfall model (Royce, 1970; Petersen et al., 2009), agile models and spiral model (Boehm, 1988). Though these models were developed in the context of software development however there are lessons that can be learnt from them, since software is a product per se. Therefore, this thesis illustrates waterfall model and spiral model briefly.

The waterfall model was proposed by Royce (1970). However, there was an alike model suggested by Benington as early as 1956 and was called stage-wise model. Royce (1970) believed that two-phase projects – meaning planning and then implementing – are doomed to fail. Thus, he suggested to add more stages and phases to the traditional model and he called this model the waterfall model (Figure 7). Waterfall model is a chain of sequential phases that have to happen in order, one after another and each phase waterfalls into the next. According to Cobb (2011) the first phase in waterfall model is the requirements definition phase, where the user requirements are defined and documented and then proceeds to the design phase which is developing a solution for the precise requirements defined in the first phase. Following, it comes the development phase that brings the solutions to a real product or software. Then, the product must be tested and finally developers implement it and look for further development needs or opportunities.



**Figure 7.** A simple waterfall model (simplified from Royce, 1970).

Waterfall model have been used in software industry for many years. However, scholars and software product developers gradually identified some incompetency in the model. Still, Raccoon (1997) believes this model will be used for much longer period of time. Petersen et al. (2009) have studied pitfalls and disadvantages of waterfall model in their paper. Figure 8 shows the improved waterfall model used by them.



**Figure 8.** Improved waterfall model used by Petersen et al. (2009).

As it can be seen, the model is upgraded slightly by adding gates and the context of the project to the model. During studies of Petersen et al. (2009), they discovered several more disadvantages than they had found in literature.

In brief, when implementing waterfall model organizations realized that sometimes the model does not match the reality going on in projects. For example, the model assumes it is always possible and easy to recognize customer requirements exactly and in details which is not the case with most of projects, or waterfall model presumes translating customer needs to product requirements can be in a phase and at once. Moreover, the model adds much bureaucracy to the product development process. Therefore, agile models emerged as revolutionary against waterfall/stage-wise models. Table 1 summarizes the literature review on the issues stated by different researchers.

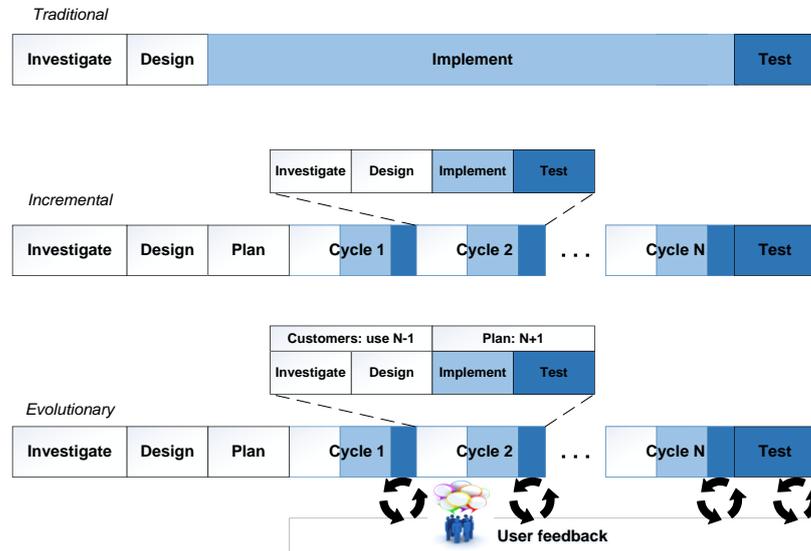
**Table 1.** Literature review on waterfall model disadvantages.

Issues	References
High effort and costs for writing and approving documents for each development phase.	Sommerville (2004) , Yin (2002)
Extremely hard to respond to changes.	DeGrace & Stahl (1990), Sommerville (2004) , Yin (2002), Pfleeger & Atlee (2006)
When iterating a phase the iteration takes considerable effort for re-work.	Sommerville (2004)
Customer discovers problems of early phases very late and system does not reflect current requirements.	Royce (1970), Sommerville (2004), Jarzombek (1999)
Problems of finished phases are left for later phases to solve.	Sommerville (2004)
Management of a large scope of requirements that have to be baselined to continue with development.	Jarzombek (1999), Thomas (2001), Johnson (2002)
Big-bang integration and test of the whole system in the end of the project can lead to unexpected quality problems, high costs, and schedule overrun.	Royce (1970), Jones (1995), Sametinger (1997)
Lack of opportunity for customer to provide feedback on the system.	DeGrace & Stahl (1990), Jones (1995)
The waterfall model increases lead-time due to that large chunks of product artifacts have to be approved at each gate.	Anderson (2003)
Confusion of who implements which version of the requirements.	Petersen et al. (2009)
High effort for maintenance	Petersen et al. (2009)
Specialized competence focus and lack of confidence of people	Petersen et al. (2009)
Problems in fault customization due to communication barriers	Petersen et al. (2009)
The users are not always capable of defining explicitly and exactly detailed requirements for everything they need without seeing it at all.	DeGrace & Stahl (1990), Cobb (2011)
Customer's needs cannot be translated to the product requirements easily at once.	DeGrace & Stahl (1990), Cobb (2011)

There are different agile models offered thus far by software developers such as scrum (1995), extreme programming (1996) and feature-driven development (1997) (Larman, 2003). The thing which is in common among different agile development models is that they offer iterations in the process which means they deliver functionality through more frequent and smaller iterations (Cohen, 2010). Cobb (2011) states that companies which applied agile processes wanted to distance themselves as far as possible from waterfall practices. As a result, when the agile movement started out, it became an extreme counterpoint for the waterfall processes. It means as minimum documentation and control in the process as possible. Both waterfall and agile models are still applied in companies.

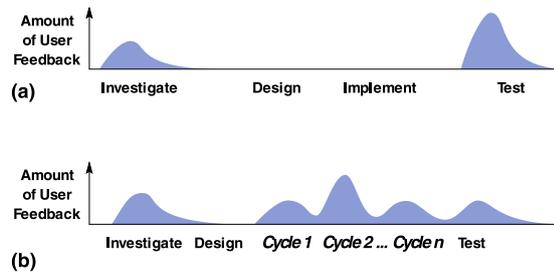
Boehm and Turner (2003) believe that there is a middle way between plan-driven, process-based and agile methods. In their book, *Balancing Agility and Discipline*, they suggest pragmatist ways that companies can apply to tailor development models for their purposes and goals in a way that they neither waste resources on bureaucratic processes and nor they unhand the knowledge gained during the development due to lack of documentation. In fact, Boehm himself had introduced a software development model in 1988 which is called spiral model (Boehm, 1989, 1991; Wasson, 2006; Rising & Janoff, 2000). Some researchers, such as West & Grant (2010) and Boehm & Turner (2003), believe that spiral model is not among agile models, nor is it a waterfall model. Instead, they label

spiral model as an iterative model along with rational unified process (RUP) and evolutionary model (EVO) which had been introduced not long before, by Glib & Finzi (1988). Figure 9 visualizes waterfall, incremental and evolutionary model and their differences. Incremental development suggests to develop the product in cycles and in each cycle a little is added to product till it is ready (Pressman, 2010).



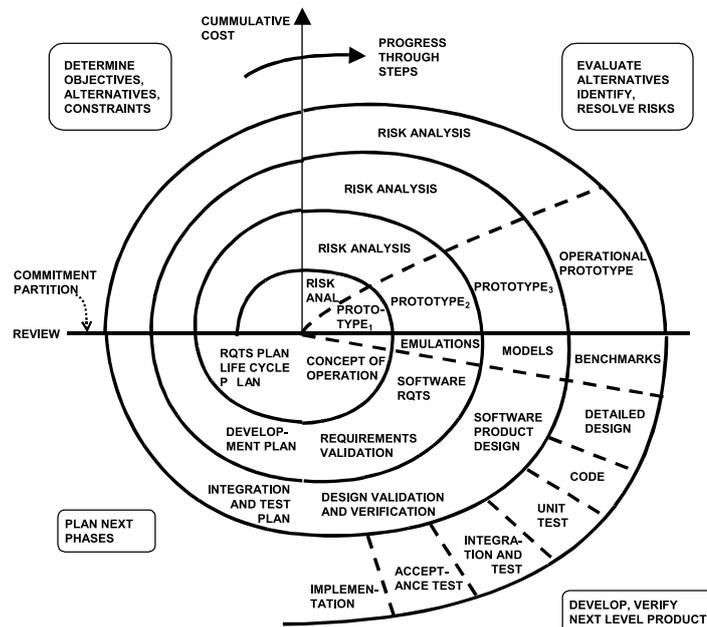
**Figure 9.** Evolutionary model vs. incremental and traditional waterfall model (Cotton, 1996).

According to May & Zimmer (1996), the evolutionary development is a method of designing and development that goes through analysis, design, development and testing in an iterative and incremental way. It means the EVO development model divides the development cycle into smaller, incremental waterfall models in which users are able to get access to the product at the end of each cycle. Rosson & Carrol (2002) state that the users give feedback on the product in each stage which will be used for the planning stage of the next cycle. The development team responds to the feedback by changing the product, plans, or process. Thus, working prototypes are needed as soon as possible in the project to enable evaluation and collecting feedback from end users and customers. Consequently, a working version of the product must be available, and it is continuously being updated to reflect the latest improvements. Rosson & Carrol (2002) add that EVO can be used in more structured projects in a different manner. For instance, if the product has multiple aspects for different users, the developers implement EVO development process for each aspect and as a whole for the entire project. May & Zimmer (1996) believe that the biggest advantage of the EVO model is the risk reduction through continuous feedback from customers and users during the development process (Figure 10).



**Figure 10.** User feedback amount in the waterfall vs. EVO (adapted from May & Zimmer, 1996).

As mentioned before, Boehm introduced his spiral model in 1988, the same year Glib suggested evolutionary model. Wasson (2006) states that spiral model develops and delivers system in builds like the waterfall model, however, it acknowledges that the user needs are not fully clear at the beginning of development even to the users themselves. Thus, the process initiates based on the given requirements at the time development began. Then, succeeding builds are delivered that meet additional requirements as they become known. Additional needs are usually identified and requirements defined as a result of user experience with the initial build (Figure 11). Moreover, spiral development model has a better understanding of risk in system requirements in comparison to waterfall model and incremental model.



**Figure 11.** Spiral model by Boehm (adapted form Boehm 2000).

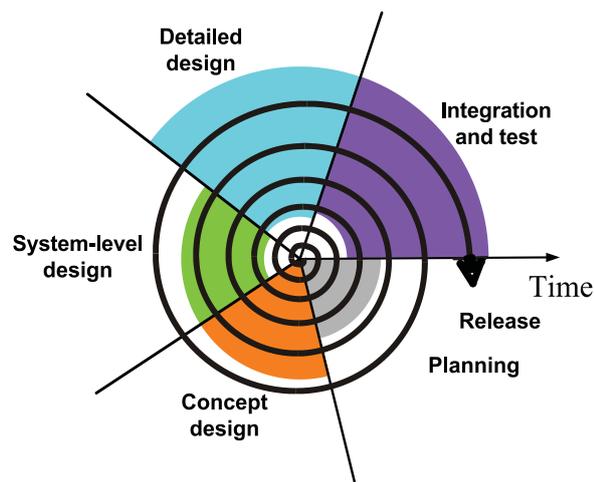
As it can be seen in Figure 11 spiral model consists of four quadrants:

- Quadrant 1: Determine objectives, alternatives, and constraints.
- Quadrant 2: Evaluate alternatives, identify and resolve risks.

- Quadrant 3: Develop, verify, next-level product.
- Quadrant 4: Plan next phases.

Wasson (2006), states that the spiral model can be applied in other industries as well and describe the quadrants as follow. In the first quadrant, developers establish an understanding of the objectives of the project which means the performance and functionality of the product. Then, they investigate implementation alternatives, to be exact, different designs, reuse or procure. The next step is to study the alternatives' constraints such as technology, cost, schedule and risk. Then, tackling risks with cost effective strategy which may possibly involve prototyping, simulation, benchmarking, reference checking, administering user questionnaires, analytic modeling or combinations of these and other risk resolution techniques. Following, in the second quadrant prototypes are built and alternatives are assessed and the one which satisfies the best aforementioned constraints – most importantly risks. Not to mention, the focus in spiral model is on mitigating risks. Boehm (2000) states that his spiral model is a risk-driven process model generator.

Wasson (2006) continues that in the third quadrant the accepted alternative from the second quadrant proceeds to detailed design, development, implementation and evaluation based on the requirements. If the prototype is effective enough to fulfill the requirements, mitigate the risks, and satisfy the constraints the product development follows a normal waterfall model to the final product. If the prototype is useful and potential to be base for a solid solution, series of evolutionary prototypes are built till the product is ready. Unger & Eppinger (2009) have generalized spiral model of product development from software development to other industries (Figure 12).

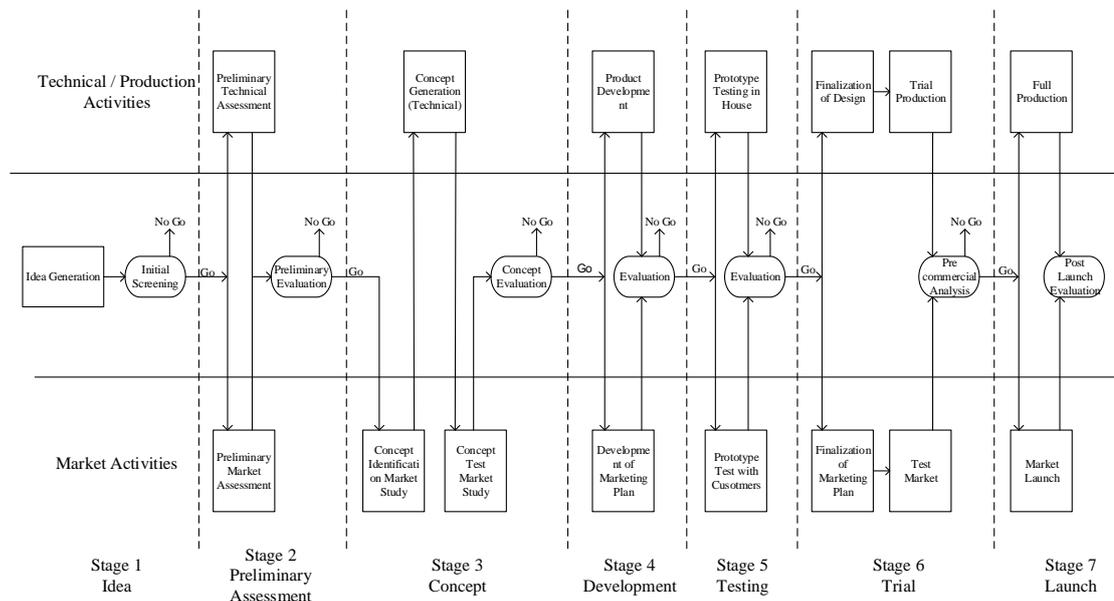


**Figure 12.** Modified spiral model (Adapted from Unger & Eppinger, 2011).

The stage-gate model refers to the use of funnel tools in decision making when dealing with new product development. According to Gadegaard (2010), the stage gate model has been introduced and developed mainly by Robert Cooper (1990, 1998, 2001, 2008, 2009) and Cooper et al. (1997, 1999, 2002a, 2002b, 2004, 2005). Stage-gate is also known as

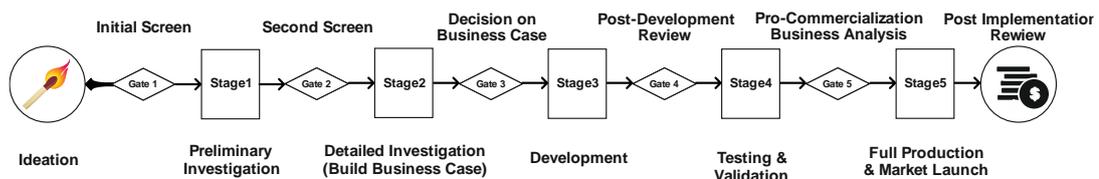
phase gates mostly in project management literature (Meredith and Mantel, 2012), toll gates (Ottosson, 2013), and quality gates (Stanford, 2007).

Cooper in 1983 independently from software development process models introduced his stage-gate model for PDP (Figure 13). Copper’s stage-gate model was introduced before agile and spiral models were suggested in software development. In this model a big checklist of items related to market and customer values, technical risks, design details, financial spending and returns, and strategic alignment issues will be reviewed for each project. The decisions made in gate reviews include passing, reworking, or killing of projects and design tasks. In principle, the product development cannot go to the next stage unless all the gate review items are decided.



**Figure 13.** The first stage-gate model (Cooper, 1983).

Cooper (2001, 2011) explains that in the stage-gate model (Figure 14) it can be seen that there is a gate after each of the product development stage. A gate review will be performed at the end of each stage, which is often referred to as a Go/Kill decision point. In each gate review, gatekeepers, who are usually senior managers involved in the product, and all relevant product team members will go through a rigorous review process. Not to mention, the gatekeepers include both technical and business managers (Cooper 2011).



**Figure 14.** An overview on the stage-gate model (Adapted from Cooper 2001).

A typical stage-gate starts with discovery or ideation. Ideas are the raw material to the process. Many companies see ideation so important that they consider it as a formal stage

in the process. Cooper (2000) believes that idea generation is everyone's job and yet no one's responsibility. Hence, some organizations even design a structured system for ideation to make ideation smoother. Throughout the system, they grease the path of getting new great product ideas by implementing variable managerial and motivational methods and collect the ideas efficiently with IT support. The system also provides gatekeepers with collected new ideas and ensure an adequate feedback flow.

The first stage is preliminary assessment. This stage entails a quick assessment or scoping of the product idea, and is usually completed by a small team of technical and marketing personnel. It includes first-cut levels of analysis, such as a preliminary market assessment, a preliminary technical assessment, and a preliminary business assessment. This is the "weeding out" stage where many ideas are typically dropped from consideration. The gate that must be passed through to move from Stage 1 to Stage 2 is called the second screen.

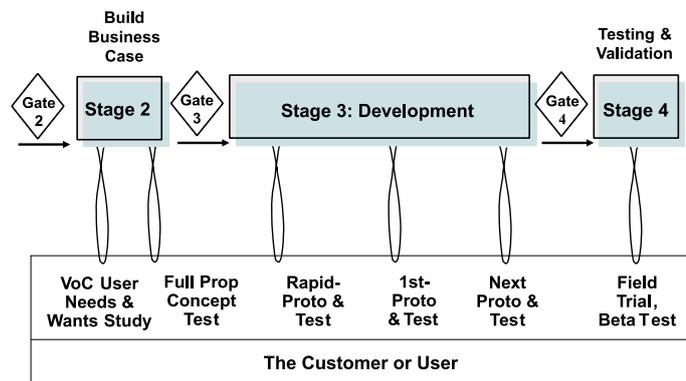
The second stage is named appropriately detailed investigation (build business case). This stage entails a more rigorous level of analysis, and includes primary and secondary market research, a concept test to obtain customer feedback, detailed technical and manufacturing assessments, and a thorough financial and business analysis. This stage is normally undertaken by more proficient specialists of market, technical, manufacturing, and financial in a firm. The deliverables from this stage include a defined product or service (on paper), a clearly defined target market, a financial analysis, and a detailed plan of action for the next stage. The gate that must be passed through to progress from Stage 2 to Stage 3 is labeled Decision on Business Case.

The third stage is Development. This stage involves the actual design and development of a new product or service, including the production of a working prototype and the assembling of an even more professional team. The manufacturing process is laid out, the marketing plan is developed, and the plans for the next stage are developed. The gate that must be passed through to move from stage 3 to stage 4 is termed post-development review.

The fourth stage is labeled testing and validation. This stage includes extensive in-house product testing, customer field-trials, pilot production in the plant (or outsourcing facility), and even test marketing or sales in one or more locations. The deliverable is a fully tested product or service, with all the complexities worked out, ready to go into production. The results of the test marketing and pilot production runs are carefully evaluated. The gate that must be passed through to move from stage 4 to stage 5 is entitled pre-commercialization business analysis.

The fifth and final stage is full production and market launch. Stage 5 marks the beginning of the product or service launch. This stage sees the implementation of the plans developed in the previous stages. Also, new members of the team may be added at this point (such as regional sales managers and accounting personnel).

Later, in 2008, Cooper suggests a modified version of stage-gate which is more flexible and can be scaled to suit different risk-level projects. Moreover, he applies spiral development concept in stage-gate model to upgrade his model to a more adaptive to the customers' current requirements by collecting valuable customer feed-back into the design even after the product definition is locked in, before going into stage 3 (Figure 15).

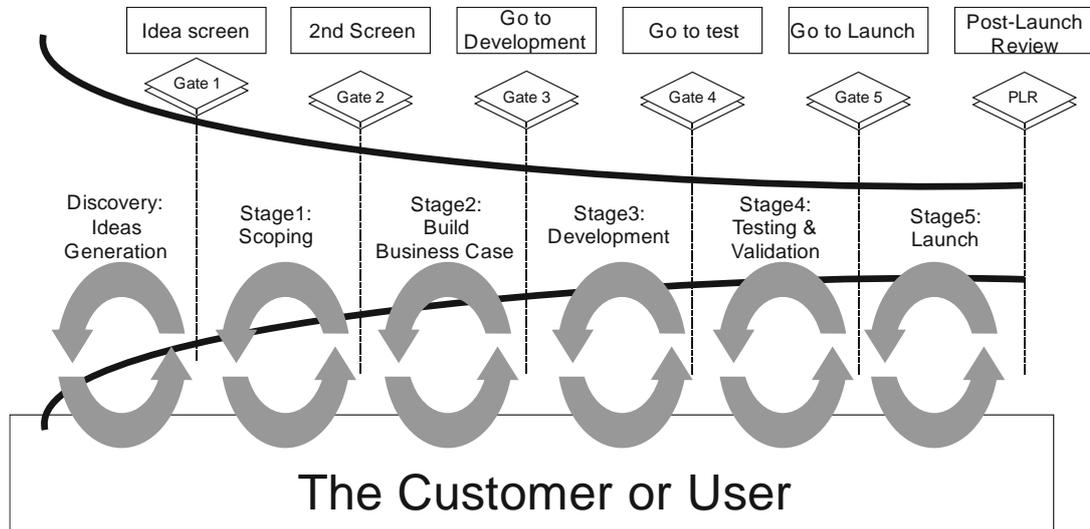


**Figure 15.** Spiral concept applied in stage-gate system (Cooper, 2008)

Cooper (2008) explains that the first loop or spiral in Figure 15 is the voice of customer (VoC) study carried out early in Stage 2, in which development team members interview customers to better comprehend their unmet needs, problems and benefits pursued in the new product. According to Madu (1998), the term voice of customer has been used by academics in different words including: house of quality, customer-driven engineering, matrix product planning features mechanization evolution, qualities function diffusion, or the most accepted one quality function deployment (QFD). Quality function deployment is defined by different authors as a methodology to develop products and processes based on customer needs and wants and to answer how the products meets these needs and finally how the products compete in the market. In other words, QFD is an approach to product development that translate customer needs into more technical requirements (Govers, 1996; Matzler & Hinterhuber, 1998; Walker, Crowson, & Boothroyd, 2006, Chan, & Wu 2002, Sullivan, 1986).

Cooper (2008) continues that in the second spiral the development team presents a representation of the proposed product. In this stage, prototypes might not be functional; however, the presentation gives the customers the feeling of how the product will be and do. To this end, the development team, depended on the type of the product and industry, represent a mock-up, prototype or even a virtual simulation. Based on the collected feed-

back, the development team finalizes its product definition in stage 2. Then in the development stage, the customers are presented with a more complete prototype. In this stage prototypes are made and become closer to the final product. Later, Cooper (2011) suggests to be in contact with customers and end users from very beginning steps and continue it to the post launch stage (Figure 16).



**Figure 16.** Getting feedback from customers and users during NPD (Cooper 2011).

Meredith and Mantel (2012) have stated the stage-gate model controls a project at different points all through its life cycle to ensure it remains on target and of value to the company, rather than waiting until the project is completed, and then finding out that it would not achieve the goals of the organization. Stage-gate model is most frequently applied for new product development (NPD) projects where it is important to regularly assess the match between the changing, dynamic market and the changing nature of the new product under development.

Regular stage-gate model performs the best when the final product features and definitions are clear. For instance, when product cycles have stable product definitions, have high quality standards, and use well-understood technologies, as is commonly the case for product updates (Unger & Eppinger, 2011; Cooper, 2001; Otto & Wood, 2001).

Cooper (2015), compares stage-gate with agile models. He believes agile and stage-gate are not substitutes for each other and they could be complementary to each other. Agile methods can be used as micro-planning project management means to improve efficiency of certain stages. Table 2 summarizes this comparison as follows:

**Table 2. Key characteristics of stage-gate and agile (Cooper 2015)**

Characteristic	Stage-Gate	Agile
Type of Model	Macro-planning	Micro-planning, project management
Scope	Idea-to-Launch, end-to-end	Development & Testing stages only

<b>Organizational Breadth</b>	Cross-functional: Development (RD&E or technical), Marketing, Sales, Operations	Technical (software code writers, engineers, IT people)
<b>End Point</b>	A launched new product in the market	Developed and tested working software product
<b>Decision Model</b>	Investment model: Go/Kill Involves a senior governance group	Largely tactical: the actions needed for the next sprint

As discussed above, DMADV and DMAIC models are general and simple models for process and product development. However, in these models financial and business aspects of process/product development have not been taken in consideration in details. Moreover, they do not focus on design process and how it should be done. Then, a very short history of software development process models and the milestones and the most famous models were discussed. Finally, this section explained stage-gate model which has been developed in years to keep pace with fast growing industries and their product and process development issues.

### 2.3. Prototype

Merriam-Webster online dictionary (2013) defines prototype “an original or first model of something from which other forms are copied or developed.” A more business specialized definition has been given by Business Dictionary (2013) as “Pre-production model of a product, engineered for full service test.” Also, Ulrich and Eppinger (2000) have defined prototype as “an approximation of the product along one or more dimensions of interest.” In this context, a prototype can be a drawing, a computer model, a plastic model, or a fully functional prototype fabricated at a pilot plant.

Ulrich and Eppinger (2000, 2011) categorized prototypes from different aspects. They have defined a prototype as being analytical or physical. An analytical prototype represents the product in a mathematical or computational form whereas a physical prototype represents a real look-alike prototype made of either substitute materials or actual materials designed for the product. Ulrich and Eppinger (2011) also further defined focused and comprehensive prototypes. Focused prototype refers to prototypes of only a part, or subset of, product functions or attributes while a comprehensive prototype represents all or most of the product functions and attributes. Yang and El-Haik (2009) introduced different types of physical prototypes:

- Experimental prototypes
- Alpha prototypes
- Beta prototypes
- Preproduction prototypes

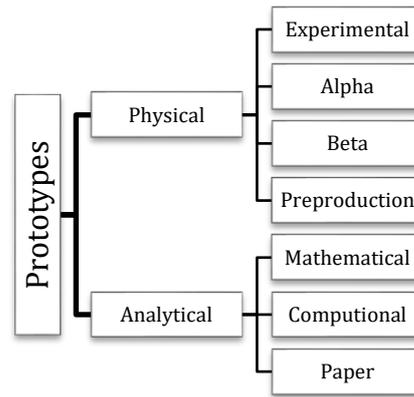
First, experimental prototypes are much focused physical prototypes, used to test or analyze a very well-defined subset of functions and attributes. Second, alpha prototypes are used in product functional performance validation. For instance, an experimental prototype made in the lab or a concept car model is an alpha prototype. Usually an alpha prototype can show all the designed functions of a product. The materials and components used in alpha prototypes are similar to what will be used in actual production. However, they are made in a prototype process, not by the mass-production-based manufacturing process.

Third, beta prototypes are used to analyze the reliability requirements validation, usage requirements validation and product specification validation. They may also be utilized to test and debug the manufacturing process. The parts in beta prototypes are usually made by actual production processes or supplied by the contracted part suppliers. But they are rarely produced at a planned mass production facility.

Finally, preproduction prototypes are the first batch of products made by the mass production process, but at this point in time the mass production process is not operating at full capacity. These prototypes are generally used to verify production process capability, as well as test and debug the mass production process.

Analytical prototyping refers to paper, mathematical, or computer models (virtual models) which are used to demonstrate and assess the product idea without investing on building a physical prototype. Many aspects of the product can be analyzed through this type of prototypes. For instance, an FEM (finite element model) can be used to evaluate various parameters of a mechanical part including force stress and deformation (Yang & El-Haik, 2003). Virtual prototyping integrates technologies such as computer aided manufacturing (CAM), computer aided engineering (CAE) and computer aided design (CAD) in a single visual environment for observation, evaluation and analysis of a product model. Virtual prototyping increase flexibility of prototyping process because modifications of virtual models are easier and cheaper than physical models. In addition, it provides cost efficient data integration and concurrent engineering approach (Liou, 2007).

According to Preece et al. (2002), paper prototyping means making a paper mock-up of an object or interface to demonstrate the look, feel and functionality. These prototypes are cheap and fast to build and it is very easy to modify them. Therefore, they are a helpful tool at the early stages of development to ensure that the designs are compatible with customer requirements. Sketching refers to a simple demonstration of the idea on a piece of paper or on a board. Story boarding consists of series of sketches which show how the prototype functions or it demonstrates how the user performs a task using the device. Figure 17 summarizes the aforementioned categorization.



**Figure 17.** Prototype categories (summarized from Yang & El-Haik, 2009).

Yet another categorization has been introduced by Sharp et al. (2007). They discussed low-fidelity prototyping and high-fidelity prototyping categories. Low-fidelity prototypes are ones that do not look very much like the final product. For instance, it uses materials that are very different from the intended final version. On the other hand, high-fidelity prototypes represent ones which are made of materials that are planned for the final product and the prototypes look much more like the final version. Rudd et al. (1996) suggested a table of advantages and disadvantages of each type (Table 3).

**Table 3.** Relative effectiveness of low- vs. high-fidelity prototypes (Rudd et al. 1996)

Types	Advantages	Disadvantages
<b>Low-fidelity prototype</b>	<ul style="list-style-type: none"> <li>• Lower development cost.</li> <li>• Evaluate multiple design concepts.</li> <li>• Useful communication device.</li> <li>• Address screen layout issues.</li> <li>• Useful for identifying market requirements.</li> <li>• Proof-of-concept.</li> </ul>	<ul style="list-style-type: none"> <li>• Limited error checking.</li> <li>• Poor detailed specification to code to.</li> <li>• Facilitator-driven.</li> <li>• Limited utility after requirements established.</li> <li>• Limited usefulness for usability tests.</li> <li>• Navigational and flow limitations.</li> </ul>
<b>High-fidelity prototype</b>	<ul style="list-style-type: none"> <li>• Complete functionality.</li> <li>• Fully interactive.</li> <li>• User-driven.</li> <li>• Clearly defines navigational scheme.</li> <li>• Use for exploration and test.</li> <li>• Look and feel of final product.</li> <li>• Serves as a living specification.</li> <li>• Marketing and sales tool.</li> </ul>	<ul style="list-style-type: none"> <li>• More expensive to develop.</li> <li>• Time-consuming to create.</li> <li>• Inefficient for proof-of-concept designs.</li> <li>• Not effective for requirements gathering.</li> </ul>

Efficient and extensive use of prototypes can make a difference in the successful entry of new products into a competitive global market (Zorriassatine et al, 2003). Kamrani and Naser (2010) has made a list of benefits of prototypes as follow:

- Quickly try out “new” design concepts
- Troubleshoot existing or new designs

- Obtain ideas for future design changes
- Better communication among engineering teams
- Functional testing of designs
- Marketing
- Production tooling and fixturing can be better planned
- Packaging and shipping methods can be explored

Also, Yang and El-Haik (2009) propose that in product development, prototypes can be helpful for many purposes. They can be used for:

- Design analysis
- Validation testing and debugging
- Interface and compatibility testing
- Communication and for demonstration purposes

First, design analysis can be served mainly by analytical prototypes. For a prototype that is analytical and focused, a subset of selected product functional performances or some very specific features of the product will be analyzed. If the expected performance goals cannot be met, the design will be changed to improve the performance.

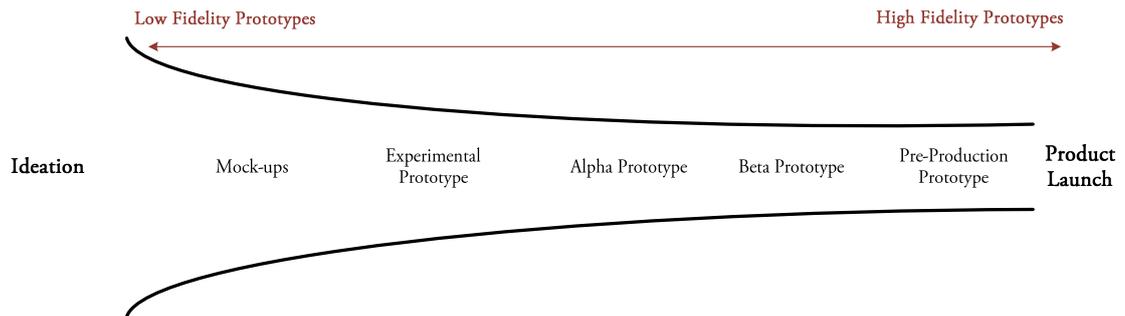
Second, real performances are delivered by physical products, therefore usually validation testing and debugging can be served much better by physical prototypes. For reliability life testing and confirmation, a physical prototype is a must. The real advantage of a true physical prototype turns up when some unexpected failures, bugs, and other defects are found only by physical prototype testing.

Third benefit of prototypes is the interface and compatibility testing. Prototypes are often used to make certain that the components and/or subsystems can be assembled well. Besides, designers may want to test to see whether different subsystems work well after being assembled together as a system or not. Finally, prototypes, especially physical prototypes, can enhance the power of communication and demonstration significantly. “A picture is worth a thousand words”; by the same token, “a real thing is worth a thousand pictures.”

Another concept related to prototyping is mock-ups which has been used in software and web designing context and refers to digital mock-ups (DMU). For instance, Jenkins (2009) suggests using mock-ups as a “graphical representation of the Web site layout used to communicate the look, feel, and functionality of a site before the graphics are optimized and the site gets constructed”. However, physical mock-ups also have been used. Interaction Design Foundation (2010) has stated that mock-ups are very early prototypes made of cardboard or other low-fidelity materials. The Academic Press Dictionary of Science and Technology defines mock-up “(in engineering) a scale model, often full-size, of a structure, apparatus, or vehicle; used for study, training, or testing and to determine if the apparatus can be manufactured easily and economically.” Limbuddha-

augson and Sahachaisaree (2010) define mock-up as “a scale or full-sized model that used for demonstrating and evaluating the functionality of a design.”

Based on the definitions given above it is possible now to plot the big picture which type of prototype to use when and on which step of product development. In the early stages, lower fidelity prototypes are used and the closer the development project gets to the final market release the higher fidelity prototypes are utilized. Figure 18 shows how prototypes are used throughout the process of product development.



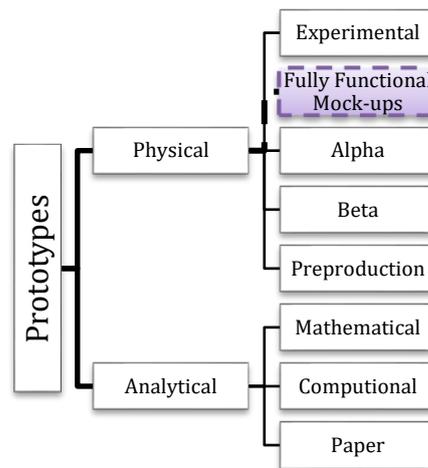
**Figure 18.** Utilizing prototypes throughout an NPD process.

Timothy et al. (2011) have defined prototype in designing workplace context as a three-dimensional (3D) representation of the workplace where the improvement is desired. They also describe mock-ups as quick and inexpensive tools which similar to the rough sketching techniques with pencil and paper, 3D mock-ups do not have to be to perfect scale, although it should be a reasonable facsimile. They also continue that often a reasonable mock-up can be built using discarded cardboard boxes, packing materials, shipping tubes, and other junk found around the office or company. Using common materials such as sturdy tape, safe scissors, safe box cutters, and tape measures, the discarded materials can be very quickly run into a rough 3D representation of what has been planned. It is not necessary to get the 3D mock-up to perfect scale, but it is a good idea to get it close so that it make more sense of final product. Also, it is not needed to put all the details into the mock-up, only the details that are required. Often, they are the dimensions and other details that are relevant to the main desired functionality.

## 2.4. Mock-ups and Iterative Development

As it is mentioned in section 2.2, the more the product matures and approaches to readiness, the more expensive the development gets (Belz, 2010). Thus, a new product concept must be tested and be refined iteratively to eventually support a business model (Annacchino, 2007). The prototype and mock-up concept introduced in section 2.3 are implemented for this purpose, to test and refine the product ideas. However, the ones which are introduced so far by scholars are not always adequate.

According to Pour (2015), in Yang and El-Haik (2009) categorization of prototypes, there is a huge gap between experimental prototypes and alpha prototypes. Depending on the product, sometimes it is possible to test the functionality of the product without building a prototype almost close the final product in details. For instance, it can be done if the model is build out of low-cost materials such as plywood. Not to mention, it is not expected to have the exact features of the final product, though it represents the functionality and helps the stakeholders to see and feel the product functionality. Pour (2015), names this type of prototypes fully functional mock-ups. Figure 19 shows the positioning of fully functional mock-ups in Yang and El-Haik (2009) categorization.



**Figure 19.** Positioning of fully functional mock-ups in Yang and El-Haik (2009) categorization.

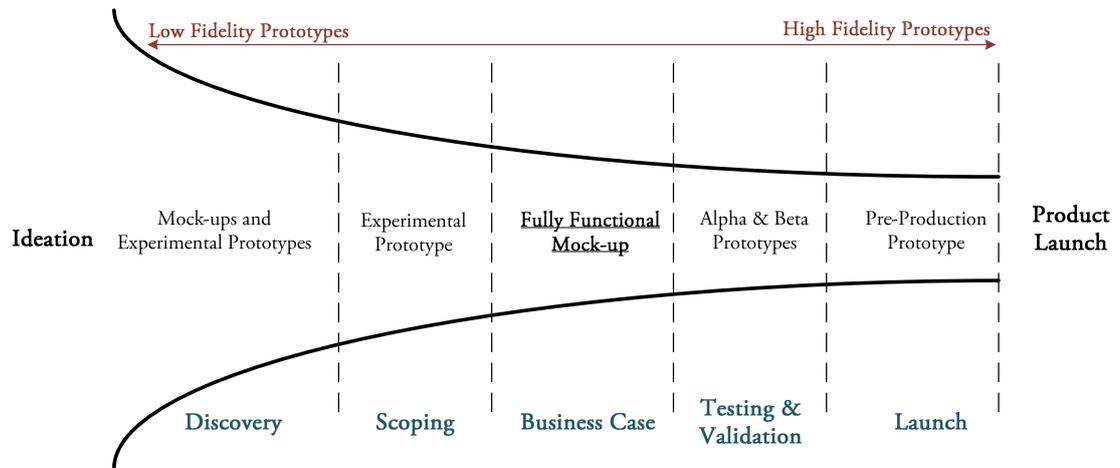
It is noteworthy that fully functional mock-up is not considered as low-fidelity nor is it high-fidelity prototype; it shares some characteristics of both. Moreover, it has some of its own features such as being adjustable for the further developments and more expensive than low-fidelity prototypes. Table 4 summarizes the comparison between fully functional mock-ups, and low and high-fidelity prototypes.

**Table 4.** Characteristics of fully functional mock-ups vs. low and high-fidelity prototypes.

<b>Types</b>	<b>Advantages</b>	<b>Disadvantages</b>
<b>Low-fidelity prototype</b>	<ul style="list-style-type: none"> <li>• Lower development cost.</li> <li>• Evaluate multiple design concepts.</li> <li>• Useful communication device.</li> <li>• Address screen layout issues.</li> <li>• Useful for identifying market requirements.</li> <li>• Proof-of-concept.</li> </ul>	<ul style="list-style-type: none"> <li>• Limited error checking.</li> <li>• Poor detailed specification to code to.</li> <li>• Facilitator-driven.</li> <li>• Limited utility after requirements established.</li> <li>• Limited usefulness for usability tests.</li> <li>• Navigational and flow limitations.</li> </ul>
<b>Mid-fidelity prototype (Fully Functional Mockup)</b>	<ul style="list-style-type: none"> <li>• Useful communication device</li> <li>• Useful for identifying market requirement</li> <li>• Proof of concept</li> <li>• Almost complete functionality</li> <li>• Use for exploration and test.</li> <li>• Evokes the look and feel of the final product.</li> <li>• Modifiable for further developments</li> <li>• Inexpensive</li> </ul>	<ul style="list-style-type: none"> <li>• Limited error checking.</li> <li>• Poor detailed specification to code to.</li> <li>• Facilitator-driven.</li> <li>• Might be more expensive than low-fidelity prototypes</li> </ul>
<b>High-fidelity prototype</b>	<ul style="list-style-type: none"> <li>• Complete functionality.</li> <li>• Fully interactive.</li> <li>• User-driven.</li> <li>• Clearly defines navigational scheme.</li> <li>• Use for exploration and test.</li> <li>• Look and feel of final product.</li> <li>• Serves as a living specification.</li> <li>• Marketing and sales tool.</li> </ul>	<ul style="list-style-type: none"> <li>• More expensive to develop.</li> <li>• Time-consuming to create.</li> <li>• Inefficient for proof-of-concept designs.</li> <li>• Not effective for requirements gathering.</li> </ul>

Thus, the prototype utilization funnel will change with Pour's (2015) suggestion. He suggests that the more an NPD project proceeds the more comprehensive prototypes are utilized to test and evaluate performance and functionality. Figure 20 illustrates the distribution of prototype types in a stage-gate model. This allocation of prototypes in the stage-gate funnel looks rigid and gives the impression that one type of prototype could be used

only in a specific stage. However, it only illustrates how the core of product development proceeds.

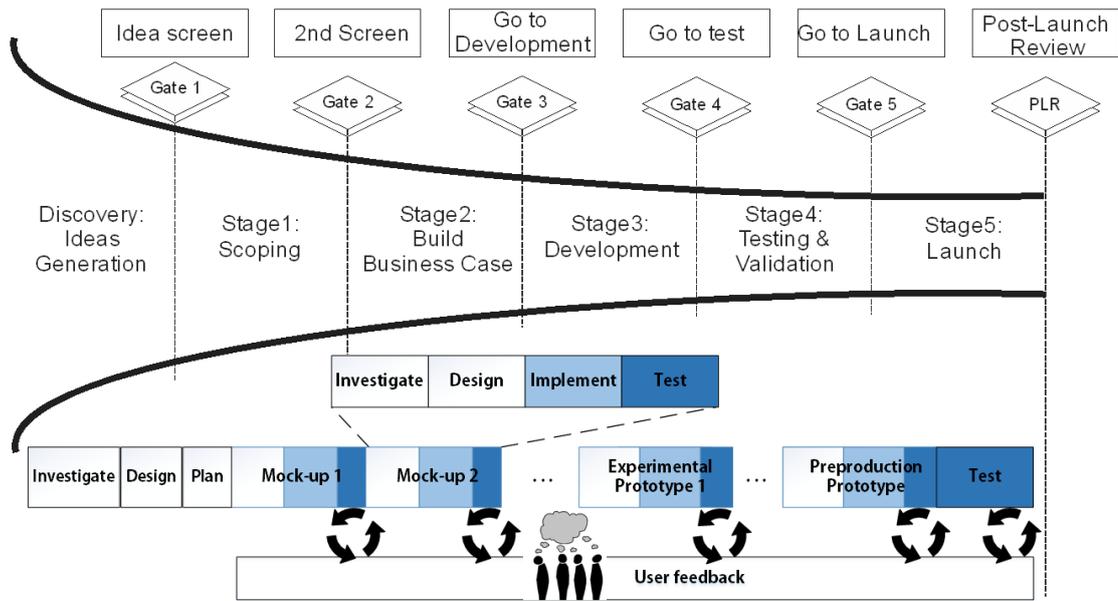


**Figure 20.** Pour (2015) allocation of prototypes in a stage-gate NPD model.

As mentioned above, staged models work the best when they are applied in projects in which the final product features and details, and customer requirements are clear. Thus, Cooper (2015) believes that agile methods can be integrated with stage-gate model to tune this model for other projects where the final product is not fully defined and it evolves during the process with the help of customers' feedback. It also increases efficiency and accelerates product development process. He suggests to apply agile methods in development and testing (stage 3 and 4). Cooper insists that agile methods cannot be used for physical products, specially in the first stages and backs up his view with following reasons:

- Software development is divisible but that is not always the case with physical products.
- It is not possible to build a model of a physical product within few weeks to collect the customers' feedback

It is true that in many cases, it is not possible to divide the product in separate functional components. However, in many cases it is possible to demonstrate the core functionality of the product with a mock-up. Besides, conversely to the second argument, as mentioned above, fully functional mock-ups can be built rapidly and inexpensively. Thus, with the help of mock-ups and fully functional mock-ups, agile methods could be applied in earlier stages right after ideation as well. The result is the agile stage-gate model (Figure 21).



*Figure 21. Agile stage-gate model.*

This model suggests first, testing ideas as soon and inexpensive as possible, second, focus on the core functions of the product, third, continuous and close work with the stakeholders to receive their feedback, fourth, implementing new ideas coming from stakeholder's feedback in the next inexpensive prototypes. In this way, agile methods and stage-gate model can merge to some extent to keep the advantages of each method and reduce their disadvantages as much as possible.

It is noteworthy that here EVO is used as representative of agile methods. However, depending on the projects the most suitable method could replace EVO in the agile stage-gate. It is noteworthy that, mock-ups built in early stages to test the core functionality of the product. As the development proceeds the next mock-ups evolve to prototypes and high-fidelity prototypes with more features and the customers test and feel the product in every development stages and give feedback to make sure the end product meet their requirements. Yet, there are few aspects missing in the model such as customer/supplier integration system, cost management and financial issues. Therefore, the next chapter discusses cost management systems, process modeling, and how mock-ups can help with these matters.

## 3. ROLE OF MOCK-UPS IN COST MANAGEMENT

### 3.1. Definition

Weil and Maher (2005) define cost as the sacrifice, measured by the price paid or to be paid, to obtain products. Business scholars frequently use cost when referring to the valuation of a product bought. In this sense, a cost is an asset. Also, the cost is considered as an expense or loss when the benefits of the acquisition of the product expire. Yet, some authors, use cost and expense as substitutes. Since the word cost is used in more than 50 accounting terms, each with sometimes subtle distinctions in meaning, it is needed that the user includes with the word cost an adjective or phrase to clarify the intended meaning.

Business Dictionary (2015) defines cost as an amount that has to be paid in order to acquire something. In business, cost is usually a monetary valuation of effort, material, resources, time and utilities consumed, risks incurred, and opportunity forgone in production and delivery of a product. It is noteworthy that all expenses are costs, but not all costs are expenses.

Depending on the purpose of the analysis, managers classify and use a single cost in several ways. They use cost information about operations to plan, perform, value, and communicate the outcome of operating activities. When measuring costs for decision making purposes, the kind of costs studied is important since some costs are irrelevant to the decision making. Weil & Maher (2005) define relevant costs as those which change as a result of choosing one option over another. Atrill and McLaney (2009) state that a cost must fulfill both of following criteria:

- It must be related to the objective of the business. In other words, since for the majority of companies, wealth creation for the shareholders is the main objective of the business, to be relevant to a particular decision, a cost must have an effect on the wealth of the business.
- It must be different from one decision making option to another.

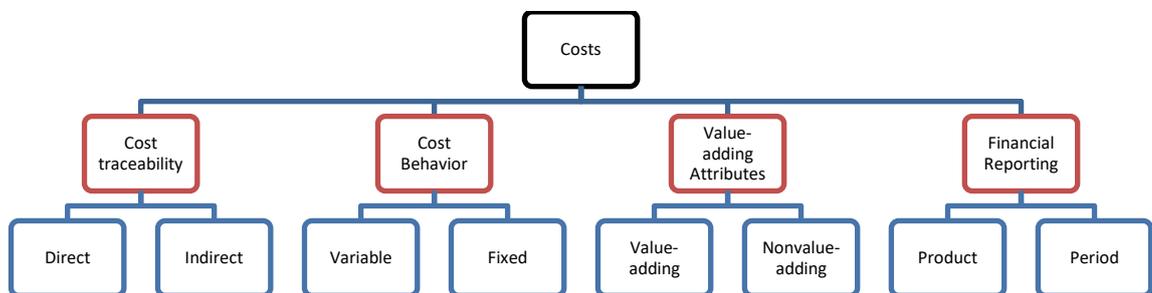
Based on these criteria past costs which are also known as historic or sunk costs are irrelevant to the decision making. Conversely, incremental or differential costs are relevant. In other words, relevant costs are future opportunity costs and future outlay costs that are of concern. Weil and Maher (2005) define opportunity costs as the net benefits that the firm would have earned from an asset used in its next best use.

Crosson & Needles (2010) also explain other methods of cost classification. They state that this classification and analysis help managers to:

- Determine which costs are traceable to a specific cost object
- Calculate the quantity or the number of units must be sold to reach a certain profit goal
- Identify value-adding activities
- Prepare financial statements

Therefore, from traceability point of view cost can be direct or indirect. Before defining direct and indirect costs it is needed to clarify the term cost object. Hansen & Mowen (2006) define cost objects as products, customers, departments, projects, activities, or any item, for which costs are measured and allocated. Thus, direct costs are those which can be traced accurately to a cost object. Conversely, indirect costs are those which managers cannot trace conveniently and economically to a cost object. Crosson & Needles (2010) also explain, costs show different behavior towards the volume of production. A cost which changes in direct proportion to changes in production output is a variable cost. On the contrary, a fixed cost remains constant within a defined activity range or period of time. The third aspect costs are looked at is value creation. A value-adding cost is the cost of an activity that increases the market value of a product or service. On the other hand, a nonvalue-adding cost is the cost of an activity that adds cost to a product or service but does not affect its market value.

Finally, from financial statements point of view costs are classified as product costs and period costs. Product costs or inventoriable costs refer to costs assigned to inventory which include direct material, direct labor, and overhead. On the income statement product costs appear as cost of goods sold and on the balance sheet as inventory. Period costs, or noninventoriable costs, mean the costs of resources used throughout the accounting period that are not assigned to products. It is noteworthy that the period costs appear as operating expenses on the income statement.



**Figure 22.** Costs classification from different aspects. Adapted from Crosson & Needles (2010).

Now that the cost itself is defined and classified, it is valuable to define cost management as well. TechTarget-Whatis (2015) defines cost management as the process of planning and controlling the budget of a business. In other words, cost management is a management accounting method that allows a business to forecast imminent expenditures to help reduce the risk of over budgeting. A more precise and academic definition is given by Hansen and Mowen (2006). They state that in contrary to financial accounting, cost management produces information for internal users. Cost management in specific identifies, collects, measures, classifies, and reports information that is useful to managers for determining the cost of products, customers, suppliers, and other relevant objects, and also is beneficial for planning, controlling, making continuous improvements, and decision making. Cost management deals with much broader issues than that found in traditional costing systems. It does not only calculate how much something costs but also investigate the factors that drive costs, such as cycle time, quality, and process productivity. Therefore, cost management necessitates a profound knowledge of a firm's cost structure. To this end, it is a must to determine the long- and short-run costs of activities and processes as well as the costs of goods, services, customers, suppliers, and other objects of interest. Moreover, cost management provides tools and methods to carefully study causes of these costs.

It is also noteworthy that often times, management accounting and cost accounting terms are used interchangeably. To be more precise, cost accounting is mostly considered the major subgroup of management accounting. Webster (2004) explains that cost accounting studies cost behavior with its well-equipped tools such as theories and approaches. To draw the distinction line, management accounting deals with the tasks of decision-makers such as framing the policies, and communicating information, whereas cost accounting aims for internal management by collecting and analyzing costing, pricing, and performance details, which crosses into financial accounting, for external reporting. It is noteworthy that although financial statements do not include the costs of activities and processes, identifying these costs and their underlying causes is crucial for companies engaging in such tasks as continuous development, total quality management, environmental cost management, productivity enhancement, and strategic cost management.

### **3.2. Costing Methods**

Some of the terms and vocabulary used in cost accounting literature were defined above. There are more terms used by scholars in this field which are defined below (Webster, 2004, Weil & Maher, 2005, Crosson & Needles, 2010).

- Cost center: a unit of activity (location or function of an organization) for which a firm collects expenditures and expenses.
- Cost driver: a measured factor, such as hours worked, that indicates an activity's costs.

- Cost object: any activity, item, or operation for which management desires a separate measurement of costs.
- Cost pool: the accumulated indirect costs allocated to a cost object
- Cost unit: a quantifiable unit of product/service for which costs are measured.

Costing in BusinessDictionary (2015) and Handbook of Cost Management by Weil and Maher (2005) is defined as a system of computing cost of production or running a business, by allocating expenditure to different steps of production or to various operations of a company.

According to Hansen & Mowen (2005), cost management can be categorized as functional-based and activity-based costing (ABC). Functional-based costing methods, currently, are more broadly used than the activity-based methods. One of the functional-based and traditional, yet wide used costing methods is full costing or absorption costing which takes account of all of the cost of producing a particular product or service (Atrill & McLaney, 2009).

Weil and Maher (2005) define full costing as the total cost of production and sales of a unit which usually is used for long-term profitability and pricing decisions. The sum of full costs for all units equals total costs of the company. They formulate full cost as follow:

$$\text{Full cost} = \text{full absorption cost} + \text{marketing} + \text{administrative} + \text{interest} \\ + \text{other central corporate expenses}$$

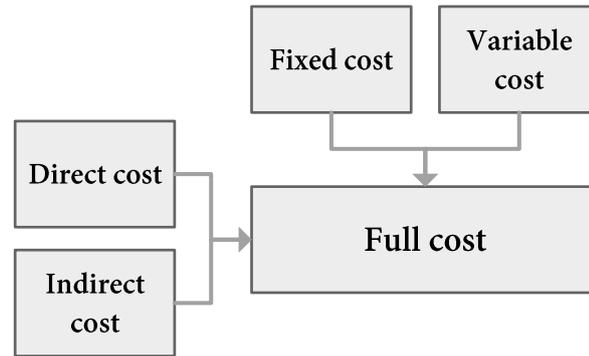
In which, absorption cost is all costs associated with manufacturing of a particular product including direct material, direct labor, and fixed and variable overhead. In other words, full cost can be simplified as:

$$\text{Full cost} = \text{Direct cost} + \text{Fair share of indirect cost (Overheads)}$$

From cost behavior perspective, full cost is formulated as:

$$\text{Full cost} = \text{Fixed cost} + \text{Variable cost}$$

The two series of notions are completely different and independent even though sometimes there is a tendency that fixed costs to be indirect costs and overhead and at the same time variable costs to be direct.



**Figure 23.** *Different formulas of full cost (Adapted from Atrill & McLaney, 2009).*

According to Hansen & Mowen (2006), there are problems with allocating indirect costs when the products or units of output are not identical. On the one hand the indirect cost of any activity must be included in the cost of each cost unit. On the other hand, indirect costs cannot, by definition, be directly related to individual cost units. Full costing leaves this question unanswered that how the indirect cost should be allocated to individual cost units.

Atrill & McLaney (2009) summarize in what historical and economic situation full costing methods emerged and why it worked well for ages despite its shortcomings. They stated that the traditional costing developed when the notion of trying to determine the cost of industrial production emerged which was around the UK industrial revolution. They outline the characteristics of the industry at that time as follow: First, businesses were direct-labor-intensive and production was direct-labor-paced. Labor was the core of production and machinery was only to support the efforts of direct labor, thus, the production pace depended on direct labor. Second, companies had a low level of indirect costs relative to direct costs. Depreciation charges were low because there was not much spent on machinery, little was spent on power, employees' services, or other overheads of modern business. Lastly, markets were relatively uncompetitive. Because of limitations at the time such as transportation difficulties, lack of customers' knowledge about competitors' products and prices, and inadequate international production resulted that businesses could be successful without being too accurate and scientific in costing. It means customers would have accepted whatever suppliers offered rather than asking what exactly they needed.

Hence, full costing method worked quite well at the time. However, as businesses became more complicated allocating overheads was not as easy as it used to be. It is important to know how the economy looked like after industrial revolution and world wars and how competition and marketing affected the costing methods.

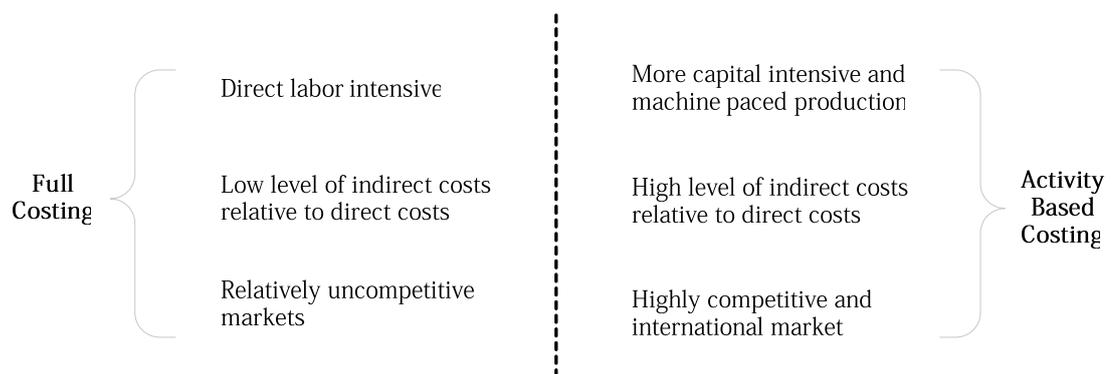
The market characteristics and business environment evolved during and after the industrial revolution which was an inevitable consequence of scientific revolution in 15<sup>th</sup> and

16<sup>th</sup> centuries (Harari, 2014). Atrill & McLaney (2009) describe this environment and its influences on costing methods.

First, businesses became more capital intensive and machine-paced production. Now machines become the essential part of manufacturing and production, and also in providing services. Moreover, most of labor job transformed from manual manufacturing to supporting, operating, and maintaining the machines. Now, frequently machines dictate the production pace. According to Ernst and Young survey in 2003, the direct labor costs in manufacturing industries is only about %14 of total manufacturing cost.

Second, companies began to have a high level of indirect costs relative to direct costs. The modern industries and businesses now have much higher depreciation, service, and power costs. Moreover, there are higher personnel and staff costs, which now are not much involved during the early stages of production. However, there are much lower or even sometimes no labor costs. Furthermore, even though the material cost is often an important part of the total cost, with the new production methods waste of material decreased and this consequently leads to lower total material cost which implies the increase in the indirect costs and overheads. According to Ernst and Young (2003), overheads form 25 per cent of manufacturers' total cost and over 51 per cent of service sector total cost.

Lastly, markets became highly competitive and more international. Thanks to the new technologies customers have access to prices and products overseas with only few clicks or a phone call from a range of suppliers. Transport is much faster than before specially with airfreight. Consequently, markets are more and more price competitive. Moreover, customers progressively more want customized products. Thus, businesses need to have more accurate approach to pricing than full costing methods. Figure 24 summarizes the different business atmospheres full costing and ABC emerged.



**Figure 24.** The grounds for implementing traditional costing method or activity-based costing method (summarized from Atrill & McLaney, 2009).

Thus, as the traditional cost management methods do not show adequate performance in recent years, new costing systems became more popular. Hope & Player (2012) describe ABC as models which bring a better understanding of product and customer net profitability to managers by providing better methods of attributing overheads. They state that only few question the need for many of these overhead costs such as controlling bureaucracy in the first place. ABC provides managers with information which helps decision makers to assess if costs should incur at all. However, as there is no such a thing as free lunch, implementing ABC comes with its complications and expenses.

A numerical example shows the difference between the two approaches. For instance, an R&D team is planning for a new product with two different designs. Both of the designs reduce direct material and labor costs over the current model. The estimated costs of each design are as follow Table 5:

*Table 5. ABC vs full costing example (Adapted from Atrill & McLaney, 2009).*

<b>Cost behavior</b>		
<b>Full costing</b>	<b>ABC system</b>	
Variable conversion activity rate: \$40 per direct labor hour  Material usage rate: \$8 per part	Material usage (direct materials): \$8 per part Machining: \$28 per machine hour Purchasing activity: \$60 per purchase order Setup activity: \$1,000 per setup hour Warranty activity: \$200 per returned unit (usually requires extensive rework) Customer repair cost: \$10 per repair hour	
<b>Activity and Resource Information (annual estimates)</b>		
	<b>Design A</b>	<b>Design B</b>
<b>Units produced</b>	10,000	10,000
<b>Direct material usage</b>	100,000 parts	60,000 parts
<b>Labor usage</b>	50,000 hours	80,000 hours
<b>Machine hours</b>	25,000	20,000
<b>Purchase orders</b>	300	200
<b>Setup hours</b>	200	100
<b>Returned units</b>	400	75
<b>Repair time (customer)</b>	800	150

The cost analysis of each design under both full costing and ABC is illustrate in Table 6. Full costing point of view calculates cost of unit production based on only manufacturing costs. The results of using this method are in favor of Design A. Thus, if the company implements only traditional method, design A will be chosen. However, with more detailed and accurate ABC system, the end results for the unit production costs are different. Implementing ABC system reveals that design B reduces manufacturing, logistic, and

after sale's costs. Overall, design B saves the company \$396,000 a year. Moreover, design B has a higher level of serviceability since the customer repair hours of design B is much lower.

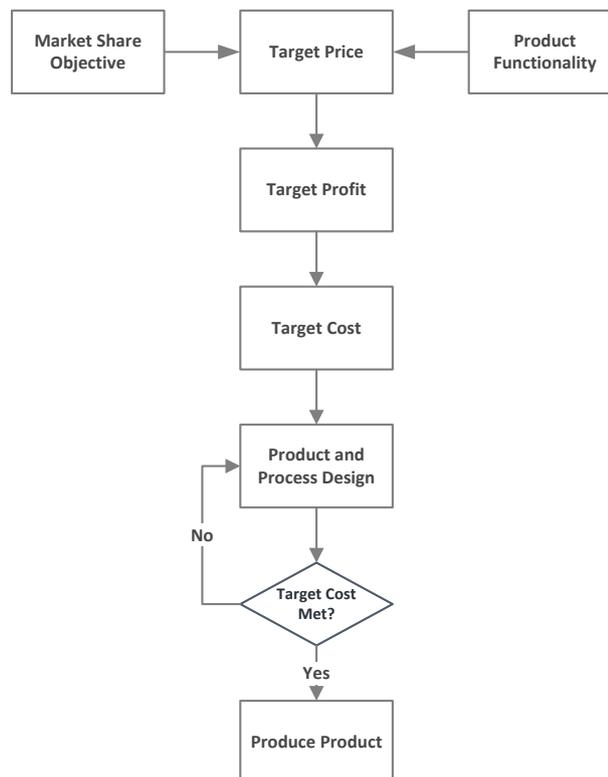
**Table 6.** The cost analysis of the example (Adapted from Atrill & McLaney, 2009).

<b>A. Traditional Costing System</b>		
	<b>Design A</b>	<b>Design B</b>
Direct materials <sup>a</sup>	\$ 800,000	\$ 480,000
Conversion cost <sup>b</sup>	2,000,000	3,200,000
<b>Total manufacturing costs</b>	<b>\$ 2,800,000</b>	<b>\$ 3,680,000</b>
Unit produced	÷ 10,000	÷ 10,000
<b>Unit Cost</b>	<b>\$ 280</b>	<b>\$ 368</b>
<sup>a</sup> \$8 × 100,000; \$8 × 60,000 <sup>b</sup> \$40 × 50,000; \$40 × 80,000		
<b>B. ABC System</b>		
Direct materials	\$ 800,000	\$ 480,000
Direct labor <sup>c</sup>	500,000	800,000
Machining <sup>d</sup>	700,000	560,000
Purchasing <sup>e</sup>	18,000	12,000
Setups <sup>e</sup>	200,000	100,000
Waranty <sup>e</sup>	80,000	15,000
<b>Total product costs</b>	<b>2,298,000</b>	<b>1,967,000</b>
Units produced	÷ 10,000	÷ 10,000
<b>Unit cost</b>	<b>\$ 230*</b>	<b>\$ 197*</b>
Purchase costs	\$ 80,000	\$ 15,000
<sup>c</sup> \$10 × 50,000; \$10 × 80,000 <sup>d</sup> \$28 × 50,000; \$28 × 20,000 <sup>e</sup> \$60 × 300; \$60 × 200; \$1,000 × 200; \$1,000 × 100; \$200 × 400; \$200 × 75 * Rounded		

Yet, another concept related to costing is target costing. According to Weil and Maher (2005), target costing help firms to structure costs when developing a new product with specified functionality and quality to assure profitability of the product over its life-cycle at its estimated selling price. Target costs includes any costs that are driven by the number of units sold. For instance, if the firm accepts responsibility for delivery, installation, or disposing a product at the end of its useful life, the target costing considers them all. Target costing is a tool for both profit management and cost management. Target costing was developed in Japan, where the lean enterprise concept began to evolve. There, companies do not see target costing as an independent program, rather it is part of the product development process. The companies which innovated and developed lean production and target costing challenged both product designers and the suppliers. If the method is applied effectively, harmony and discipline are brought to different stakeholders of the product development, from designers and engineers to suppliers, marketers, and final consumers.

A Dictionary of Business and Management (2016) and Kurian (2013) define target costing as a system of costing products to answer the price customers are willing to pay and match with their target price. The former summarizes the four steps of the implementation of target costing method as follow:

1. Identify the target price that customers are willing to pay for the product or the service. In this step, companies also evaluate and their competitors' price and take it into account when making decisions.
2. Given the profit margin, which varies from company to company, and the target price, identify the target cost by deducing the former from the latter.
3. Estimate the actual cost of the product or service.
4. If the estimated actual cost is more than the target cost (from step 2), the production managers and engineers will have to lower the cost by increasing efficiency, optimizing production, or even change the product design accordingly. Figure 25 summarizes target costing model.



**Figure 25.** Summary of target costing model. Adapted from Hansen and Mowen (2006).

Hansen & Mowen (2006) mention three methods of cost reduction used in the fourth step: reverse engineering, value analysis, and process improvement. Reverse engineering refers to analyzing competitors' products to identify design features that help cost reduction. Value analysis includes assessing the value customers allocate to different product functions. If the target price for a function is lower than its cost, that function is even subject to elimination. But before that, other options to provide that function less costly such as

using common components are considered. The first two methods focus on the product design. Conversely, the third method focuses on supply, production, and marketing cost reduction. Hence, production process improvement can play a crucial role in cost reduction.

A numerical example of target costing could explain this concept clearer. A company is considering to develop a design for a product. The two variables influencing the target price, meaning targeted market share and current product specifications, identify the sales price as €1500. The target profit of the company is €200. Thus, the target cost is €1,300 (€1500 – €200). The estimations show that the current design and manufacturing process result in the production cost of €1400. Hence, the production cost must be reduced to meet the target cost. By analyzing a competitor's product engineers reveal an improvement in design which reduce production costs by €40. Moreover, the production manager comes up with an idea which increases the production pace which reduces labor cost by €65. Now the company meets the target cost.

Epstein et al. (2010) in their literature review found out that there is a correlation between Hofstede (1980) national culture variables and the costing method used more commonly in countries. They cited to Ciambotti (2001) research and stated that ABC is more often applied in Anglo-Saxon and Scandinavian companies than in Mediterranean and Latin America companies. Bhimani et al. (2007) also approve this result and in their paper show that ABC is quite common in English-speaking countries and in France, whereas in Germany, Japan, and Italy, ABC is applied only in a small number of firms. It is noteworthy that target costing is implemented primarily in Japan, South Korea, Taiwan, and Germany, whereas in other European countries, specially Mediterranean countries, it is seldom applied (Ciambotti, 2001). There are more studies done on different cost accounting practices in different countries such as Schröder (2015).

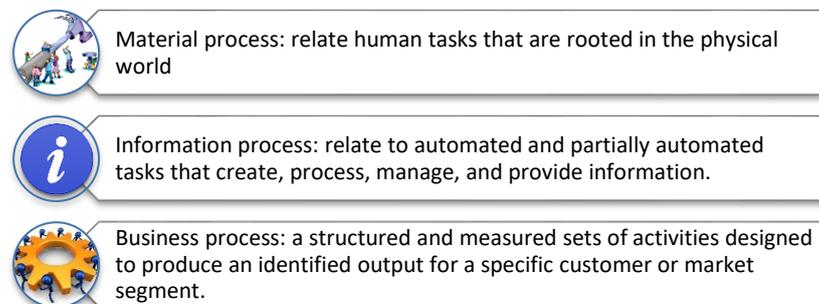
Based on the concepts introduced in this section full costing and ABC are systems which apply to compute or forecast costs of a product or service. This information is used as an input for target costing to fulfill customers' needs and serve them better. Either full costing method or ABC system study processes from cost point of view. Next section discusses processes and how scholars study them.

### **3.3. Process modeling**

As mentioned above, cost management provides information for internal uses. For this purpose, it uses tools to model and then measure. One of the tools is process models. It is necessary to define process itself first. Keller and Pyzdek (2009) define process simply as a set of repeatable tasks that are carried out in a certain sequence. They continue, in case processes cannot be defined as a series of repeatable tasks, then there may be several

processes in operation, or it can simply mean the process is not well-defined. Also, Aguilar-Savén (2004) has defined processes as a series of activities which add value to inputs and transform them into outputs.

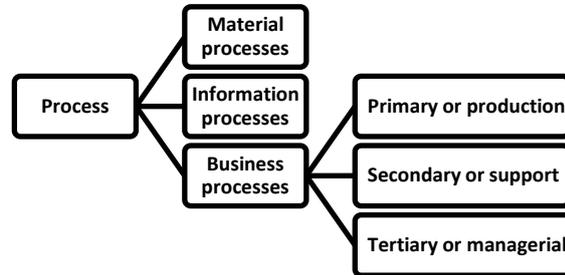
Processes in organizations have been categorized by scholars. Medina-Mores et al. (1992) have divided processes in organizations into material processes, information processes and business processes. Material processes refer to assembling physical components or to move and deliver physical products. In other words, material processes relate human tasks which are rooted in physical world which include moving, storing, measuring, transforming, and assembling physical objects. Then, information processes include fully or partially automated tasks in which either tasks performed by machines or by humans interacting with machines. Characteristically, information processes are rooted in organizations' structure and the current atmosphere of information systems. The basic infrastructure of information processes is usually provided by database, transaction processing, and distributed systems technologies. Lastly, business processes come to picture. When an organization's activities are implemented as material processes and information processes, a market-centered description of these activities refers to business process. That means a business process is designed and engineered to fulfil a customer or a business deal. Also, Davenport (1993) has defined business processes as a structured and measured sets of activities designed to produce an identified output for a specific customer or market segment. Therefore, the business process concept is perceptually at higher level than the information process or material process concepts. Figure 26 summarizes different kind of processes and their definition.



**Figure 26.** *Three processes in an organization.*

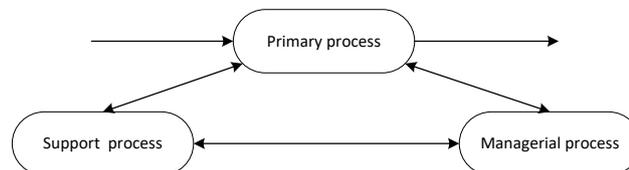
Aalst et al. (2004) have categorized business processes into production, support, and managerial processes. Production or primary processes refer to the business processes which produce a company's products or services. Primary processes generate income for companies, and they are undoubtedly customer-oriented. Purchasing of raw materials and components, the production itself, the sale, and the distribution are examples of primary processes. Support or secondary processes are those which support the production. Secondary processes include maintaining the means of production, employees' management, marketing, and financial administration. Managerial or tertiary processes refer to pro-

cesses which coordinate and manage the primary and secondary processes. Defining objectives and preconditions of other processes, allocating resources, and maintenance of contacts with financiers and stakeholders are included in tertiary processes. Figure 27 summarizes this categorization.



*Figure 27. Process categorization.*

Figure 28 illustrates the relationships between the three types of business processes. Aalst et al. (2004) explain that the managerial processes must deliver performance (often profit) with the capital and objectives as their input. From the managerial processes, support processes receive the means to acquire new resources or dispose the old resources which do not function anymore. The output of support processes is the material and resources passed to primary processes which will be returned after work. Besides the resources from support processes, primary processes receive orders as their input. After working on the resources, primary processes deliver products or services as their output. Both primary and support processes give reports to the managerial processes.



*Figure 28. Links among the three types of business processes (Adapted from Aalst et al., 2004).*

According to Georgakopoulos et al. (1995), when an organization has designed its activities in terms of business processes, it can redesign or reengineer each process to either improve it or adapt it to dynamic requirements. Companies usually reengineer their business processes to increase customer satisfaction, to improve efficiency of business operations, to increase quality of products, to reduce costs, and to face new business challenges and opportunities through developing existing products or developing new products. Business process reengineering starts before automating these processes with information systems and computers. Information process reengineering encompasses using information systems and computers to automate the redesigned business processes. Thus, information process reengineering is a complementary task of business process reengi-

neering. Georgakopoulos et al. (1995) also suggest that business and process reengineering tasks can be performed iteratively to optimize the process development through mutual feedback.

There are different tools to measure, define, and visualize processes. One of the most important tools is modeling. Models are simplified reality with the aim of bringing clarity to some aspects of problems which often times come with complexity (Lindsay et al., 2003). Curtis and Kellner (1992) have defined model as a representation of reality in abstract and without many details. Thus, the main purpose of a model is to simplify understanding and interaction with the phenomenon by removing unnecessary details which do not affect its relevant performance. The two concepts, process and model, can be combined to create a new concept which is process model. Process model is formalized view of a business process, represented as a coordinated set of activities and steps which can be parallel and/or serial. These activities and steps are linked in order to accomplish a common goal (ISO, 2014). Also, State of California Franchise Tax Board (2009) defines process modeling as creating integrated visual models illustrative of business, system, and human processes which is applied to capture, design, reengineer, simulate, and optimize processes. There are different business process modeling techniques available and each has its attributes, purposes, and characteristics (Aguilar-Savén, 2001).

Aguilar-Savén (2004) has done a literature review on the different business process modeling techniques and described their most important characteristics. She has listed nine methods as main techniques. However, in this thesis, the ones that are more useful in costing are briefly explained: Gantt chart and workflow. Gantt chart is named after its creator the American engineer, Henry Gantt who for the first time invented this technique in 1917 (Doyle, 2016; Upton & Cook, 2014; Law, 2014; Law, 2016). Hill (2014) describes the Gantt chart as the first scheduling model ever devised and the main purpose of this techniques was to assign and monitor tasks on factory machines, in that way minimizing delays and conflicts in planning. In other words, Gantt chart us a visual tool that illustrates tasks, employees, machines, and all resources required to accomplish a job on a calendar-oriented grid. Figure 29 shows a simple Gantt chart.

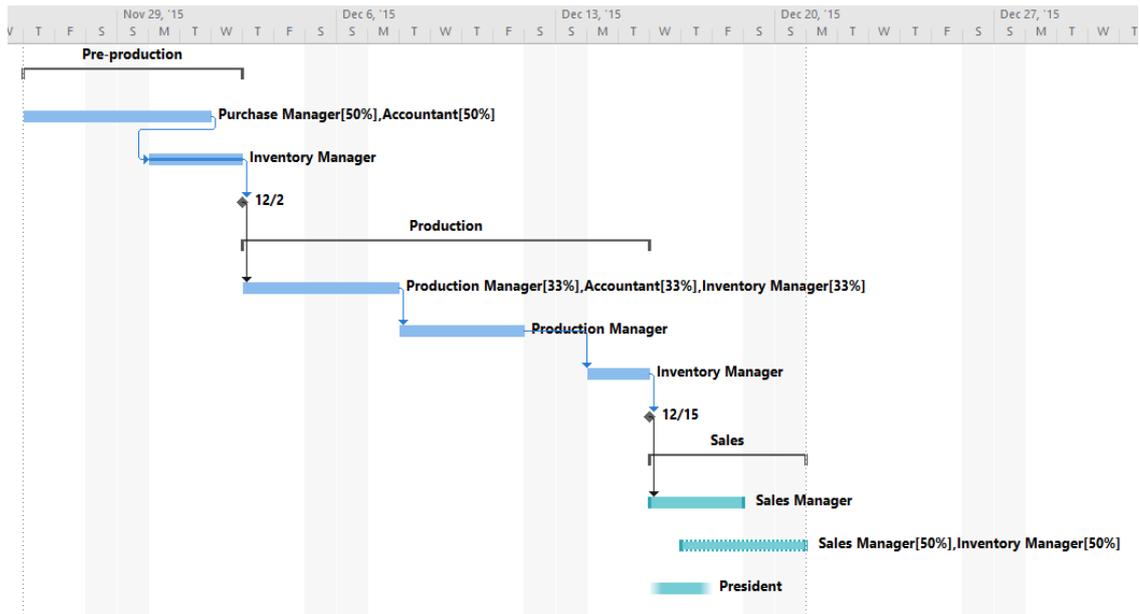


Figure 29. A sample Gantt chart.

As the figure shows, Gantt chart contains different information of a project such as, tasks, deadlines, dependency of tasks, resources, responsible people, and duration. Gantt charts usually come with a key to illustrate the signs used in the chart (Figure 30). Belz (2011) states that an important aspect of Gantt charts are milestones and progress towards them. Milestones could illustrate either project activities at a given time, or the desired outcome at a given time.

Depending on the purpose, managers might need to go some levels deeper into activities and break them down in smaller tasks. For example, in Figure 29 production is divided to take the raw material from inventory to shop floor and loading it, then production, and lastly to packaging and delivering the final product to the warehouse or the customers depending on the case. Yet, the second task, production, can be divided to more precise tasks such as cutting, machining, molding, or installation of sub systems (Roy, 2007).

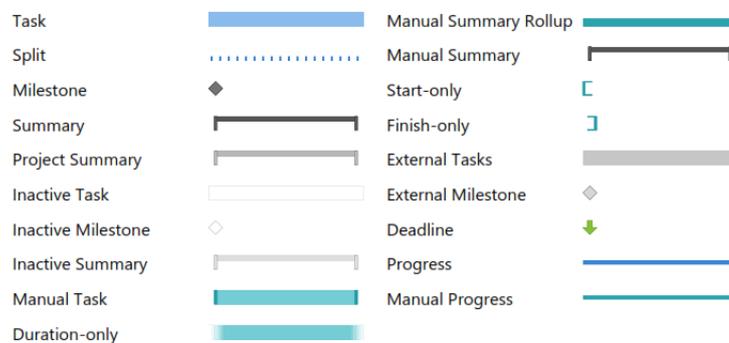


Figure 30. Gantt Chart key sample.

Hill (2014) summarizes the pros and cons of Gantt chart by stating that keeping a Gantt chart updated reveals problems came across in the conduct of a project. Based on the explanations given above, the Gantt chart is one of the most effective tools for planning and scheduling operations. It is easy to construct and understand a Gantt chart, even if it contains a lot of information. However, this method is not well equipped to show dependencies and interrelationships among activities in very complex operations. Also, there is no provision for handling uncertainty and ambiguity.

Another modeling technique is workflow which has evolved from the notion of process in office and manufacturing (Georgakopoulos et al., 1995). Workflow could be defined as an organizational scheme that contains the timetables and relationships of operations, materials, process control elements and locations in the process (ISO, 2004). Nowadays, firms in different industries such as banks, insurance companies, hospitals, and factories implement workflow technique quite often to automate their business processes (Han et al., 2005). Also, Mentzas et al. (2001) define workflow as a series of tasks designed to accomplish a business process. One or more software systems, a human or a team, or a combination of these can perform a task. However, workflow concept is mostly used when human-machine interaction is involved and automation plays a significant role in the process (Hollingsworth, 1994).

Workflow visualization can be done in several ways such as graphic diagrams, standards like SIPOC (Supplier–Input–Process–Output–Customer) or BPMN (Business Process Modeling Notation), flowcharts like ANSI (American National Standards Institute) or UML (Unified Modeling Language), and swimlane (Kupersmith et al., 2013).

Georgakopoulos et al. (1995) state that workflow concept is closely related to the process reengineering and automating business and information processes. A workflow may illustrate business process tasks at an abstract level necessary for understanding, evaluating, and redesigning the business process. Alternatively, workflows may explain information process tasks at a level that describes the process requirements for information system functionality and human skills. The difference between these workflow viewpoints is not always made, and sometimes the term workflow is used to describe either, or both, of the business and information systems perspectives.

Based on the application, required accuracy, business processes' nature, and companies' objectives, managers use one or more modeling techniques (Aguilar-Savén, 2004). In a product or process development business processes also change. Also, based on the design of a new product development, production processes might be different. Annacchino (2007) states that different processes have different cost centers and cost drivers. Thus, in a product development project, managers should consider the production process scheme when the product is approved for the launch.

### 3.4. Mock-ups as a Tool to Analyze Possible Process Models

Scientific management, Taylor method, or Taylorism was developed in late 19<sup>th</sup> and early 20<sup>th</sup> centuries (Scott, 2014; Law, 2016) a few decades before activity-based costing was introduced by Bruns and Kaplan in 1987. Berlingher (2013) states that Frederick William Taylor, the creator of scientific management, was inspired by former studies done; specifically, Henry R. Towne, the president of the famous enterprise “Yale and Towne Manufacturing Company”, who applied the new management methods at his time in his company workshops.

Hoxie (1911) receives Taylor’s approval for the following definition of scientific management (Nyland, 1996): “Scientific management is a system devised by industrial engineers for the purpose of serving the common interests of employers, workmen and society at large through the elimination of avoidable wastes, the general improvement of the processes and methods of production, and the just and scientific distribution of the product”.

Berlingher (2013) summarizes Taylor’s fundamental principles of scientific management as follow:

- Documenting and analyzing traditional knowledge and transforming this knowledge into scientific laws.
- Scientific selection of workers and investing in their qualities and knowledge improvement.
- Implementing the survey work by trained scientific workers.
- Nearly equal work distributed between workers and managers.
- Establishing cooperation among people instead of chaotic individualism.

Golden and Leslie (2011) have made a list of scientific management contributions areas mentioned by other researchers. They cite to Flynn (1998) who listed Taylorism contributions in work management, production planning and control, process design, quality control, cost accounting, and human engineering and ergonomics. Moreover, they refer to Bedeian (1998), Copely (1923), Fry (1976), Locke (1982), Wilkinson & du Pont (1965), Werge & Greenwood (1991), Wren & Bedeian (1994), and Wren (2005) which have mentioned other areas of scientific contribution such as industrial efficiency, delineation and task management, standardization, organizational behavior, and work study or time and motion study.

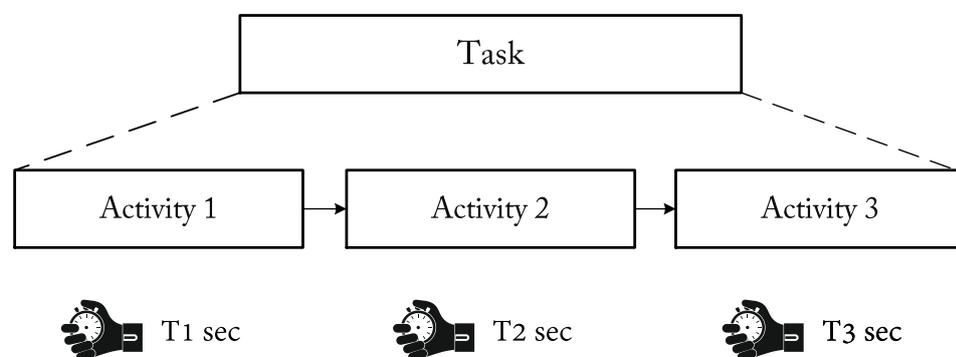
In 1952, “work study” journal started its work by sharing studies and insights on work study and since 2004 this journal is published under the name of “International Journal of Productivity and Performance Management”. In one of its early issues Anson (1953) states that one of the most important aspects of work study is time study. Anson (1953) and Tikhomirov (2011) carried out studies to track time study down in scholars’ literature.

Anson (1953) refers to Church (1914) that time study was a re-discovery by Taylor and there were studies done before him. Merrick (1928) approves this by referring to the French engineer, Peronnet and the English mathematician, Babbage's experiments and documented use of time study methods in factories.

Regardless of how this term emerged in literature, time study is defined as the study of time taken to get a task done (Ivanovic & Collin, 2009). According to Law (2009), time and motion study refers to operating this study in an office or factory to study time taken to finish tasks by employees and/or machines. Time and motion study contains of breaking the activity down into smaller tasks and measuring the time taken to get that task done. This helps that performance standards to be set. These standards work as guidelines and can be utilized to plan and control production, forecast costs, estimate prices and delivery times, and formulate incentive plans.

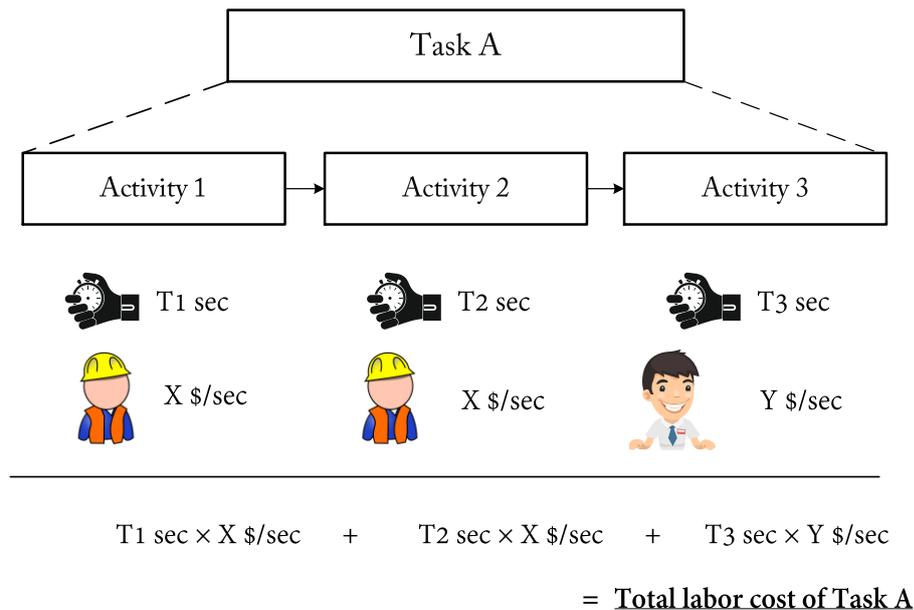
Citing to Merrick (1928) Anson (1953) states that the mistakes done in early time studies were due to, firstly, that the jobs were not sufficiently standardized, secondly, failure in steady material flow maintenance, and thirdly, workers awareness of the experiment. Also, Taylor (1912) indicates that the standardization is part of the time study method. Standardization is to define and set adequate ideals in production and quality of products, and also invariant measurements and specifications for products in the manufacturing process (Kurian ,2013).

Anson (1953) believes that the simplest time study procedure was described by Drury (1915) which consists of four steps. First, dividing a task to simplest activities, second, measuring with a stopwatch how long each activity takes, third, calculating accumulative time to complete a task, and fourth, multiplying the total time by a factor to take unpredictable and unnecessary delays into account. Merrick (1919) gives almost the same description of the time study method, unless he adds notes on the number of observations and how to deal with the outliers. He suggested to observe each full operation for at least 20 times and also to ignore times which are 25 percent below or 35 percent above their adjacent times. Figure 31 illustrates time study method steps.



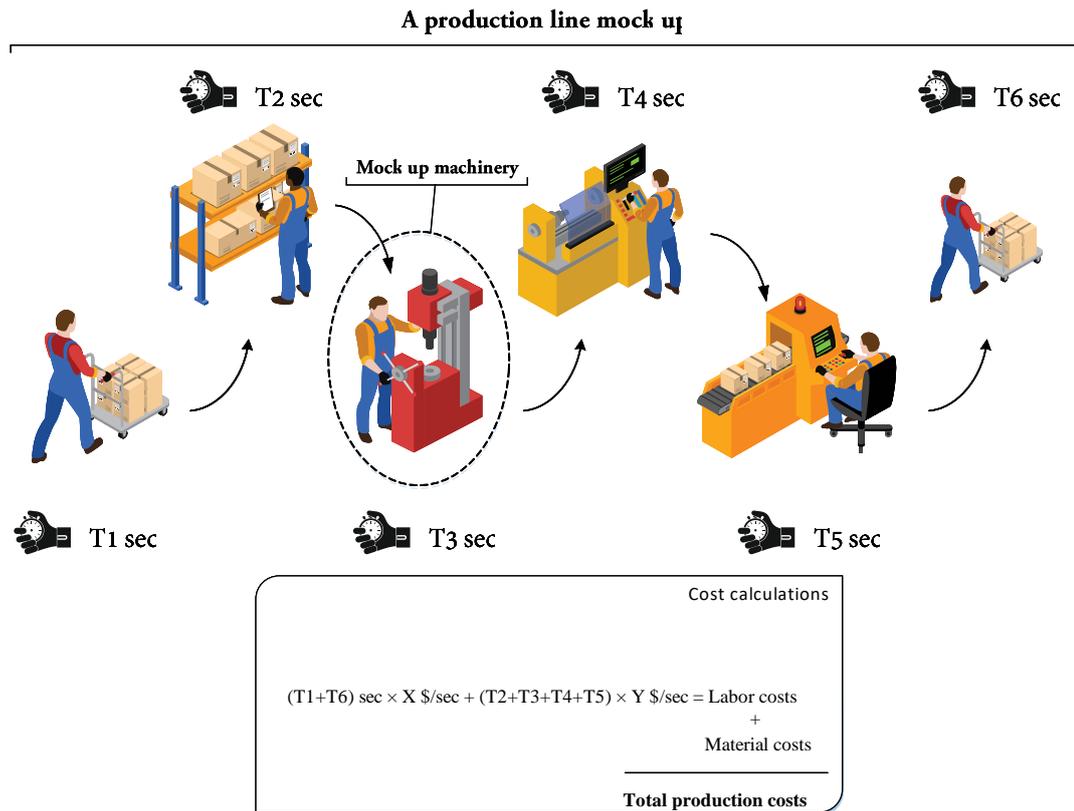
*Figure 31. Time study steps.*

When modeling a process time study can provide valuable information to the model. For instance, considering and adding data gathered through the time study to a Gantt chart model or a workflow model the duration of each task can be provided more precisely than mere estimations based on assumptions. This information is valuable for managers to calculate activity costs. Thus, given the employees and workers' wages on one hand and the times measured through the time study on the other hand, job costs can be calculated. Figure 32 illustrates an example of applying the time study on a process model to calculate activity costs.



**Figure 32.** Applying time study on a simple process model.

Whether an NPD project leads to a totally new manufacturing process or adjusts an old process to have a new product, the change in the production process is inevitable. However, as mentioned in Section 2.3, often companies test the production process with the preproduction prototypes, after bearing all the product development costs. Having mind Section 2.2 and Figure 4 which shows how product development costs increase exponentially with time, testing production process as the last step of product development could be extremely expensive. Again, it is noteworthy to remind from Section 2.2 that the go/kill decision in this stage could be harder due to the incurred costs and the sunk cost fallacy that managers could fall into. Thus, it is suggested to apply and test fully functional mock-up in the production line after the early mock-ups pass the functionality test before developing further. Figure 33 illustrates an adjusted mock-up production line. In most of the steps of production the old machinery is used. Only in the third step, a fully-functional mock-up machine (red in the figure) is placed.



**Figure 33.** A workflow model of a fully functional production line mock-up.

Hence, a fully functional mock-up of the production line is built only with the old machinery or with inexpensive mock-up machinery. By applying this method, not only the NPD managers can receive feedback from stakeholders by showing them tangible product, which might not be complete or elegant yet, but also have a more accurate estimation of production costs before they proceed further with the product development itself and bear huge development costs.

Thus far, the role of mock-ups in product development from two points of view has been explained. With the focus on B2B atmosphere, the next chapter discusses how agile stage-gate NPD method and cost estimations with the help of mock-ups can balance between product development quality and its costs.

## 4. SUPPLIER/CUSTOMER INTEGRATION IN NPD

### 4.1. Lean Manufacturing Concept

Bhamu and Sangwan (2014) share their belief about the contemporary businesses by stating that customized products are the brand of manufacturing in twenty first century. Customization mean more complex production planning and control systems which makes mass production of goods challenging. Customer driven markets on one hand and global competition on the other hand, challenged many businesses, particularly car manufacturers. These issues have forced organizations to research and innovate new tools and methods to keep their growth steady. Some organizations continued to grow because of their understanding of the new economic changes. On the other hand, others were heaving to due to lack of understanding of the evolved customer habits, mindsets, and cost management. Many manufacturers implemented lean manufacturing (LM) to overcome the circumstances. The goal of LM is to provide customers with the goods/services as fast they require and at the same time at lowest cost.

Elbert (2012) states that the lean concept originated in Japan in 1950, after World War II, when Japanese manufacturers realized that they do not have the funds for the large-scale investment required to rebuild ruined factories. Mr. Toyoda and Mr. Ohno rebuilt Toyota corporation with producing cars with minor inventory, lesser human effort, small investment, and reduced defects; and at the same time Toyota presented higher quality products with ever growing variety. For further studies on the history of manufacturing, a more detailed history of manufacturing is told by Roser (2016).

Some scholars have defined LM as a combination of different tools to eradicate non-value-adding activities by increasing the value of each activity, with the goal of eliminating or reducing waste and at the same time improving processes (García-alcaraz, 2014; Elbert, 2012; Liker, 2004; Womack, 1991; Womack & Jones, 2003). Liker (2004) refers to Mr. Ohno's quote in 1988 to demonstrate the lean philosophy: "All we are doing is looking at the time line from the moment the customer gives us an order to the point when we collect the cash. And we are reducing that time line by removing the non-value-added wastes."

Moor (2007) describes the main characteristics of a lean organization as follows:

- Minimum inventory in all three forms of raw material, WIP (work in process), or finish goods
- Least mismatches, rejects, returns, or rework in production

- Minimum loss in production due downtimes, changeover and transition time, rate reductions and short stops, and quality issues
- Minimum system cycle times and delays between processes
- Standardized production rates and processes
- Minimum production unit costs
- In time delivery and customer satisfaction
- Focus on continuous improvement and gaining market share

Other references such as Plenert (2007; 2010), Moor (2007), Elbert (2012), and Roser (2016) also approve the above characteristics with some small differences in phrasing. Other researchers such as Yang and El-Haik (2003), Husby and Swartwood (2009), and Gitlow (2009) have studied lean organizations characteristics from organizational habits, routines, and culture as well.

The product development framework introduced in Section 2.4 matches with lean concept and goals. However, developing a new idea and a new product which totally fulfill the customer's need might not necessarily be successful. To have a successful new product, customers should be able to afford the price and at the same time be willing to pay for the product. The next sections provide a framework to increase the NPD success chance in this regard as well.

## 4.2. Customer/supplier Integration in NPD

According to Kazmane et al. (2014), LM has generated significant results in continuous performance improvement and gaining market share through cost reduction, quality improvement, raising the standard bars, and customer satisfaction. However, several studies show that all these results would not be achievable with implementing lean concept alone within an organization. To accomplish competitive advantage, the supply chain should be aligned with the goals and standards of LM in up and downstream of the supply chain. This will lead to a lean supply chain. Besides, the supply chain management and LM have common goals. Fig shows the relationship of SCM and LM.



*Figure 34. SCM and LM relationship (Adapted from Kazmane et al., 2014).*

Moreover, scholars have mentioned different variables involved in success of new product development. Ragatz et al. (2002) based on their literature review, summarize the variables that are crucial to successful NPD:

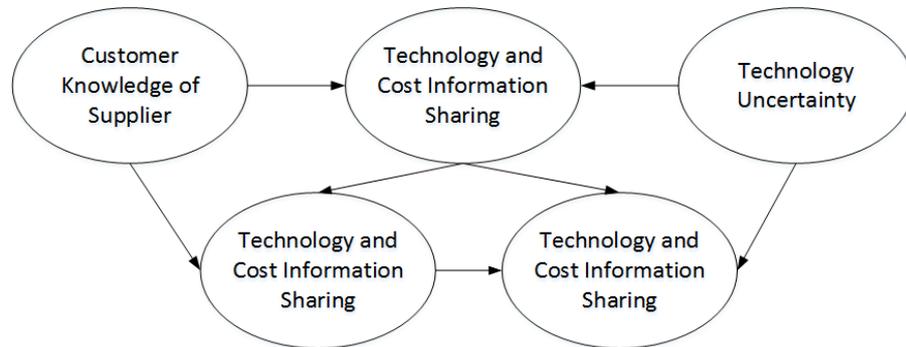
- Team composition, organization, and processes
- Project leadership and senior management support
- Product effectiveness
- Market issues
- Customer/supplier integration

The latter is one of the frequent concepts pointed out by academics (Clark & Fujimoto, 1991; Griffin et al., 1992; Kanter, 1994; Karlsson & Ahlstrom 1996; Keller, 1994; Mabert, 1992, Smith and Reinertsen, 1991; Teece, 1989; Zirgir & Maidique, 1990). Thus, to gain the competitive advantage, the customer/supplier integration in product development projects is vital. Customer/supplier integration is a concept implemented mostly in business to business (B2B) context. As Monczka and Trent's (1997) study show that even though many US firms plan to rely more and more on suppliers for the design and technical capabilities to support NPD, almost 70% of the firms which studied to plan early supplier design involvement indicated that there are momentous barriers that limit the supplier/buyer integrability.

Referring to Chesbrough (2003), Gassmann & Enkel (2004), von Hippel (2005) studies, Song et al. (2013) state that it is becoming more and more important for companies to open up organization boundaries to reach external resources of innovation; and often customers are seen as a vital source of product innovation. Yet it is important to study risks of strategic alliance implementation. Strategic alliance is a form of cooperative procedure between two or more organization (Das & Teng, 1998). In their research, they have assessed risk factors from literature review with statistical methods. According to He et al. (2014), some companies fail to integrate customers in their NPD process due to the fact customers are worried about the risks which come along with integration such as the loss of know-how to the outsiders, dependence on manufacturers, increased costs of harmonization, and inflexibility.

Peterson et al. (2003) have done a thorough study on the matter of customer/supplier integration in NPD. They state that many researchers have illustrated the need for customer/supplier integration in NPD. This integration may range from consultation between the customer and the supplier to define a common NPD. Nevertheless, there have not been enough frameworks and models to help with the execution of this approach. They outline the main factors of customer/supplier integration as (a) customer knowledge of supplier; (b) technology and cost information sharing; (c) supplier involvement in decision-making; and (d) technology uncertainty (Figure 35). Even though there are more

variables play role in difference in the success of supplier/customer integration, for simplification reasons they chose these factors and the interconnection among them for their model.



**Figure 35.** Simplified structural equation model (adapted from Peterson et al., 2003).

Through running surveys in different companies, Peterson et al. (2003) tried to find out the most important factors and interpreted the results as follows:

1. The more the sides have knowledge of each other, the higher are chances for them to involve in knowledge and information sharing
2. Sharing of technology information consequences in greater levels of supplier participation and improved results
3. When suppliers are involved in NPD teams, usually the goals of NPD are met better
4. When there is a technology uncertainty, supplier and buyers are more likely to share information on NPD teams
5. The problems linked to technology uncertainty can be lessened by applying more technology sharing and involving the supplier directly.

He et al. (2014) also conclude their literature review and empirical studies with several suggestions as follow. First, it is suggested to emphasize on both supplier and customer integration since collaborative NPD environment has a positive impact. Hence, it is recommended to provide incentives for suppliers to propose suggestions with regard to product design and component simplifications. Second, managers are suggested to implement both up and downstream integration rather than channeling the firm's efforts on one side only. There are misunderstanding and distrust coming along scattered supply chains. Third, integration through supply chain for the product development is not an easy job and requires investment in different areas such as IT infrastructure. It also crucial to spend time with suppliers and customers since integration is more than some technical matters. In most cases, it is suggested to integrate with suppliers first and then develop the integration with customers. Fourth, it has been proposed to develop customer action-oriented service rather than product based service only, since it makes the product/service less

imitable and at the time adds more value to the product. This will lead to serving better customers with complex demands which may enhance the trust with customers.

### 4.3. Open Book Accounting a Tool for Integration

Thus, based on above mentioned literature review, internal integration, supplier integration, and customer integration have positive impact on the NPD process and outcomes. Also, some general hints are provided through surveys to improve strategic alliance implementation. One of the aspects of integration frequently mentioned above is the information sharing and one of the most important information to share is financial information. Kulmala et al. (2002) believes that nowadays networking is more intensive teamwork and partnership between companies than before. A true partnership is established when the customer has provided the supplier a complete, detailed, open, and long-term information regarding his/her business and the supplier and customer work closely to reach their common goal. Nowadays, companies do not own their businesses; rather the business is held by strategies, cooperation, and common objectives with other competence companies (Drucker, 1997).

In the third chapter, costing and its related terms were discussed. According to Kulmala et al. (2002), cost accounting provides crucial knowledge for management at both strategic and operational level. Now costs have to be managed both aggressively and intelligently more than ever due to the fact competitive advantages are not guaranteed to sustain. If a firm fail to cut costs as fast as its competitors, it will face its profit margins decreased and even its existence vulnerable. Hence, because of the competitive environment, managers have to develop sophisticated cost management practices to keep costs as low as possible. Thus, developing effective cost management systems in supply networks is a success factor. Glad et al. (1996) suggests the following characteristics for an effective cost accounting system:

- Cover different aspects and dimensions of cost objects such as customers, products, services, functions, processes, and activities.
- Rather than emphasis on cost tracking and reporting, focus on cost planning and control.
- Back every main business decision such as sourcing, pricing, investment justification, efficiency and productivity measures, product elimination and new product introduction.

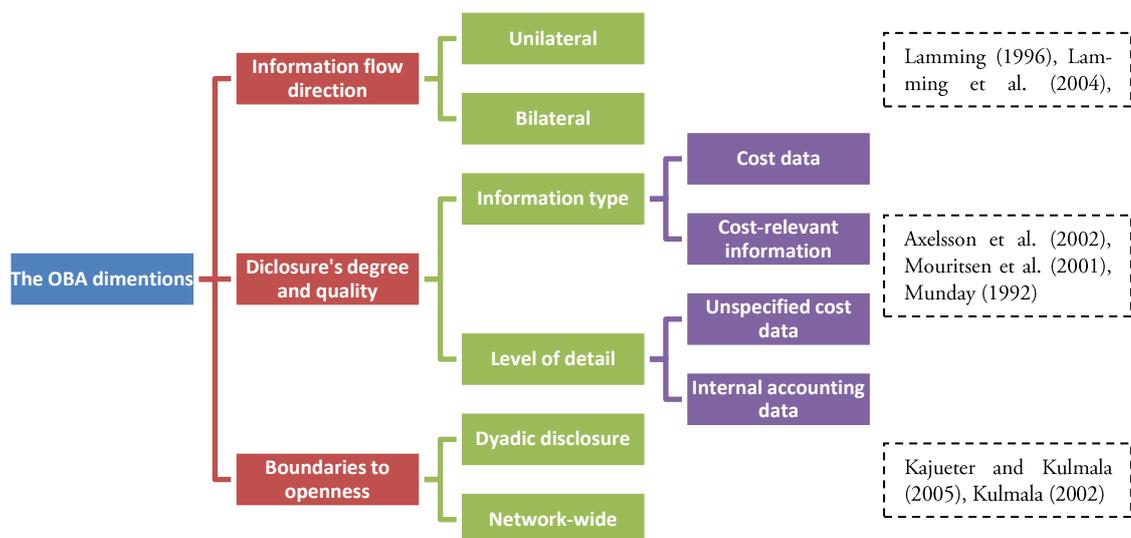
Close relationships are important for the company's short-term financial performance, but they are even more significant for its long-term development (Håkansson & Snehota, 1995). On one hand, in a lean supply network integration and supplier integration are of a high importance. On the other hand, integration has different aspects; it requires close cooperation and information sharing. Moreover, to have competitive advantage in the market, and reach to the target price, costs must be kept as low as possible. At the same

time the whole supply chain must stay profitable to justify its existence. Thus, an accounting and financial strategy should be implemented cooperatively between entities of supply network, specially in NPD projects.

One of the well-known methods introduced by scholars with regard to an accounting strategy for close relationships in supply network is open book accounting (OBA) (Alenius et al., 2015). OBA is an accounting method that offers tools and suggestions for managing inter-firm accounting to maintain control of outsourced activities and at the same time increase supply network efficiency (Agndal & Nilsson, 2010). Another definition is given by Hoffjan and Kurse (2006) as to systematically disclose cost information between legally independent ally companies. Thus, it can be said that the core of OBA is cost data disclosure with strategically ally businesses. By implementing open book accounting, project team members have access to information such as operating costs and all other data that are of importance to profitability (Levoy, 2007).

Mouritsen et al. (2001) show that after outsourcing some companies could suffer from losing knowledge about production processes or control of them which is crucial. Some recognize the importance of managing their new supplier relationship and implement OBA to regain the vital knowledge which could improve the profitability. With the information gathered through OBA implementation, a company can coordinate its supply network more efficiently. OBA is about not only sharing financial information, but also technical and non-quantitative information as well (Carr & Ng, 1995).

OBA has different aspects which are studied by Windolph and Moeller (2012). In their literature review they found out that OBA practices can be studied from three points of view: (1) the direction of the information exchange, (2) to what extent and how information is shared, and (3) boundaries to openness. Figure 36 summarizes the three dimensions that have been discussed in literature.



**Figure 36.** The OBA dimentionts (Adapted from Windolph & Moeller, 2012).

Thus, information flow could be bidirectional or unidirectional, in which case usually only supplier discloses the cost data (Hoffjan and Kruse, 2006; McIvor, 2001). Windolph & Moeller (2012) explain that depending on the purpose and main goals of integration, the degree and quality of cost data disclosure could vary. It could be from only cost data to all cost related information such as sales forecasts. Moreover, the level of details could range from some unspecific cost data to fully disclose numbers used in the internal accounting system. Finally, OBA case studies have been done mostly on mutual buyer-supplier relationship. However, lately, researchers are also focusing on supply network wide OBA practices as well.

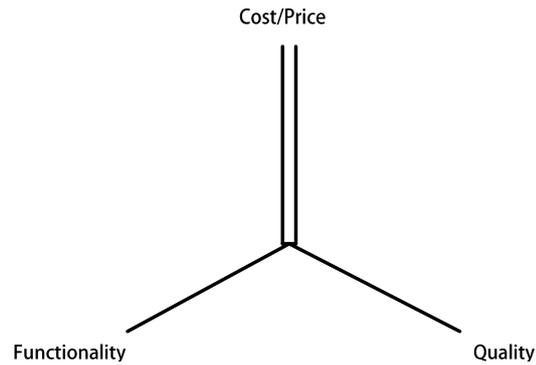
Alenius et al. (2015) have studied OBA implementation to gain a deeper understanding of OBA when there is conflict of interest in interdependencies among supply network. Their empirical studies approve what other researchers, such as Agndal & Nilsson (2010), Dekker (2003), and Kajüter & Kulmala (2005), had stated before on the impacts OBA on direct relationships. However, they also found out that OBA not only influences direct relationships but also indirect relationships which might be even more important. It is because while the OBA is serving the interests of some entities in the supply network, it works against the others since they are not involved in the open calculations. Thus, to have a better outcome companies are suggested not only to use open calculations, but also to carefully design their OBA usage in the supply network.

Another finding of Alenius et al. (2015) is that OBA can be used further than cost enhancements or managing of interdependencies between existing resource interfaces between a buyer and a seller. OBA can be a strong tool to approach new suppliers or customers as well. Therefore, OBA is not only a tool for cost reduction or efficiency improvement within an organization or between strategic allies, but also it can help managers to see priorities clearer.

Finally, they found out how important the open calculations are when the business entities try to define the network boundaries. Therefore, OBA is important in networking activities since the OBA information enlightens the way for actors in the network to which direction they should take.

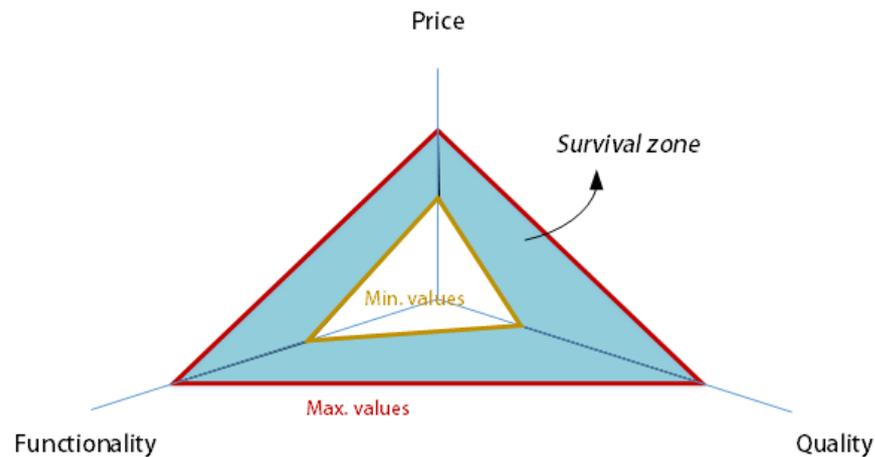
#### **4.4. Iterative Development and Cost Sharing**

Cooper and Slagmulder (1997) introduced the product survival triplet (Figure 37) with three dimensions: functionality, price, and quality. This triplet suggests that only products that receive acceptable values along these three dimensions stand a chance of being successful.



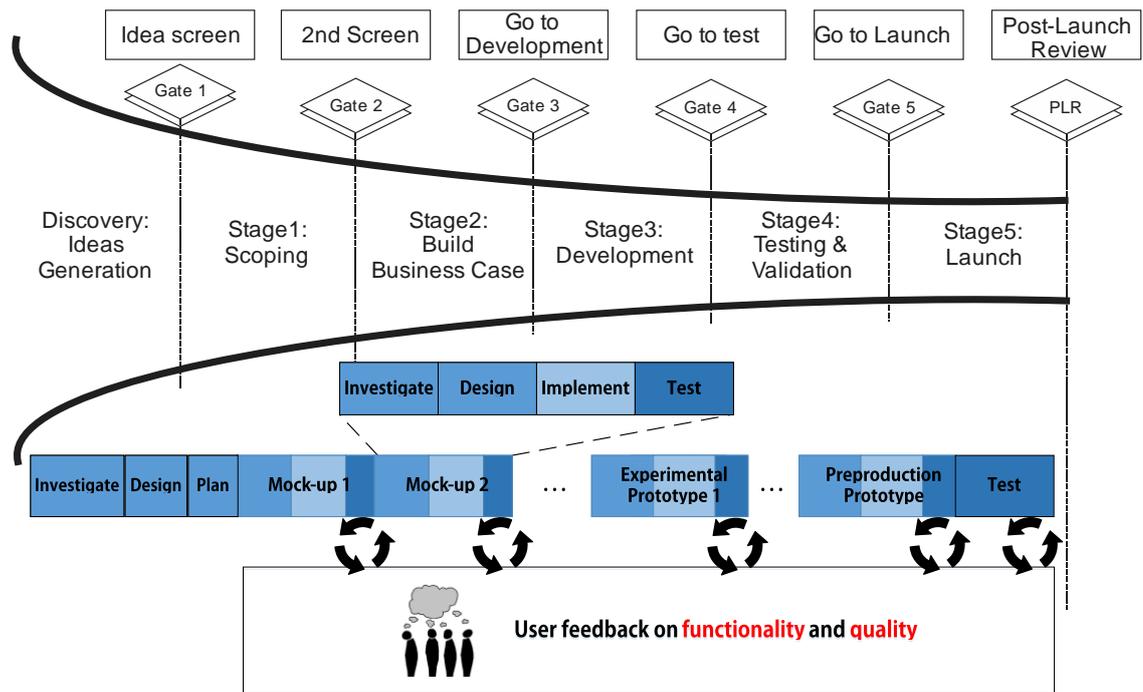
**Figure 37.** *The survival triplet (Adapted from Cooper & Slagmulder, 1997).*

They also define a survival zone for a product on this three-dimensional model. The survival zone is defined by finding out the minimum and maximum values accepted by customers on the survival triplet. Figure 38 is a schematic example of identifying survival zone for a product.



**Figure 38.** *Survival zone for a product (Adapted from Cooper & Slagmulder, 1997).*

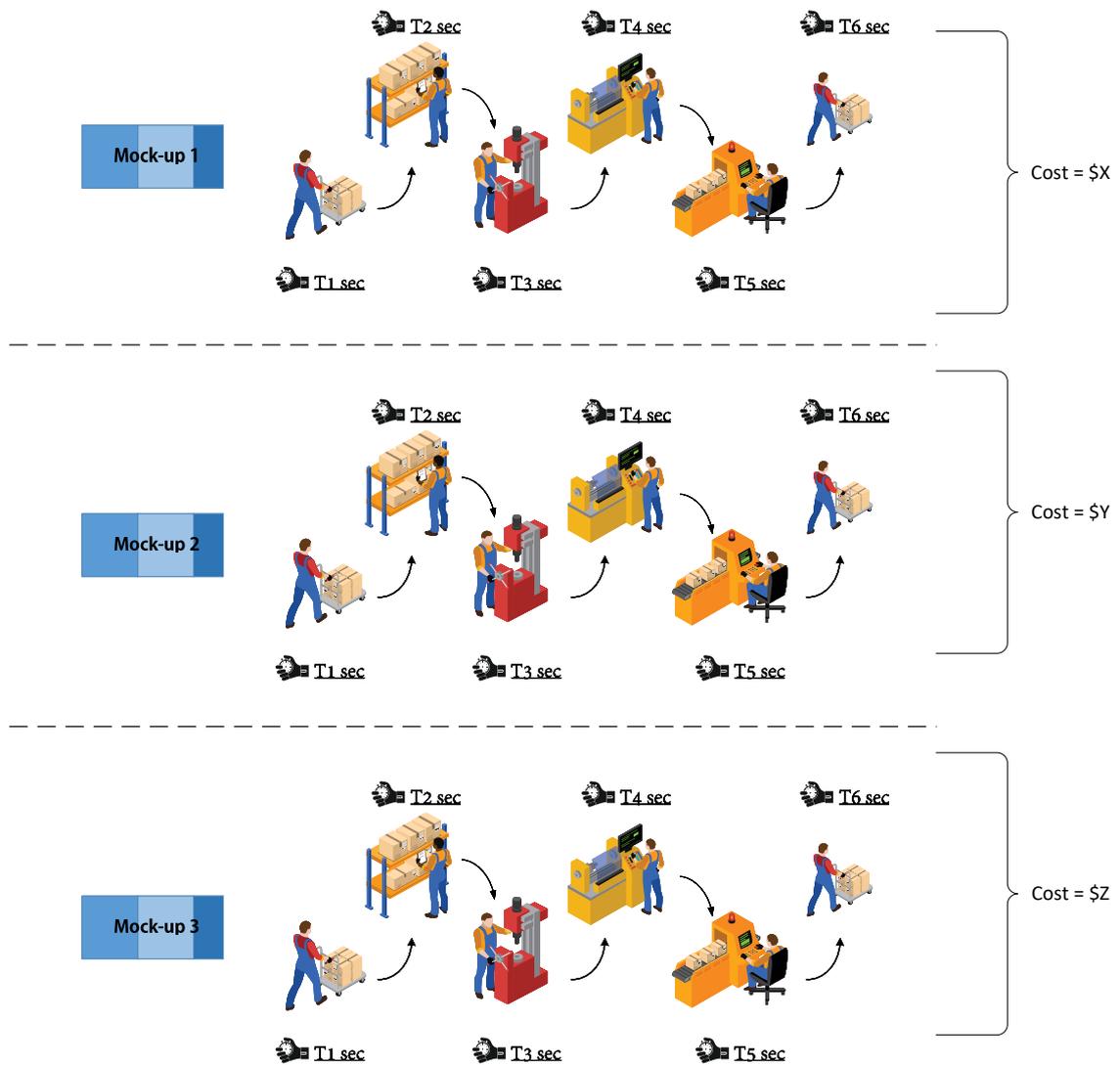
In the second chapter, different methodologies and approaches to NPD were introduced. It was mentioned that one of the main goals of these product development methods is to offer a framework for decision makers to manage NPD project as efficient as possible. Since the costs of development exponentially increase it is crucial to evaluate different aspects of the product frequently. One of vital success factors of a product is that the product would fulfill customers' needs adequately. Hence, the importance of receiving feedback from customers in NPD processes was discussed. The chapter was concluded with an improved stage-gate model which emphasizes on testing ideas as fast and cheap as possible through mock-ups. Thus, mock-ups are used as communication tools with customers and other stakeholders to receive feedback on functionality and quality of the product (Figure 39).



*Figure 39. Mock-ups as communication tools.*

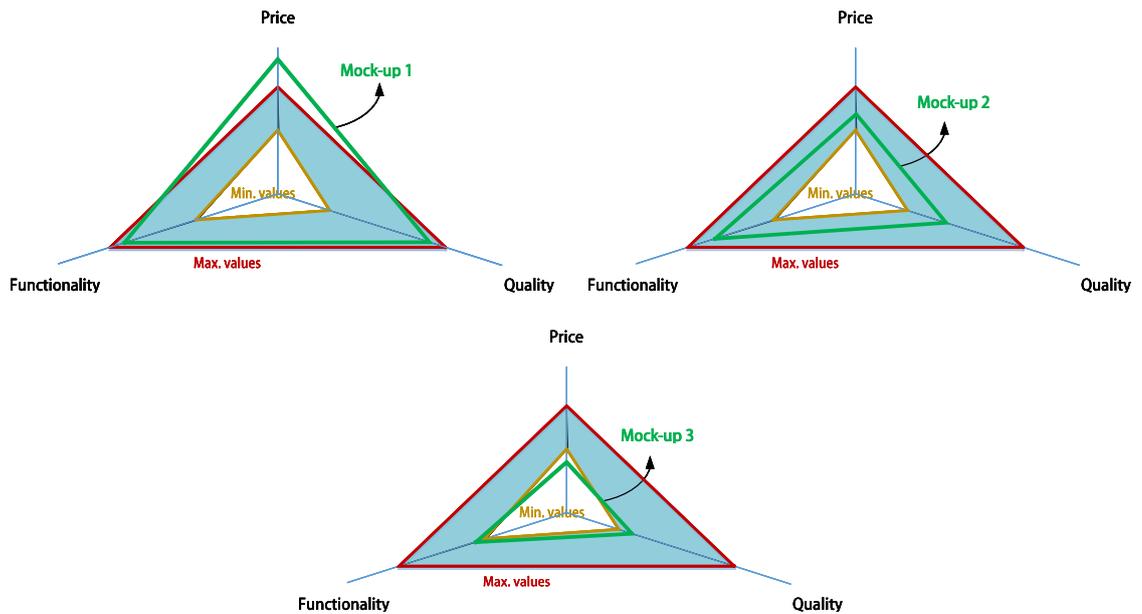
This will help managers to repetitively and frequently be in contact with the main NPD project stakeholders to make sure the development project is going to the right direction with the functionality of the product and its quality. However, another survival factor of products is still vague and that is where this chapter alongside the third chapter draw a framework and an approach to tackle this problem.

Third chapter introduced costing methods which help managers to translate all activities within a company to more comprehensive numbers and costs. Different methods were explained to give some insight over cost allocation problem. Then, process modeling methods were briefly illustrated. The chapter was concluded by showing how implementing mock-up concept to the whole production line can help decision makers to estimate the cost of production of a new product which is being developed (Figure 40).



**Figure 40.** Final product cost estimation for several product ideas.

In this chapter, the LM concept was introduced. Then, the importance of customer and supplier integration in NPD projects was explained. Next, the importance of information sharing, specially cost data, was demonstrated. Finally, OBA concept was introduced as a framework to smoothen the integration from accounting and cost information sharing aspect. By sharing the cost estimations, calculated from mock-ups and mock-up production line/cells, with customers a company can reduce customers price discontent. Figure 41 shows an instance of three different products with the same purpose but with different quality and price.



**Figure 41.** Comparison between three different products.

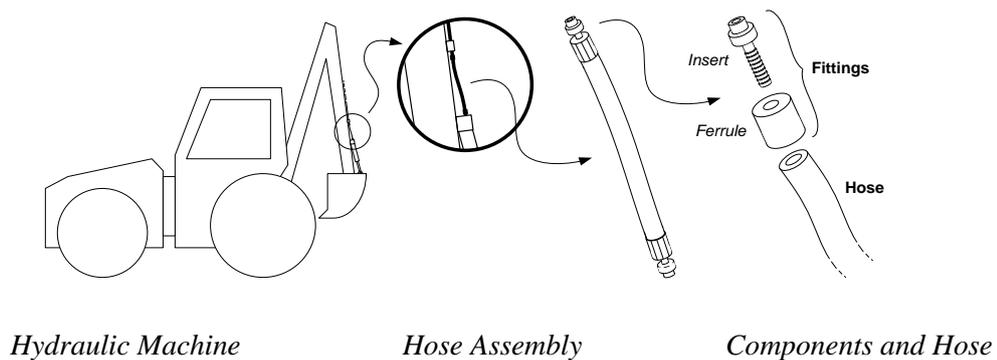
This graph is provided before the products are fully developed. This framework helps companies to integrate their customers in the NPD projects more efficiently. Customer can see the functionality of the product, have an actual feeling about it, and more also has an estimation of the final product price. So, the customers can cooperate with the company and together they develop the best available product idea. On the other hand, it gives valuable information for the company to compare its suppliers as well.

The next chapters show how these frameworks were implemented in a case company. It discusses how the company supply network looks like and how LM concept is implemented there and how agile stage-gate model, mock-up production cell, and open-book accounting were successfully implemented in an NPD project.

## 5. THE CASE COMPANY AND ITS CHALLENGES

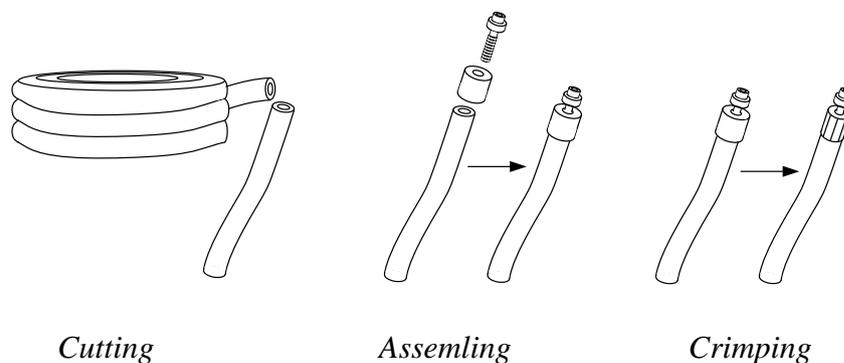
### 5.1. Introduction to the Case Company

The case company is the main hose assembly supplier of the best-known mining machines maker in Finland. The main factors of a good hose assembly supplier are production and delivery speed, flexibility and quality. There have been many innovations in the case company which has made the company the fastest hose assembly supplier in the world. On the other hand, the company managers have had plans to improve the quality at the same time. From the beginning, since the company was established, scientific management has been one of their core methods in business development. The case company business is providing about half a million hose assemblies a year to heavy machine makers. A hose assembly consists of a hydraulic hose, ferrule, and insert (Figure 42).



**Figure 42.** *The Application and Components of a Hose Assembly.*

As it can be seen in Figure 42, insert and the ferrule are generally steel parts that enable the hose to be attached to the machine. An ordinary hose assembly is consisting of three components, which are hose, ferrule and insert. Hose assembly process starts with cutting measuring and cutting, then assembly and finally crimping (Figure 43).



**Figure 43.** *Hose assembly process.*

Hydraulic hoses are used in hydraulic systems to transfer pressure from one component to another. Hydraulics is a technology which applies fluid mechanics in practice to control and transmit power by the use of pressurized liquid. This pressure in heavy machines' hydraulic systems is much higher than the water pressure in gardening hoses. Thus, they are designed to easily undergo high pressures. Thus, depending on the circumstances a hose is used engineers have designed different types of hydraulic hoses with different material, number of layers, and sizes. A few examples of different hydraulic hoses are shown in Figure 44. Hydraulic hoses diameters are usually presented in inches.



**Figure 44.** Few samples of different hydraulic hoses.

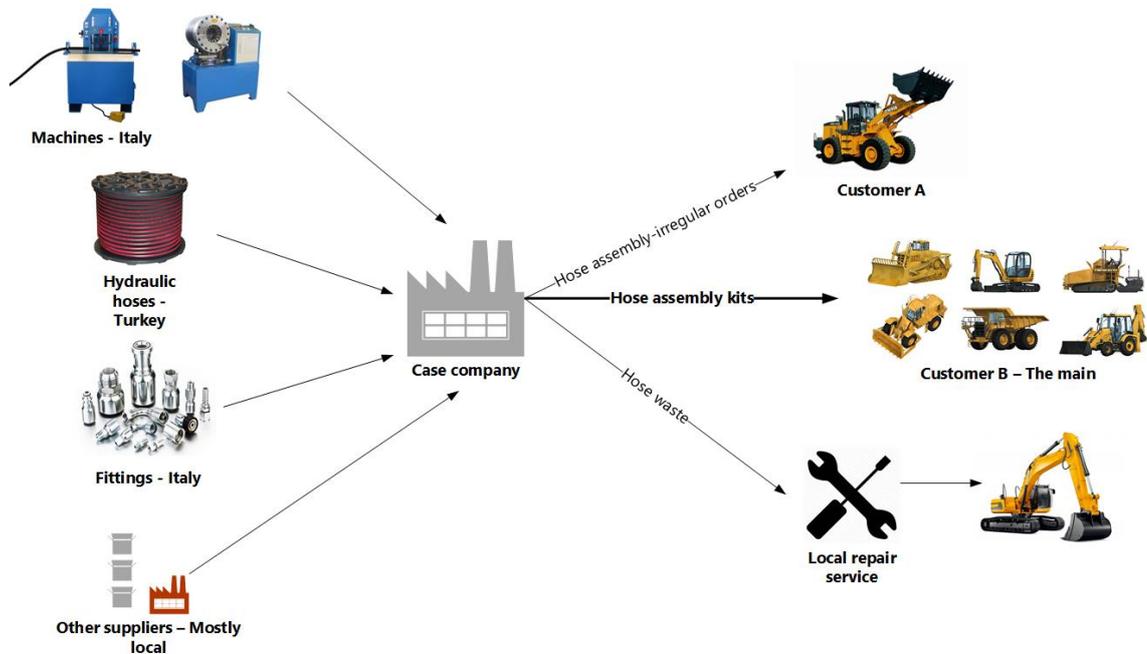
Since the hydraulic hoses are created to be applied under harsh conditions such as high pressure, high temperature, and also getting hit with rocks during the work, cutting them cannot be done with simple tools. There are different types of hydraulic hose assembly cutters introduced: wet cut and dry cut. Dry cut machines cut the hose with a circular saw. Wet cut machines also contain a circular saw blade which is being cooled with a mixture of water and industrial oils (Figure 45).



**Figure 45.** Different hydraulic hose cutting machine.

The fittings are also in different shapes depending on where and how they are going to attach. The main players in the industry have standardized the fittings to reduce human errors and reduce the production and service time. Since, fittings are also under high pressures first of all they are made of high performance material under pressure and second, special machines are designed to crimp the fittings tightly to the hydraulic hose.

The company does not have a complex supply network. Mostly the machinery and fittings are imported and serviced by few Italian suppliers. The hydraulic hose rolls are imported from Turkey. The hoses are usually rolled on a plastic spool. These spools are usually returned to the supplier for the next orders. The smaller hose pieces remaining from cutting also are sold to small manual hose assembly workshops in Middle-East.



**Figure 46.** The case company supply network.

The company was established in 2012 and many outsiders did not predict a successful future for this business. One of the board members says:

*“Many business consultants told us to forget about hydraulic hose assembly business. They said it’s madness.*

However, implementing scientific management and LM concepts boosted their business and the company surprised the pessimists. He continues:

*“We believed we can do it differently. We aimed to be the fastest and best hydraulic hose assembly manufacturer and we succeeded. In a year, our small workshop had become the fastest hose assembly manufacturer on the planet”*

The decision makers are not satisfied yet and are constantly working on cost reduction as they are improving the quality. He adds:

*“We cannot stop. We have to constantly improve and invest in innovative ideas. That is the source of our competitive advantages”*

The company has shown a reliable performance and its financial status approves it. Table 7 summarizes the case company's performance since 2012 till the end of 2015.

*Table 7. Financial summary of the case company (Finder.fi)*

	2012/12	2013/12	2014/12	2015/12
<b>Net sales (EUR thousand)</b>	1747	5288	4825	5462
<b>change in net sales</b>		101.8%	-8.8%	13.2%
<b>Profit for the year (EUR thousand)</b>	-128	193	118	243
<b>Gains</b>	-7.3%	4.7%	3.7%	6%
<b>Personnel</b>	9	7	13	-

The company manufactures different sizes of hose assemblies from 1 inch (1") to 0.25 inches ( $\frac{1}{4}$  "). The most produced size is the 3/8" which is almost half of the whole production. Also, the case company assembles hoses with different types of fittings and connectors based on the orders it receives.



*Figure 47. Different types of fittings and connectors used in the case company.*

The other important fact about the case company is that the owners and investors who established the company in 2012, had spent most of their career life in this industry and had good relationships with their main customers. This, helped them to establish the professional relationship rather smoothly. On the other hand, their main customer is a well-known international mining machine maker which has implemented LM in their organization as well. Thus, they also value strong relationship and constructive cooperation.

## 5.2. Challenges

As mentioned above, the case company started its job and aimed for supplying a well-known and successful mining machines manufacturer. Therefore, the case company had to redesign the old structures, that the shareholders had learnt before, to reach to the level that they could compete with the existing hose assembly suppliers. The case company decreased the production costs by automating, redesigning production shop floor, and standardizing processes. In this way, the company was able to run with less workers, less inventory costs, and less production time.

On the other hand, these methods helped them to improve the quality at the same time. Quality is crucial for the customers since hydraulic systems contain expensive components and any problem caused by any component might end up quite expensive. For instance, one of the common problems is damages to the pumps due to small particles in the oil circulating in the hydraulic system. Thus, each component supplier has to provide the hydraulic system manufacturers with as clean products as possible.

Gates (2002) states that more than 70% of hydraulic systems failure is due to contamination. Bosch Rexroth (2011) also estimates that 75% of hydraulic system failures are caused by tiny particles in the hydraulic system oil. It also claims that monitoring hardware only detects about 20% of all unexpected downtimes. Ultra Clean (2014) in its website also states that 80% of hydraulic failures come from contaminated oil. Hence, contaminated oil not only causes direct costs due to damages on the equipment, but also adds costs due to the delays and low system performance. They also emphasize that small metal particles cause the most damage in the pumps and other components.

The International Organization for Standardization (ISO) has given codes for different contamination levels in hydraulic power systems. According to ISO (1999), ISO is an international federation of national standards bodies which are called ISO member bodies. ISO technical committees carry out the work of preparing international standards. Each ISO member body which is interested in a subject relevant to a technical committee has the right to be represented on that committee. Each draft of International Standards introduced by the committees is circulated among member bodies for voting. For an international standard to be published it requires at least 75% approval of the member bodies which vote.

There is an International Standard published for hydraulic fluids for coding the level of contamination by solid particles which is labeled as ISO 4406. ISO 4406 was prepared by technical committee ISO/TC 131 or fluid power systems and in a subcommittee SC 6 or contamination control and hydraulic fluids. It is also mentioned in this document that the motive to prepare this standard was that solid particle contaminants may cause serious problems.

ISO (1999) explains that ISO 4406 offers a table with which contamination level can be labeled (Figure 48). ISO contamination levels are reported as three numbers. These three numbers indicate the number of particles in a specific range of size. For example, the ISO Code 24/22/19 is translated as follow:

1. 24: In 1 cc (1 ml) of fluid, the number of particles with the size 4  $\mu\text{m}$  and larger is maximum about 160000 and minimum 80000 solid particles. In mathematic language:  $\lfloor \frac{2^{23}}{100} \rfloor \leq \text{number of } 4 \mu\text{m and larger particles} \leq \lfloor \frac{2^{24}}{100} \rfloor$

2. **22**: In 1 cc (1 ml) of fluid, the number of particles with the size 6 μm and larger is maximum about 40000 and minimum 20000 solid particles. In mathematic language:  $\lfloor \frac{2^{21}}{100} \rfloor \leq \text{number of } 4 \mu\text{m and larger particles} \leq \lfloor \frac{2^{22}}{100} \rfloor$
3. **19**: In 1 cc (1 ml) of fluid, the number of particles with the size 14 μm and larger is maximum about 2500 and minimum 5000 solid particles. In mathematic language:  $\lfloor \frac{2^{13}}{100} \rfloor \leq \text{number of } 4 \mu\text{m and larger particles} \leq \lfloor \frac{2^{14}}{100} \rfloor$

ISO 4406:1999 Code Chart			ISO 4406:1999 Code Chart			
Range Code	Particles per Milliliter		Particle Size	Particles per Milliliter	ISO 4406 Code Range	ISO Code
	More Than	Up To/Including				
24	80000	160000	4μm <sub>[c]</sub>	151773	80000~160000	24
23	40000	80000	4.6μm <sub>[c]</sub>	87210		
22	20000	40000	6μm <sub>[c]</sub>	38363	20000~40000	22
21	10000	20000	10μm <sub>[c]</sub>	8229		
20	5000	10000	14μm <sub>[c]</sub>	3339	2500~5000	19
19	2500	5000	21μm <sub>[c]</sub>	1048		
18	1300	2500	38μm <sub>[c]</sub>	112		
17	640	1300	68μm <sub>[c]</sub>	2		
16	320	640				
15	160	320				
14	80	160				
13	40	80				
12	20	40				
11	10	20				
10	5	10				
9	2.5	5				
8	1.3	2.5				
7	0.64	1.3				
6	0.32	0.64				

Particle Size	Particles per Milliliter	ISO 4406 Code Range	ISO Code
4μm <sub>[c]</sub>	492	320~ 640	16
4.6μm <sub>[c]</sub>	348		
6μm <sub>[c]</sub>	149	80~160	14
10μm <sub>[c]</sub>	41		
14μm <sub>[c]</sub>	15	10~20	11
21μm <sub>[c]</sub>	5		
38μm <sub>[c]</sub>	1		
68μm <sub>[c]</sub>	0.0		

Figure 48. ISO 4406 reading guide.

Another example for ISO Code 16/14/11 and its meaning is also provided in Figure 48. The difference between these two samples under a microscope is shown in Figure 49. As it can be seen in photo 1 the higher ISO grades indicates more solid particles in 1 cc of hydraulic fluid.

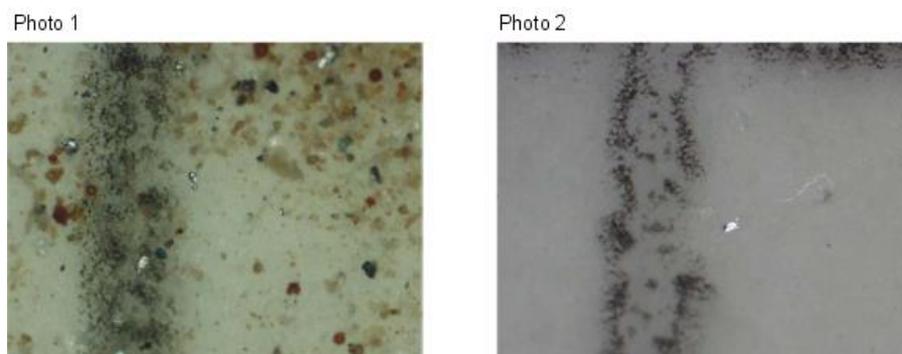


Figure 49. ISO 24/22/19 VS 16/14/11

Contamination reduction is so important that a company in its commercial shows how much they have reduced in the number of particles circulating in their machine in a year (Figure 50). In the picture, the left glass container represents the amount of dirt circulated in one year when the fluid contamination level reached to 16/13 and the right container shows how it was before the improvements and ISO 21/18.



**Figure 50.** How much less dirt circulating in a hydraulic system after improvements.

Contamination in hydraulic systems could have different origins; it could be from any of the parts and components or the fluid itself. Hydraulic hoses also transform contaminations to the oil as well. So, reducing the particles and generally increasing hose assembly quality level is a serious challenge for the case company to satisfy its important customers.

## 6. WASHING MACHINE

### 6.1. The Problem Statement

As mentioned in the previous chapter, one of the key issues in quality is the cleanliness level of hoses which is crucial because of high-sensitivity of hydraulic systems to contaminations; and the hose assemblies could be also a source of contamination in a hydraulic system. When quality improvement team started to work on the case they listed all possible contamination sources in hose assemblies as follow:

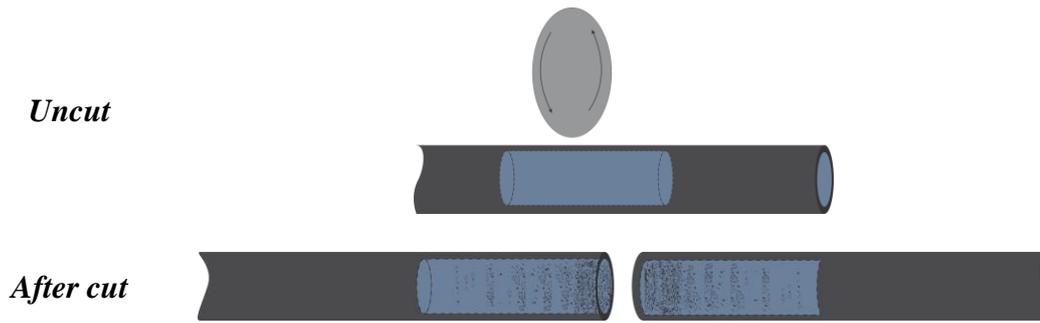
- Innate contamination when the hose is manufactured in Turkey
- Dust and particles in air which get inside the hose or hose assemblies during the transportations
- Contamination generated when cutting the hose
- Contamination generated when crimping the fittings

The hydraulic hose supplier stated that:

*“The only source of contamination during the production of the hydraulic hoses could be a thin layer of plastic remaining from the mandrel on which the hoses are made. However, we clean inside of the hoses before shipping them to you and there must not be a considerable number of particles left inside.”*

The company also receives the hydraulic hoses neatly wrapped and protected from dust. On the other hand, when shipping the hose assemblies to the customers the ends of each hose assembly is closed with plastic caps. Thus, the team focused on the other two sources of contamination, specially the cutting.

When cutting hoses, there are rubber and metal particles left inside the hose which are harmful to hydraulic systems, especially the latter. There are two cutting methods in hose assembly industry used, dry-cut and wet-cut. In a dry-cut machine there is a rotating blade which cuts hoses. The idea is the same in wet-cut machines as well, but the blade is cooled down instantly by a mixture of water and industrial oil. Figure 51 shows how the development team analyzed the contamination made when cutting a hose assembly. The small particles are a mixture of rubber and metal from the wires inside the hose body.



**Figure 51.** Cutting a hose.

Cleaning the edges of cut hose with a clean towel left visible and bit mark on the towel. This simple test shows that cutting leaves a serious amount of dirt inside the hoses, specially near the edges of the cut (Figure 51). Therefore, the cleanliness development team focused on this problem. The next sections discuss how the development project moved on.

## 6.2. Problem Solving Process

The project kicked off in September 2012. The first thing team did was to find out the current cleaning methods available. There are different methods used to clean hoses such as blowing high pressure air inside hoses, pumping high pressure detergent throughout hose assemblies, and shooting foam bullets through the hose (Figure 52). Micro Jet basically offers blowing high pressure air through the cut hose. It is noteworthy that the managers had tried washing hoses with high pressure detergent before and did not want to implement it again due to safety issues with the moisture and vaporized detergent in the air. However, the case company purchased sponge shooting guns in order to establish the hydraulic hose cleanliness lab.



**Micro Jet**

**Speed Clean**  
Detergent solution and 60 bar  
16/13

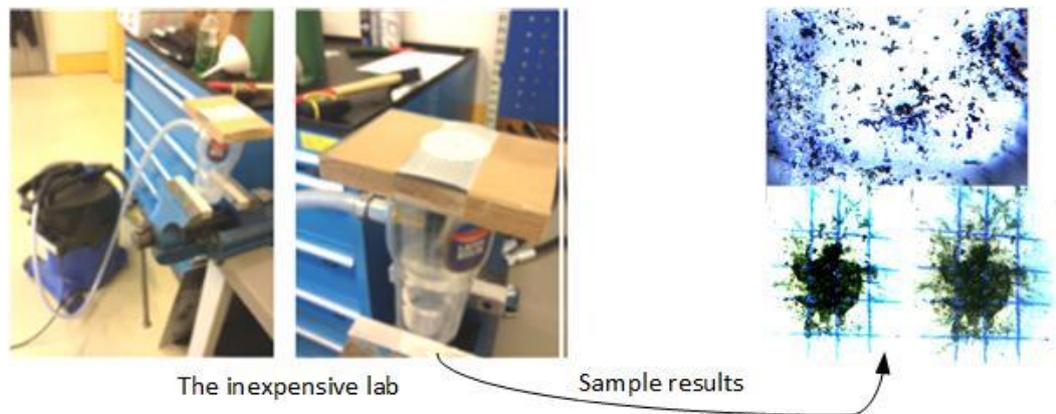
**Ultraclean and Goodway**  
Claimed ISO4406: 13/10

**Figure 52.** Different cleaning methods available in the market.

Before the development team went further with trying different methods and bringing up new ones, they wanted to test different ideas as fast and inexpensive as possible. Thus, a

lab was needed to compare different methods that were going to be tested. However, installation of precise particle analysis lab is expensive. The estimations showed that the cost of installation of a professional particle analysis lab is more than 50,000 Euros. Therefore, an inexpensive lab with cheap materials available was built. Not to precisely count the particles but to compare different ideas and find the right development direction.

Before suggesting new methods or comparing existing ones, there must be a scale to measure efficiency of methods. In this case, using professional lab was not possible because on the one hand installing a professional lab was too expensive for the company and on the other hand, sending sample to the existing labs took few months each time due to the procedure and the fact that the labs were fully booked most of the times. Thus, the case company engineers built their own simple testing lab to compare the efficiency of different existing methods and also to test new possible methods. As shown in Figure 53 the testing lab is made up of a glass, a piece of wood and membrane. Test steps are (1) injection of detergent to the hose, (2) shaking the hose to make sure particles are washed into the detergent, (3) evacuating the detergent from the hose on the membrane while the vacuum intake the liquid to the glass and particles are left on the membrane and finally (4) taking microscopic pictures with available camera loops and analyzing black to white ratio.



**Figure 53.** Simple testing lab.

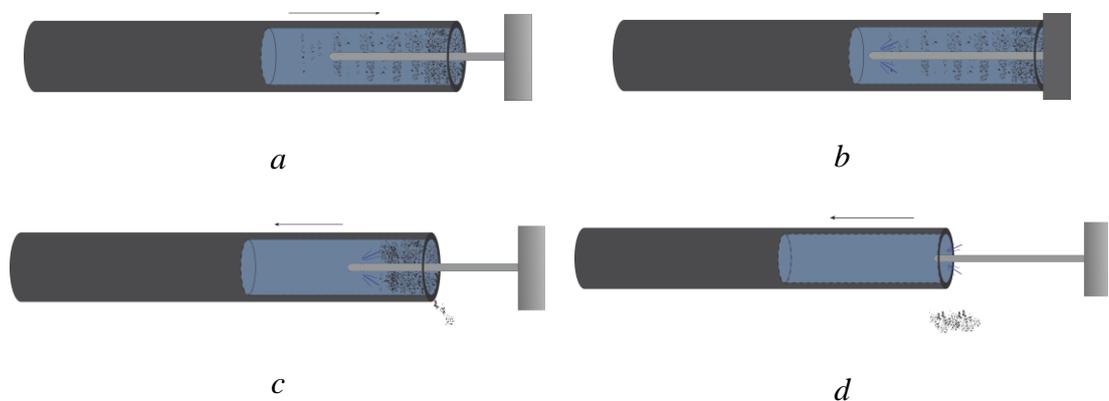
The team was eager to come up with new ideas since the existing methods had serious drawbacks. For instance, when using these methods, hoses are cleaned from one end to another which raises the possibility of spreading contamination all along the hose. On the other hand, companies are not satisfied with air blowing method and Ultra Clean method is expensive and time consuming. One of the managers says:

*“Shooting sponges is time consuming and also it is expensive since only the sponge bullets cost us \$100,000 a year”*

The early tests on wet-cut and dry-cut methods showed that using wet-cut machines reduces the cutting contamination significantly. Nevertheless, wet-cut method causes some moisture inside hoses too, which is not preferable either. The membranes picture in Figure

53 show the results from the inexpensive lab. Of course, this does not indicate precisely the ISO 4406 grades of each method. Yet, it definitely shows to which direction the development should head.

Thus, the case company's engineers came up with the idea of cleaning ends of hoses (Figure 54). The core of this idea is to wash just the hose ends instead of washing the whole hose from one end to another since the contamination is caused in the cutting step and contaminations are spread near the edges. The method itself was not new and an application had been seen in practice in another well-known factory in Japan, but the commercial machine is not available and on the other hand there were doubts if it was an acceptable method or not. This approach, however, was the starting point of a new plant cleanliness to develop even further.



**Figure 54.** Washing out cut edges.

Instead of clicking a development project and investing a fortune to design a whole new machine based on the washing nozzle idea, the decision was made to test the idea performance itself very quickly. As it can be seen in Figure 55, the mock-up is made up of inexpensive components a nozzle attached to a piece of plywood, a container and a pump.



**Figure 55.** The first mock-up of the washing inside edges idea.

Afterward tests were running in the factory's simple lab and the results showed that the washing idea improved the quality (Figure 56). Figure 56-left shows the result for the hose which was cut with dry-cut method and without using any cleaning method, Figure 56-middle shows the lab membrane for wet cut hose without any cleaning method, and

the far right in the figure indicates the wet cut hose washed with the mock-up washing machine.



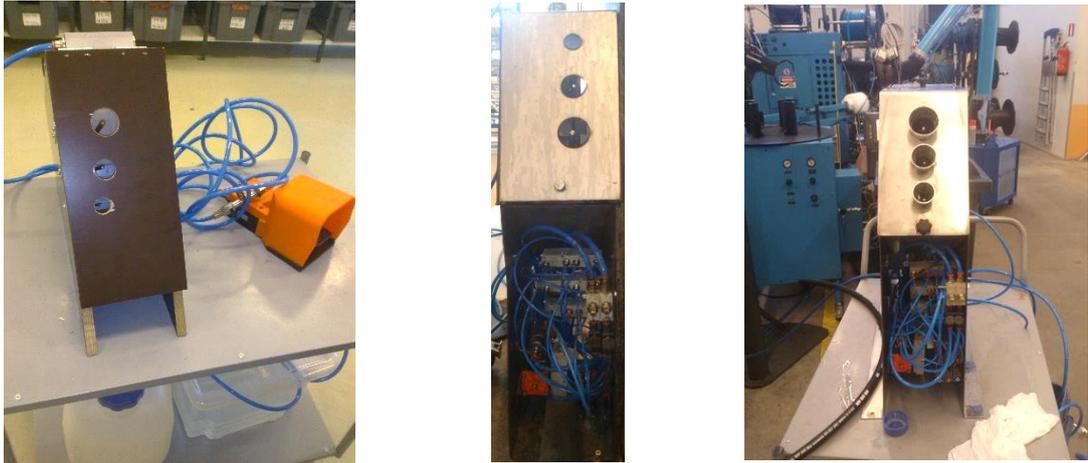
**Figure 56.** *Different results from the inexpensive lab.*

The first mock-up was rapidly replaced with another inexpensive mock-up. The second mock-up was equipped with three nozzles for different hose sizes. Of course, the ideal washing machine would be automated, however for simplicity the engineers decided to build the washing machine with a pneumatic pedal to pumps water and air mixture to the nozzles (Figure 57). The table of costs of the mock-up washing machine and the mock-up lab can be found in Appendix A.



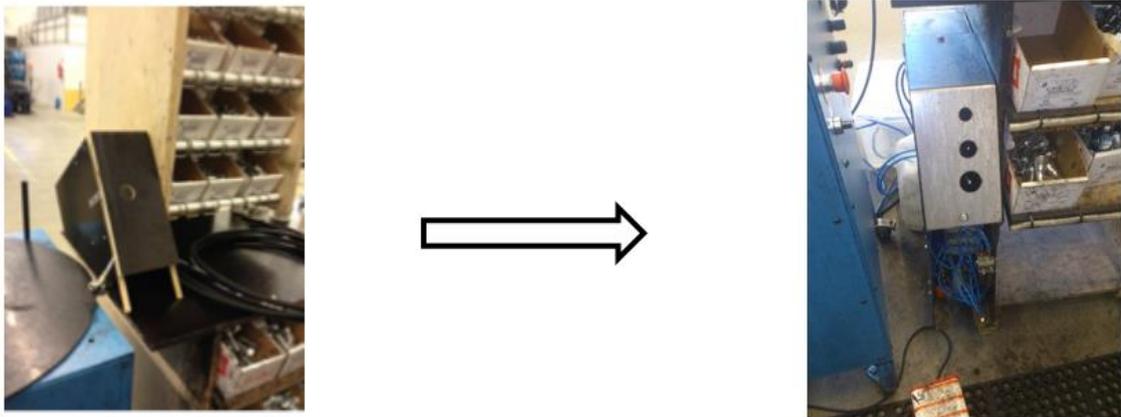
**Figure 57.** *Plywood mock-up washing machine with pedal actuator*

Although the idea worked, there were uncertainties about its functionality in assembly manufacturing line. Therefore, a working mock-up (Figure 58-left) was put in a manufacturing cell to be tested in practice. The first mock-up was made up of plywood, a trash can, 3 nozzles, valves and a pedal which are all inexpensive. Since timing is crucial in manufacturing the next prototypes were designed to be automated and more user friendly (Figure 58-middle and Figure 58-right).



**Figure 58.** *The three mock-ups used before prototyping proceed further*

To make sure about all functionality aspects such as timing and efficiency in assembly line, all the mock-ups have been tested in a working cell (Figure 59), in other words there has been implemented a mock-up cell in the factory for quick tests of new ideas.



**Figure 59.** *Mock-ups installed in the mock-up cell*

Now the development team had different methods in its hands, and it was time to continuously try different cutting and cleaning methods to draw a better picture of the effectiveness of different methods. The development team tested many different combinations of cutting and cleaning methods. Then tested the results with their fully functional lab and documented the results. A sample could be found in Appendix B.

In this section the main steps in development process of an idea from very raw ideation to a fully functional mock-up has been illustrated. First it has been explained how a need led engineers to a new idea, then how they made their inexpensive lab to evaluate their new ideas, then how mock-ups have been used within the process to test and get feedback from users and customers about its functionality before investing on detail designing.

### 6.3. Results

During the work with different cleaning methods, the cleanliness lab understood better the probable sources of contamination and variables in cleaning methods which might affect the efficiency. Moreover, some of the test results looked very similar on the membranes. Whenever, there were enough different methods which had close results in the mock-up lab, the engineers prepared carefully samples and shipped them to a professional fluid lab for precise particle counting. Table 8 summarizes the results. It is noteworthy that the customer goal was to receive components with ISO 4406: xx/xx/xx.

*Table 8. Fluidlab results for the first samples (May-July 2013)*

	<b>Sample explanations</b>	<b>Results in ISO 4406</b>
<b>1</b>	Wet cut (original coolant liquid)	-/xx/xx
<b>2</b>	Wet cut (the case company coolant liquid)	-/xx/xx
<b>3</b>	Wet cut + washing machine	-/xx/xx
<b>4</b>	Wet cut + washing machine	-/xx/xx
<b>5</b>	Wet cut + 2 sponges from both ends	-/xx/xx
<b>6</b>	Wet cut + 2 sponges from both ends	-/xx/xx
<b>7</b>	Dry cut + air blow	-/xx/xx
<b>8</b>	Dry cut	-
<b>9</b>	Dry cut + 2 sponges from both ends	-/xx/xx

As it can be seen from the table shooting plugs was the most effective method to clean hoses. However, it did not show a reliable cleanliness level when used after wet-cut. The results also show that the homemade washing machine does not have much effect on the cleanliness level. As it can be seen none of above mentioned methods meet the customer's requirement. Therefore, team started to investigate more on each case closely with the main customer frequent feedbacks.

Also, washing developments in the washing machine showed promising results in the mock-up lab. Therefore, the engineers kept developing new prototypes of the washing machine. Figure 60 shows the latest version washing machine including two tanks for clean water and drain. In this version, the pneumatic system is separated from the nozzle and there is an easy access to it. So, in case of any break down, technicians have easier access to the valves and actuators.



*Figure 60. The design of latest version of the washing machine*

There were following changes made before the second batch of samples were sent to the lab. Each of these discoveries has a learning curve and story behind them, however it would exceed the limitations of this thesis to explain every detail thoroughly.

- Tilting wet cutter does not affect much on contamination level, but lifting end of hoses reduces contamination level.
- The customer is not satisfied with the greasy liquid remained in the hose assemblies. Hence, the right coolant was selected. Also, a systematic study was carried out on different coolants, their stickiness over time, water-coolant ratio, and the impact of water evaporation in coolant tanks.
- The water remaining in the hoses is also harmful to hydraulic systems:
  - The water/air mixture in cleaning machine reduction to the point that the nozzles spray mist-like gas reduces the effectiveness of washing machine significantly.
  - air blow role became bolder. It takes at least 3 seconds of high pressure air blow to dry wet cut hose.
  - It makes lifting the end of hose while it is getting cut even more important to prevent liquid from flowing deep inside the hose.
- Some of the dirt remains on the very edges of cut hose, hence testes showed that brushing the edges reduces the contamination, however, brushing inside the hose is not reliable yet due to in efficiency of cleaning the brush itself after every use.
- The length of nozzle plays an important role in effectiveness of the washing machine.
- If a nozzle has two rows of holes to spray it cleans more effectively.

- Crimping may leave some metal particles inside. Cleaning after crimping is important as well.
- Sponges get dirty easily in open spaces of the shop floor. Thus, fresh and new sponges were used for the second samples.
- Hot water slightly increases the effectiveness of the washing machine.

Table 9 shows the summary of the results of the second batch sent to the professional lab.

*Table 9. Fluidlab results for the second samples (Jan 2014)*

	<b>Sample explanations</b>	<b>Results in ISO 4406</b>
<b>1</b>	Wet cut + 2 sponges from both ends	-/xx/xx
<b>2</b>	Wet cut + 2 sponges from both ends	-/xx/xx
<b>3</b>	Wet cut + Washing machine + Air blow	-/xx/xx
<b>4</b>	Wet cut + Washing machine + Air blow	-/xx/xx
<b>5</b>	Wet cut + Brush + Washing machine	-/xx/xx
<b>6</b>	Wet cut + Brush + Washing machine	-/xx/xx
<b>7</b>	Wet cut + Brush + Washing machine + Air blow	-/xx/xx
<b>8</b>	Wet cut + Brush + Washing machine + Air blow	-/xx/xx
<b>9</b>	Wet cut + Air blow	-/xx/xx
<b>10</b>	Wet cut + Air blow	-/xx/xx

Comparing the tests results shows that the case company could improve the cleanliness level in general with a combination of different methods. Now, the case company can meet their customer requirements with sponge shooting. Also, adding air blow to the homemade washing machine has improved the cleanliness level. Comparing 3 and 4 with 9 and 10 results, empowers the hypothesis that air-blow has a significant impact on cleanliness level. Moreover, it can be claimed from 7 and 8 that brushing the edges results in more reliable cleanliness level. To sum up, the factors which improve the cleanliness level are:

- Using clean sponges
- Lifting end of hoses while they are getting cut with wet cut machine to prevent coolant liquid from flowing inside the hoses.
- Longer nozzles and with two rounds of holes are more effective.
- The water-air ratio in the washing machine was adjusted to get the highest pressure and at the same time not to push water inside hoses. At the moment, this ratio should be adjusted manually.

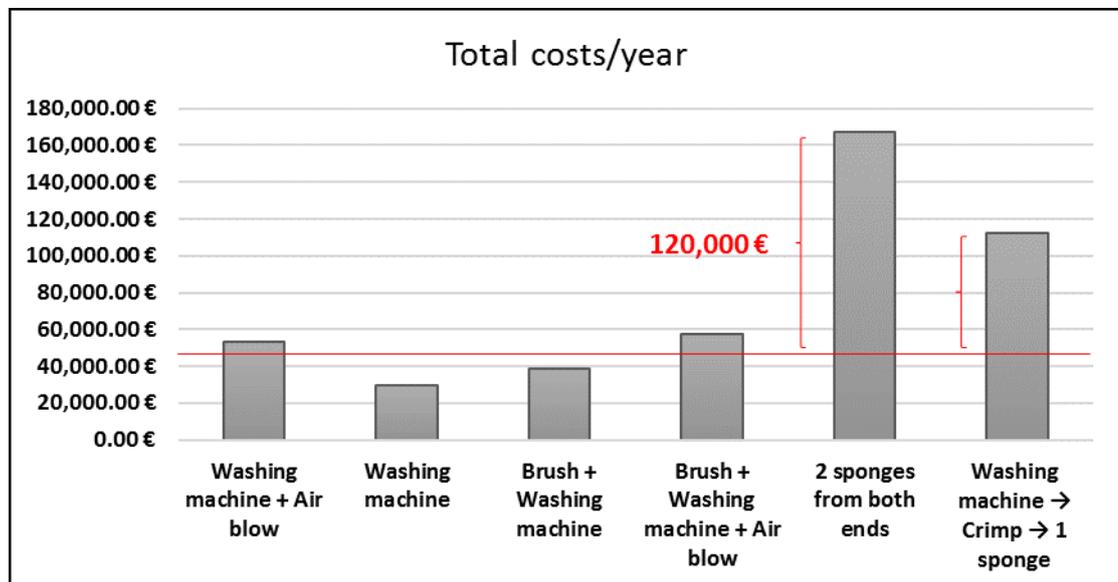
The development team has gained valuable knowledge without investing substantially on developing one specific idea to perfection. Having actual material in hand from the mock-up lab results also has made cooperating with other players in supply network easier. The

case company also carried out time studies for different methods to more accurately calculate cost of production with implementing each method in the production cells. The engineers measured time spent to complete each cleaning method with two different tools, stop watch and shooting videos. The results were the same, however, the videos turned into a strong documentation mean and also an effective communication tool with different project stakeholders. Table 10 shows one of the time studies done in the case company.

**Table 10.** Time study results for different methods. Times are reported in Sec

	Cleaning method	T1	T2	T3	T4	T5	Avg.
1	Washing machine + Air blow	16.7	15	15.5	15.5	13.7	15.3
2	Washing machine	8	8.9	8.6	8.2	8.6	8.5
3	Brush + Washing machine	11	12.5	10.5	10.6	11.2	11.2
4	Brush + Washing machine + Air blow	18	15	16.2	17.1	16.7	16.6
5	2 sponges from both ends	13	13.5	14.4	13.7	13.3	13.6
6	Washing machine → Crimp → 1 sponge	13	15	15.9	15.7	15.9	15.1

The average cost of an operator in Finland is 25€ per hour. Therefore, given the time study results total cost of implementing each method can be calculated. The detailed calculations are shown in Appendix C. The results suggest that the labor costs of each method are not considerably different from one another. The major cost object among different methods are sponges which cost 0.12€/sponge.

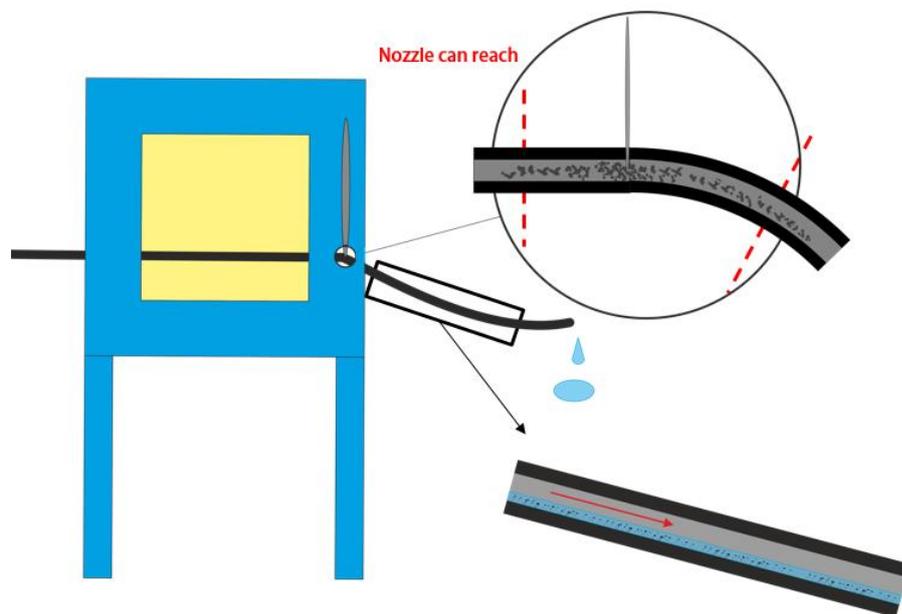


**Figure 61.** Total costs of implementing each method per year

Because of close relationships and trust between the case company and its main customer all the relevant information and results, from quality to costs, were shared. Thus, the company and its strategic ally customer have different options in their hands. They can meet the cleanliness goal of ISO 4406: 20/15/12 with one method which is shooting sponges.

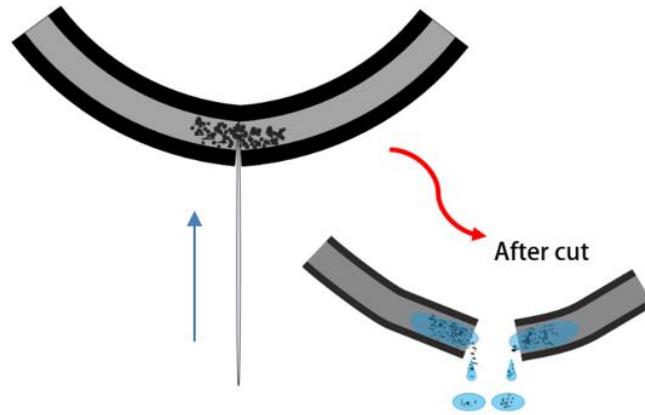
However, it increases the case company costs significantly. On the other hand, other cleaning methods can be improved and developed further with considerable research and development costs. Hence, the customer knows exactly the situation of the case company and accordingly it has several options ahead; to pay for the extra costs of sponges, to participate more actively in the development of washing machine concept, or accept one of the lower quality lower cost methods and focus on other component suppliers.

Moreover, there were findings during the development project about current machinery which the company could not change a lot since the machines were purchased and not built by the company itself. For instance, wet cut machine cuts the hydraulic hoses from up to down while the hose end faces downwards (Figure 62). This causes that the coolant liquid with the contamination from the cut flows inside the hose. This contaminates too deep inside the hose to be washed by the washing machine nozzle.



**Figure 62.** *Wet cut machine problem*

One fast solution for this problem is to lift the end of the hose when it is cut. However, this cannot be a long-term solution since lifting the end of the hose increases the friction between the blade and hose and consequently reduces the blade lifespan. It is also not comfortable for the operator and kills his valuable time he could spend on another value adding activity. The development team came up with an idea to improve the cutting machine. The idea is to cut the hose upwards as it is shown in Figure 63.



*Figure 63. Upward cutting concept*

The company could not develop this idea alone and inexpensively. Thus, it has to be discussed with the cutting machine manufacturer. This method might reduce the contamination for two reasons: first that the coolant might not flow inside the hose, and second that the contaminated coolant liquid flushes out right after the cut before some of the contamination stick to the inside walls of the hose.

## 7. DISCUSSION

### 7.1. Overview of the Problem and the Framework

“Innovators are the winners” is the common belief in nowadays business literature and it is no longer a question of why to innovate since the importance of competitive advantages of innovative companies is well-known and many success stories of innovative companies are wide-spread, but the question of how to be innovative is being investigated more and more (Grönlund et al. 2010). Therefore, it has been decades that researchers design and test various models to systematically proceed with PDPs so they increase the success chance. NPD models are not designed to only increase the success rate of the projects, but also to decrease the costs. Belay (2009) explains that the costs of product development projects increase exponentially with time. Thus, it is important to evaluate new product ideas as soon and cheap as possible, before investing a fortune in the NPD.

Different NPD models have introduced and evolved in the past few decades. There are two groups of these models that are widely implemented: stage wise models and agile models. Stage wise models divide the development project in stages and proceed according to the stages and after each stage there are check points to evaluate the outcome so far and decide if the project is qualified to proceed further it has to be shut down. On the other hand, agile models do not offer rigid stages for the development. Under the agile development models solutions and ideas evolve through iterative development and collaborative cross-functional teams. The agile models are usually applied for software development since developing software is much more flexible and does not include material costs. That is why Cooper (2015) states agile methods cannot be implemented for new physical products development.

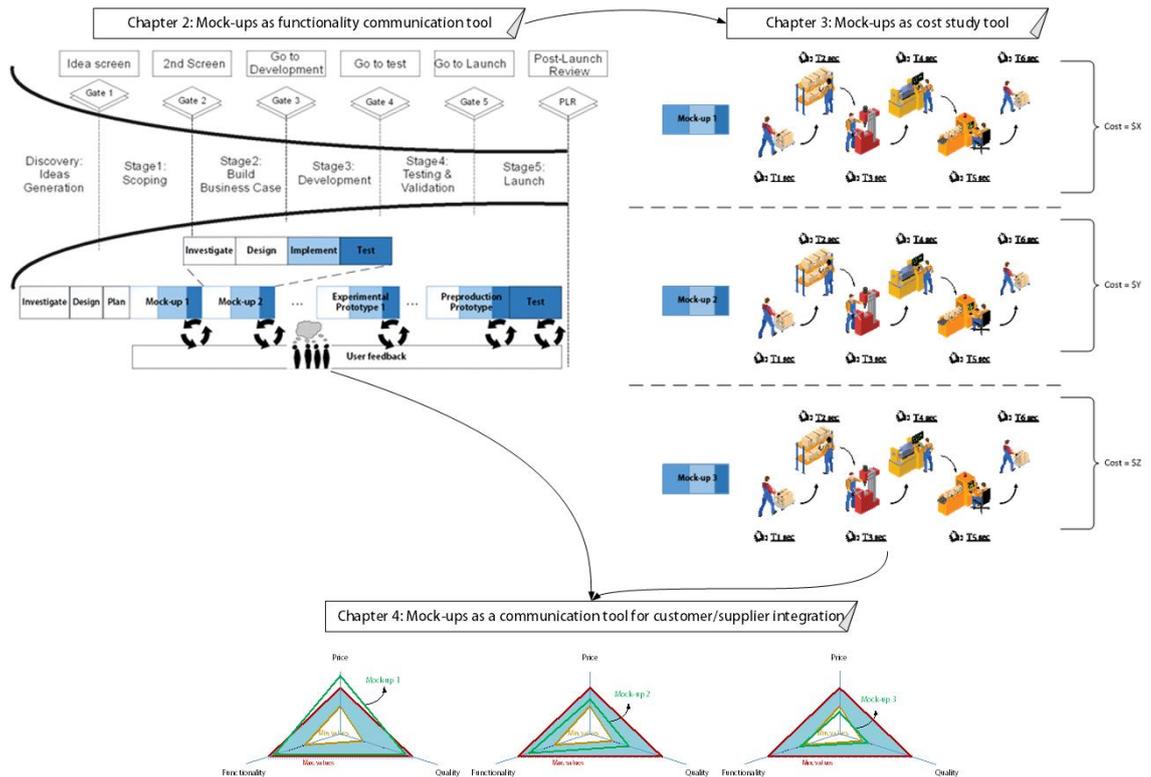
Different types of prototypes are used during NPD projects. Prototypes are categorized from different aspects. Yang and El-Haik (2009) have categorized prototypes to physical and analytical prototypes and physical prototypes into experimental, alpha, beta, and pre-production prototypes. Moreover, Rudd et al. (1996) have categorized prototypes into low and high-fidelity prototypes. Experimental prototypes are low fidelity and the further the development goes to preproduction prototypes, they have more characteristics of high fidelity prototypes. Pour (2015) believes that there is huge gap between experimental prototypes and alpha prototypes; thus, he suggests to fill the gap with fully functional mock-ups. This thesis provides arguments to support this concept and shows functional mock-ups are have a mixture of characteristics of low and high-fidelity prototypes at the same time; most importantly, they are functional and at the same time inexpensive.

Thus, fully-functional mock-ups are tools to test new ideas as fast and cheap as possible. This means, unlike many researchers, this thesis supports the idea of implementing agile

development models for physical products as well. Of course, still physical products dictate various limitations on the development and prototyping, however, in many cases inexpensive fully functional mock-ups can be built to test and compare different ideas.

New products are developed for customers who will pay for the product. Hence there is another dimension to NPD which is crucial to the success of an NPD project costs. There are two costing methods: traditional (full costing), and activity-based costing (ABC). The two methods emerged in different historical contexts and consequently different business atmosphere. Their main difference is how they allocate overheads to the costs. ABC studies the tasks closely and allocates costs to activities. Hence, managers model the business processes in different ways and study them to allocate costs. This thesis claims that mock-ups and inexpensive prototypes can be used to model a future process to estimate the associated costs to the new product, before fully developed.

To gain competitive advantage, many firms put LM concept into practice. The LM concept focuses on minimizing costs, production time, inventory, shipping time, and waste and at the same time maximizing customization, quality, market share, and customer satisfaction. Thus, on one hand, LM has common goals as SCM. On the other hand, lean firms invest in innovations and rely on them. Therefore, to reach their goals, companies need to investigate their supply network and work closely with their suppliers and customers to increase the supply chain profitability and at the same time reducing the prices. Working closely with suppliers or buyers requires dedication and frequent communication to precisely understand each other and build strategic alliance. One of the concerns and difficulties is communication about costs. Open book accounting suggests to systematically companies share relevant information to smoothen the cooperation and reach better outcomes. This thesis recommends that mock-ups and the information generated from testing inexpensive prototypes provide material for more constructive cooperation with buyers and also suppliers.

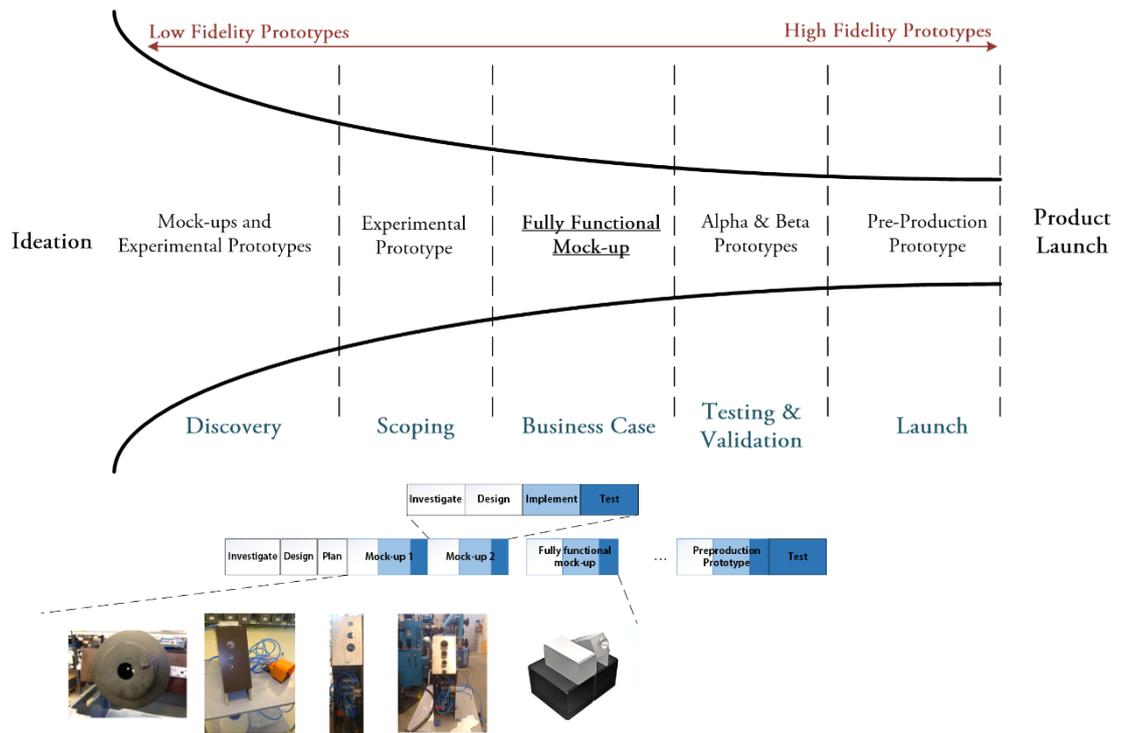


**Figure 64.** The framework illustrated in this thesis

For instance, buyers can see the estimated price and specifications of different ideas being generated and tested rapidly and decide which product they are more interested in or on which concept they are willing to invest and participate in the development project closely with the company. On the other hand, mock-up generated material can be a strong tool to communicate with suppliers as well. For example, the company can show to the supplier how they can change the design of their products in a positive way to the new product, and show the benefits of it and how they can improve their profitability through it.

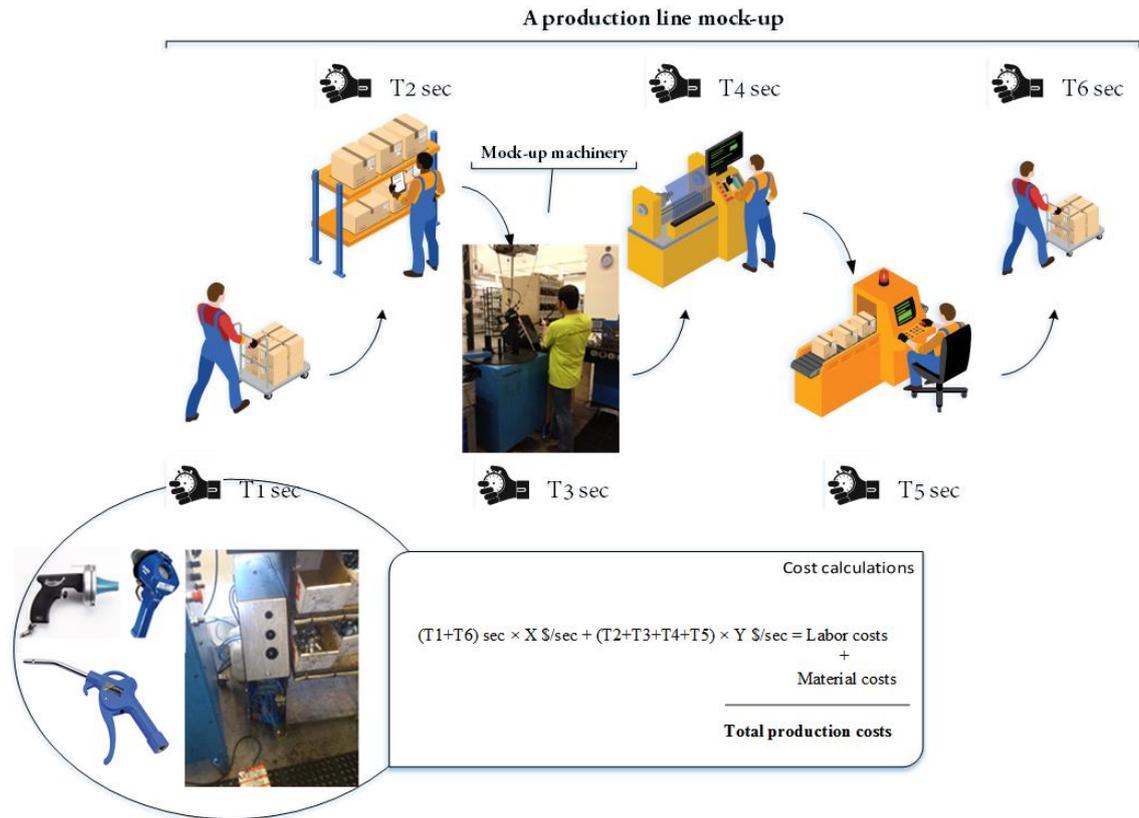
## 7.2. The Reflection of the Case in the Framework

As discussed in Section 6.1 the goal of the project was to increase the cleanliness level of the hydraulic hose assemblies. To do so several sources of contamination were investigated and the engineers argued that the most of contamination is generated when cutting hoses and it contaminates near the edges of cut. Hence, they built the first mock up in only few days and tested the results in their mock-up lab to see if there had been any improvements. The preliminary results were satisfying so the development project proceeded further. Inexpensive prototypes and fully functional mock-ups were implemented and tested and every single step provided valuable information to the team. Figure 65 shows how different mock-ups were developed to rapidly test their core functionality.



**Figure 65.** Washing machine development

To test the actual working experience with the washing machine, a washing machine mock-up was installed in the mock-up production cell. The cell contained all other machinery and tools as usual, plus the washing machine. This cell was designed for rapid testing; that is why many parts of the cell were built from plywood to give the flexibility to different process and product development teams. By putting the washing machine prototypes in practice, the engineers kept testing the functionality, received feedback from operators, and with shipping the hose assembly batches and kits to the customer they also received valuable feedback from customer. Moreover, the developers studied the production processes of each method and carried out time studies to calculate the extra production costs each cleaning method added to the production cost (Figure 66).



**Figure 66.** Mock-ups installed in production cells to estimate costs

Calculating the estimated costs along with valuable knowledge gained through the tests provided the case company with a strong communication material about the costs and quality of the hydraulic hose assemblies. In this case the customer received the same old product as before, however, the quality and cost of production changed depending on the cleaning method the case company used. This can impact the purchasing price for the customer. Now the case company and its strategic ally, the main buyer, were able to openly discuss the matter with them. Figure 67 shows a sample material which includes all information the company has gained over different cleaning methods, from costs to quality level and caution points. The company even shared information about other ideas which were more complicated and consequently the company could not test them with the cheap mock-ups. However, the knowledge share can generate more ideas and better outcomes.



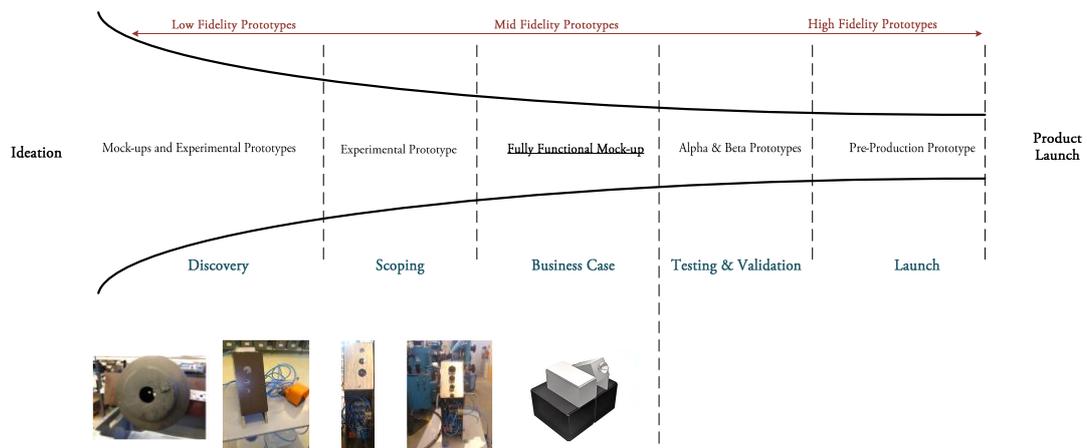
**Figure 67.** The material generated from agile staged model

The same material could be shared with the suppliers as well. The company can decide now to share what with which supply network member and plan its integration with partner firms more precisely. For example, the company now knows that cooperating with cutting machine manufacturer at the moment could bring more value to the cleanliness

development project, since the studies showed that most of contamination is made when cutting.

### 7.3. Analysis of the Case Based on the Framework

The theoretical framework introduced in this thesis was implemented in the cleanliness improving project and now it is possible to assess the framework and see how practical it was in a real business case. The project kicked off since the customer required higher cleanliness level in hydraulic parts from different suppliers; the parts include valves, fittings, adaptors, and the hose assemblies. By investigating the hose assembly production and detecting possible sources of contamination idea generation started. From very beginning different mock-ups and prototypes were built to test the ideas as fast as possible. Even a mock-up lab was made to evaluate the mock-ups and prototypes and shortlist them to send them to a professional lab. Moreover, mock-ups and inexpensive prototypes became a strong communication tool among all the project stakeholders; since there was a tangible mock-up there made of cheap and flexible materials, the stakeholders did not have to assume anything. They could design a test or make changes in the mock-ups to generate more information and have authentic facts in their hands rather than assumptions and guesses. Figure 68 shows how mock-up evolved to mid fidelity prototypes.



**Figure 68.** *Implementing stage-gate model in the case*

One of the ideas showed its potential in the preliminary tests on inexpensive mock-ups, the washing cut edges from inside or simply the washing machine. For that particular idea, stage gate model was implemented. Other ideas such as brushing and blowing air were not as sophisticated as the washing machine and could be tested easily with the company current tools. Therefore, by installing each method in the fully functional mock-up production cell, the developers were able to study the process and estimate extra production costs each method dictated to the process. Figure 69 illustrates how each method was tested in production cell and the added costs to the production were estimated.

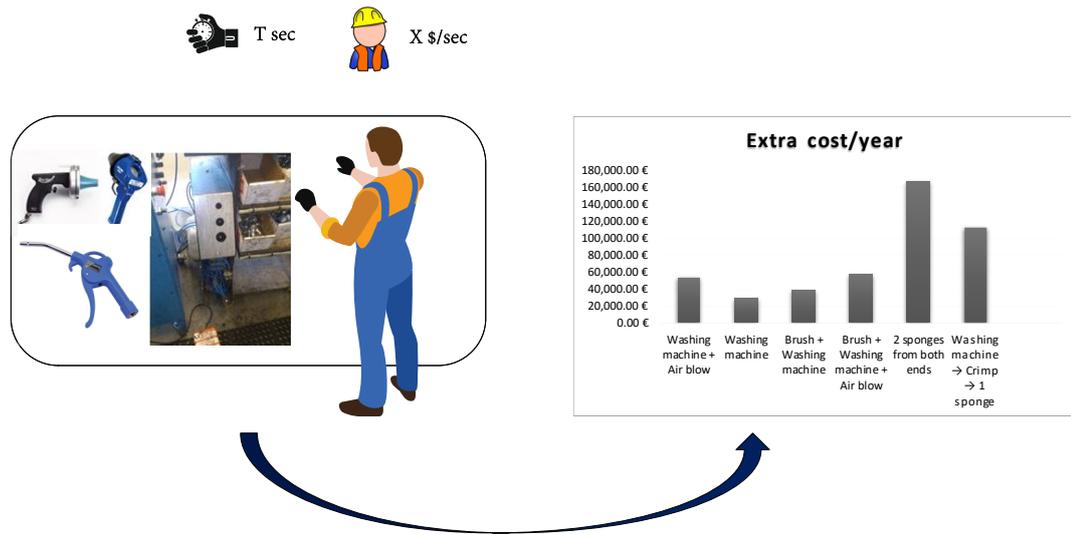


Figure 69. The cost impact of each cleaning method in hose assembly production

Having the cost data along with the quality data reported in both descriptive and quantitative according to ISO 4406 provided the company with a strong communication material. The customer was involved from early steps of the development project, however, now the company could discuss the cleaning methods deeper and with more accurate data. Figure 70 illustrates how the generated information and knowledge from low-cost prototypes and process studies were used as a tool for smoothening integration with the customer in the cleanliness development project.

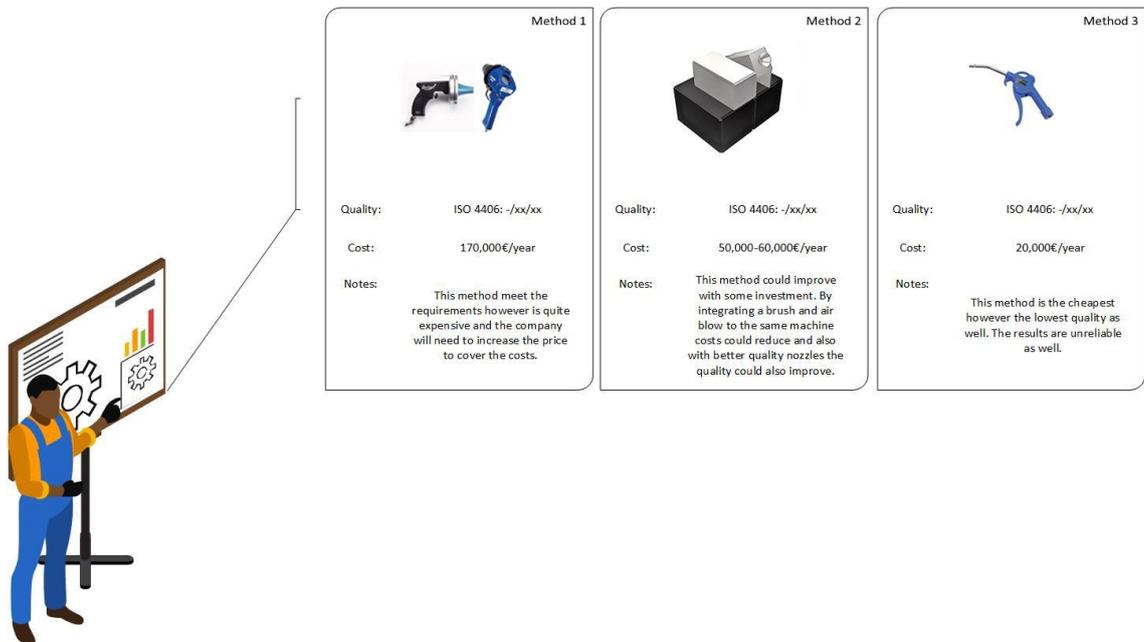


Figure 70. Communicating quality and cost with allies

This information and tools have been effectively improving the communication between the two allies. Moreover, the generated knowledge improved the understanding of suppliers' quality. In some cases, the engineers came up with ideas to improve suppliers' products. In a specific case, the developers brought the idea of new cutting machine on the table. Thus, having the rational and factual communication tools and materials in have helped smoother relationships with the other supply network entities.

#### **7.4. Analysis of the Results**

This project could proceed further in different ways and various scenarios are imaginable. First, the customer accepts to cover the extra costs of the sponge shooting method and the case company installs sponge shooting machine and purchases sponges. This is highly unlikely to happen since the extra costs of this method are extremely high. Second, the customer work closely with the company to develop the washing machine. The self-cleaner brush, washing machine, and air blower could can be integrated in one machine. The nozzle can be significantly improved. The length of the nozzles, the hole angles, and the water and air mixture can be optimized and the company lab proved that all of these factors are important in the washing machine effectiveness. Third, the company pushes the cutting machine supplier to produce or adjust the cutter machines. This approach however depends on how close the company and the supplier develop their relationship.

The core of this thesis is mid-fidelity prototypes and their benefits to NPD projects. This thesis discusses how they can bring more flexibility to the product development to the level that agile development methods which are mostly used in software development can be implemented for physical products development as well. However, there are questions remaining about effectiveness of this framework: Which industries can apply this framework? To what extend can companies rely on the numbers generated from fully functional mock-up and especially cost estimations? How companies identify a confidence interval for the mock-up generated information? It is also an interesting subject for further researches to see the impact of 3D printing on mid-fidelity prototyping.

## 8. CONCLUSIONS

Since the industrial revolution in the 19<sup>th</sup> century, business atmosphere has become more and more competitive and thank to the modern technologies global markets have emerged. Hence, companies are investing in innovations to keep their competitive advantage and guarantee their success when outperform their competitors. Therefore, successful new product development is a must to survive. For a new product to be successful it has to be appealing to the customers. However, customers can tell if they like a product or not if they actually have hands on experience. With the current NPD models and introduced prototypes in the literature customers and other stakeholders can try the product in late stages of product development. They usually try high-fidelity prototypes after a lot of product development costs were incurred. As a result, if they are not satisfied with the product it might be too costly for the company to redesign and reproduce a high-fidelity prototype of the product. On the other hand, a mere appealing product to the customers is not necessarily a successful product. The price also plays a significant role in the success of a product.

The objective of this thesis was to introduce mid-fidelity prototypes as a tool to improve current stage wise NPD models by reducing costs and testing different ideas as fast an inexpensive as possible, also to point out how mid-fidelity prototypes enable managers to implement OBA concept with their suppliers and customers. For this purpose, this thesis proposed fully functional mock-ups or mid-fidelity prototypes. They share some characteristics of both low and high-fidelity prototypes. Thus, as they represent the core functionality of a product, at the same time they are made of inexpensive materials such as plywood, aluminum, or plastic and simple production tools such a screw driver, saw, and hammer. To address the objectives of this thesis, a literature review was done and a theoretical framework was formed. Then, to test the framework, it was put in practice in a real case.

The first key finding of this research was that fully-functional mock-ups can be used as a great communication tool among the development project stakeholders. The customers can try the product even before it is actually developed. Their feedback is a key for the next step decision-making. In case a change is needed in the product, engineers can build another fully functional mock-up very fast and cheap. Thus, mid-fidelity prototypes enable managers to practice stage gate more flexible and closer to agile software development methods.

Second, managers can run studies on the mock-ups to estimate the cost impacts of the product. By implementing mid-fidelity prototyping concept in a production line/cell, the development managers can carry out time study to accurately estimate the production, maintenance, and other related costs. The cost information derived from fully functional

mock-ups are valuable since they provide stakeholders with factual information and decisions would not be made based on speculations.

The cost data and quality measures, generated from studying fully functional mock-ups, build a meaningful material to share with the key customers or suppliers. Thus, fully functional mock-ups enable the company to implement OBA and share factual information with its strategic allies. Sharing information based on facts help the partner companies to have clearer idea of the situation and make better decisions for their supply network.

Even though the framework, worked well and the company in the end could offer its customers with different product qualities and different prices, this method is not perfect and has its limitations. There are high-tech industries in which mid-fidelity prototypes provide no value. Moreover, in some cases even if it is possible to make mid-fidelity prototypes, it is not cheap or even possible to make the fully-functional production line. The impact of new technologies such as 3D printing and virtual reality devices on mid-fidelity prototyping and implement more flexible development models for physical products are valuable and possible future studies in this field. As Levitt (1965) said “business management will probably never be a science—always an art”, fully functional mock-ups or mid-fidelity prototypes are tools for business managers, the economic sculptors.

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## APPENDIX A

Costs of the first washing machine mock-up and mock-up lab are as follow.

<b>Washing machine bill of material</b>	<b>Costs €</b>
Plywood	20.00
Trash can	9.00
Hoses and fittings	50.00
Nozzles	200.00
Container	50.00
<b>Total</b>	<b>330.00</b>

<b>Mock-up lab bill of material</b>	<b>Costs €</b>
Membranes	30.00
Dissolvent	20.00
Mosquito net	2.00
Hoses and fittings	3.00
KeepLoop	100.00
<b>Total</b>	<b>155.00</b>

## APPENDIX B

Samples of mock-up lab results:



Wet cut



Wet cut + wash



Wet cut + wash +  
brush



Brush + wash + crimp



Wash + brush + air blow

## APPENDIX C

Detailed calculations of costs for each cleaning method.

Sample explanations	T1	T2	T3	T4	T5	Avg.	Hour/year	Labor Cost/year	Material/assembly	Material/year	Total/year
Washing machine + Air blow	16.7	15	15.5	15.5	13.7	15.3	2125	53,125 €	0.00 €	0.00 €	53,125.00 €
Washing machine	8	8.9	8.6	8.2	8.6	8.5	1180.6	29,515 €	0.00 €	0.00 €	29,515.00 €
Brush + Washing machine	11	12.5	10.5	10.6	11.2	11.2	1555.6	38,890 €	0.00 €	0.00 €	38,890.00 €
Washing machine + Air blow	18	15	16.2	17.1	16.7	16.6	2305.6	57,640 €	0.00 €	0.00 €	57,640.00 €
2 sponges from both ends	13	13.5	14.4	13.7	13.3	13.6	1888.9	47,223 €	0.24 €	120,000.00 €	167,223.00 €
Washing machine → Crimp → 1 sponge	13	15	15.9	15.7	15.9	15.1	2097.2	52,430 €	0.12 €	60,000.00 €	112,430.00 €