THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Improving engineering change processes by using lean principles

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Abstract

The purpose of this research was to test the usefulness of the 13 lean principles for product development by Morgan & Liker when improving an engineering change (EC) process.

The EC-process was studied at four firms. The firms were active in three different industrial branches. Two of the firms are situated in Sweden and two in Finland. First an exploratory single case study was carried out at one of the Swedish firms. This study was later merged into a multiple case study involving three more firms. The single case study included a thorough investigation on lead times in three explicit EC cases. The problems found in the EC processes in the multiple case studies were compared with the lean principles. If the problem caused a violation of one or several of the principles a solution to the problem was sought in line with the principle. From the results of the studies a synthesis was done to develop a lean Information Model to be used as a framework when improving information management aspects of engineering processes. The work was done in cooperation between Swerea IVF and Aalto University School of Science (previously Helsinki University of Technology).

Also a two case study was carried out involving one of the Swedish firms from the previous work and one other firm not involved in the previous work, both from the automotive industry. The purpose with this study was to study the transformation process to lean product development. The study was done in cooperation between Swerea IVF AB and Chalmers university of Technology. The result from this study was later compared with the lean principles of Morgan & Liker. The results from these studies are published in four papers and further developed in this thesis.

The results show that the lean principles can be used as a means to analyze and improve an engineering change process.

The conclusions are:

- There is a good match between the problems connected to ECs at the studied firms and the lean principles.
- Lean principles can be used as guidance when improving an EC process in the industrial context of this research.
- There were no contradictions found between improvements of an EC process and the lean principles.
- Lean principle one, six, eleven, twelve and thirteen explicitly and principle seven implicitly support transformation to Lean Product Development at a supplier of mechanical and electromechanical products in the vehicle industry.
- A better overview of ECs and a reduction of the time for information transfer are achieved when an EC process is designed according to the lean principles.

Acknowledgements

The research work in this thesis was carried out in cooperation with colleagues at Chalmers University of Technology and Helsinki University of Technology in Finland.

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Gothenburg, May 2013
Mikael Ström

Appended publications

The following papers form the foundation for this thesis. They are listed in chronological order according to when the research work was carried out and when they were published.

Paper A Ström, M., Malmqvist, J. and Jokinen, K. Redesign of the Engineering Change Process of a Supplier in the Automotive Industry. In Proceedings of the 2nd Nordic Conference on Product Lifecycle Management - NordPLM'09, Gothenburg, January 28-29 2009.

Paper B Mahlamäki, K., Ström, M., Eisto, T. and Hölttä, V. Lean Product Development Point of View to Current Challenges of Engineering Change Management in Traditional Manufacturing Industries. In Proceedings of the 15th International Conference on Concurrent Enterprising – ICE 2009, Leiden, The Netherlands, 22-24 June 2009.

Paper C Hölttä, V. Mahlamäki, K., Eisto, T., and Ström, M. (2010) Lean Information Management Model for Engineering Changes. In Proceedings of the International Conference on Business, Economics and Management (ICBEM 2010), Paris, France, 28-30 June 2010.

Paper D M. Ström, M. Alemyr, S. Bükk, G. Gustafsson, and H. Johannesson. Transformation to Lean Product Development – Approaches at Two Automotive Suppliers, Design 2012, Dubrovnik, Croatia, 21-24 May 2012.

The work in the appended publications was distributed among the authors as follows:

Paper A: Mikael Ström did the major part of the data collection. Theory was studied by Mikael Ström and Katrine Mahlamäki. Data analysis was carried out by Mikael Ström and Katrine Mahlamäki (previously Jokinen) in cooperation. Analysis of lead time data was solely made by Mikael Ström. Mikael Ström elaborated on the findings and did the main editing of the paper. Johan Malmqvist contributed advice on scientific correctness. All authors reviewed the paper and contributed corrections.

Paper B: Data was collected and analyzed by all authors. Mikael Ström did the main data collection in Sweden and Katrine Mahlamäki, Venlakaisa Hölttä and Taneli Eisto did the data collection in Finland. Research design was partly done by Mikael Ström and partly by Katrine Mahlamäki. However, the part involving transcriptions of recorded interviews and graphical presentation of data was done by Katrine Mahlamäki, Venlakaisa Hölttä and Taneli Eisto. The main editing was done by Katrine Mahlamäki. All authors reviewed the paper and contributed corrections.

Paper C: Data was collected and analyzed by all authors of the paper. However the part involving transcriptions of recorded interviews and graphical presentation of data was carried out by Katrine Mahlamäki, Venlakaisa Hölttä and Taneli Eisto. The main editing work and synthesis was done by Venlakaisa Hölttä. All authors reviewed the paper and contributed corrections.

Paper D: Data was collected by all authors. Research design was carried out by Mikael Ström and Stefan Bükk. Action research activities were carried out by all authors. The main editing of the paper was done by Mikael Ström and Göran Gustafsson. All authors reviewed the paper and contributed corrections.

Contents

1 Introduction

It is of vital importance to commercial firms to be able to develop products that are competitive on the market. Many of them have some kind of company practice for planning and conducting the realization of products. One such practice is a product development process similar to the phase – review process (Cooper 1994) or the stage – gate model (Cooper 1994). Other processes resemble the one described in Ulrich & Eppinger (2012). The practice of realizing products is often described in the operational manual of these firms or exists as an informal and undocumented process. These processes have in their simplest description a linear layout. In the description of them it is however not uncommon to point out that iterations are often required to do necessary rework in order to achieve the design objectives. Firms that use this kind of practice emphasize that design projects often have problems achieving their objectives on time and budget. Firefighting measures are often resorted to in order to solve problems regarding product performance and performance in production. Such measures can be late and costly Engineering Changes (EC). Many firms are therefore seeking an alternative to today's practice to be able to increase the efficiency and precision in their product realization work.

The practice used by Toyota Motor Corporation (TMC) (Ward 1995) has emerged as a feasible alternative to the abovementioned present process. TMCs practice is referred to as Lean Product Development (LPD) (Morgan, Liker 2006). LPD has been applied in different ways, and also described in different ways in literature. It is not unambiguous how to introduce and apply LPD. Morgan & Liker (2006) describe how Toyota is applying LPD as a framework of 13 principles. Kennedy (2006) describes successful implementations in the USA. Ward describes LPD in a third way (Ward 2009). The approach to applying LPD in these descriptions is slightly different from each other. Another attempt to describe LPD is made by Holmdahl (2010), who puts LPD in a Swedish context. Modig and Åhlström (2012) also describe lean processes in a Swedish.

From the descriptions above, the following main components in an LPD process can be identified:

A design process based on Set-based design, where the design spaces of multiple concepts are thoroughly explored and the least feasible solutions are successively eliminated in a converging process. Decisions that put constraints on the solution are treated as intervals that are narrowed as knowledge is gained regarding the consequences of these decisions (Ward 2009).

Visual planning of product development projects, to control and monitor the work. Product development projects and the adherent design work are planned using whiteboards and aids such as sticky notes and magnets to mark work tasks to be performed and to highlight problems. The planning boards are often placed in a dedicated space referred to as an Obeya room (Horikiri etal. 2008). According to Google Translate the Japanese word Obeya means big room.

Structured problem solving, using loops such as the PDCA (Plan, Do, Check, Act) or the LAMDA (Look, Ask, Model, Discuss, Act). These loops are often documented on paper sheets of size A3, which are commonly referred to as A3s (Sobek 2008).

Formalized ways of gaining and documenting knowledge during the design process for later reuse. The design space of a concept is explored by testing the limits of the design and documenting the results, preferably on A3s. When extensive results regarding a particular part of the design space are gained, they can be used to describe the dependency between design parameters in the form of trade-off and limit curves.

A thorough investigation of the customer value of an anticipated product. This value shall be monitored throughout the development project and serve as the objective of the project team to focus on in order to avoid (or at least minimize) waste.

The concept of waste (Womack & Jones 1996) and the concept of lean principles (Morgan & Liker 2006) are often used in the descriptions of LPD.

In the work of Womack & Jones (1996), different categories of waste are used to describe which operations add value to the product and which are wasteful, and should consequently be avoided. An extensive description of different models of waste categories and the relations between them is given by Bauch (2004). From these descriptions and from descriptions of Lean Production (LP), work that is not value adding to the product being developed and manufactured is classified as wasteful. For this reason, it is referred to and named waste. Another significant part of the description made by Morgan & Liker (2006) is the 13 lean principles. A similar set of principles exists in the descriptions of Set-based design by Sobek (1999). Early adopters of LPD in Sweden have in many cases created a metaphor in the shape of a “lean house” which describes the principles and components that they impose on their organization when practicing LPD and LP.

Many firms in Sweden were considering adapting LPD at the time of this study. One plausible way for them to get guidance in the work to reshape their product realization process is to use the lean principles of Morgan & Liker. The product realization process in this sense also includes Engineering Change Management (ECM).

It is of course of great importance to minimize the amount of waste in the product realization process. It is therefore tempting to focus on the removal of waste as the prime objective and activity in a lean implementation program.

An alternative way of addressing this issue is instead to focus on the value adding operations. If these are improved, the value adding process is anticipated to become more efficient, thus resulting in better products. If focus is put on waste removal it is still possible that customer requirements are not fully understood and the Product Development (PD) projects end up developing the wrong product in a highly efficient way.

A third way is to focus on the lean principles as a guiding aid. They have a wider scope compared to the approach based on the waste categories. The lean principles point out what to do right in PD. The approach based on the waste categories points out what not to do and cannot be part of a future vision in the same sense as the lean principles. Currently and in the past, research has been carried out on how to detect and analyze waste in the product development process (Hicks 2007, Siyam 2012). No similar work has been done on how to use the lean principles of Morgan and Liker to get guidance on whether the ECM process of a firm, developing and manufacturing assembled mechanical products, is tuned to be competitive in the sense of these principles. Some work has been done on how to use the principles of Set-based design (Raudberget & Sunnersjö 2010). These, although simple, are assessed to be of good guidance for the practical adaption of lean industrial design processes (Raudberget 2013). Examples on the use of the lean principles to illuminate possible ways to implement lean product development are the ones by Måhede & Collin (2007) and Garza (2005). A comparison of the lean principles and the way product development and engineering changes are performed is anticipated to reveal shortcomings in the processes and point out in what direction to change them. For this reason the research focus of this work has been on the usability of the lean principles as a guide to improve the engineering change process in a firm developing and manufacturing assembled mechanical products.

1.1 Research Questions

Regarding what is stated above we pose the following research questions.

RQ1: How do the lean principles match the current problems in ECM?

RQ2: How can the lean principles provide guidance on how to improve an EC process?

RQ3: How can the lean principles provide guidance in a transformation process to LPD?

1.2 Delimitations of research

The focus of the suggested research is on product development and engineering change management in the manufacturing industry. The types of products that are in focus are assembled mechanical and electromechanical products. The research does not include the development of electronic and software intensive electronic products. Neither are product service systems included in the scope of the research. The studied firms are all located within Scandinavia and for this reason the research does not include environments with a culture different from the Scandinavian corporate culture.

2 Frame of reference

Systematic descriptions of the product realization process and different perspectives on the product to be developed are given by many. In particular Pahl & Beitz (1996) describe systematic design with some focus on the product. Andreassen & Hein (1987) describe Integrated Product development, with a wider scope on the process compared to Pahl & Beitz. Hubka & Eder (1988) describe the product to be developed with a Theory of Technical System and Suh (1990) prescribes two axioms to be followed when developing products. Blanchard & Fabrycky (2006) have a system engineering perspective, and Ward (2009) describes Lean Product development. Table 1 displays the above-mentioned references, their branch in design science and an abbreviation of the branch.

Table 1.

Authors	**Branch**	**Abbreviation**
Andreassen & Hein (1987)	Integrated Product Development	IPD
Hubka & Eder (1988)	Theory of Technical Systems	TTS
Suh (1990)	Axiomatic Design	AD
Pahl & Beitz (1996)	Systematic Design	SD
Blanchard & Fabrycky (2006)	Systems Engineering	SE
Ward (2009), Morgan (2006)	Lean Product Development	LPD
Ulrich & Eppinger (2012)	Systematic Design/Integrated Product Development	SD/IPD

One way to classify these descriptions is to use the map of design science suggested by Hubka & Eder (1988). This classification uses two dimensions. The first dimension is the different types of design science: descriptive (describing the phenomena of development) or prescriptive (having a purpose to influence the development). The second dimension is to what extent the design science is oriented towards the product to be developed or towards the process of how to develop it. Each of the science branches in Table 1 are classified according to these two dimensions in Figure 1.

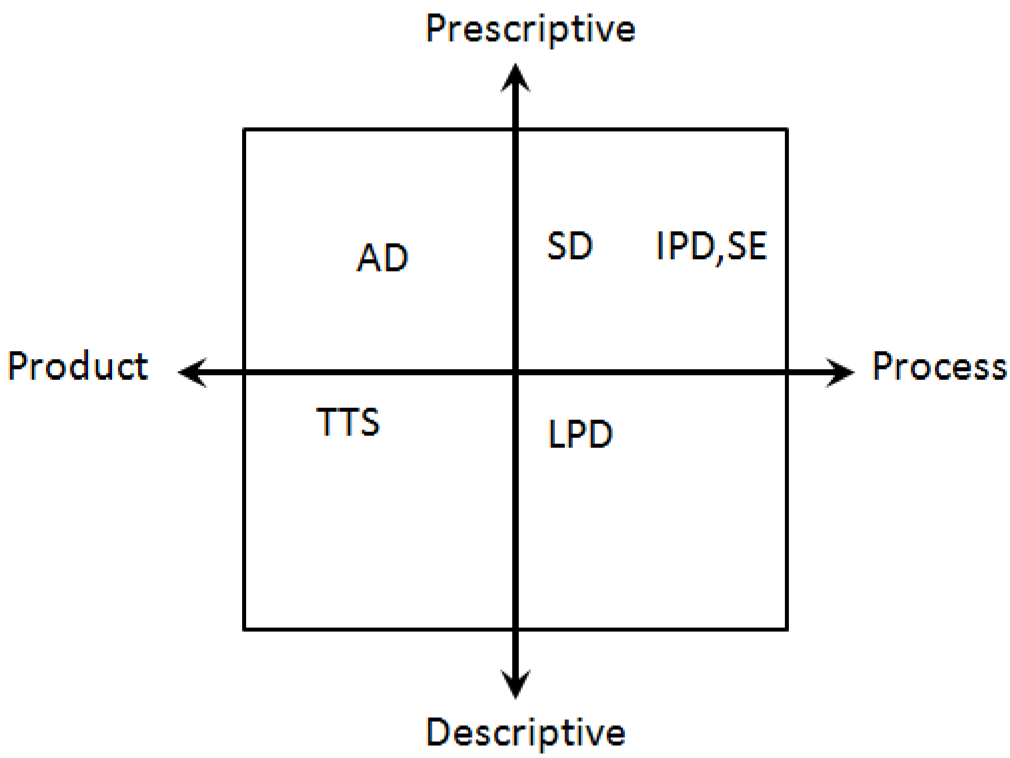

Figure 1. Classification of science branches inspired by Hubka & Eder (1988). The positions in the diagram are approximate.

Axiomatic design (AD) is based on two axioms (Shu 1990):

1. The independence axiom: Maintain the independence of functional requirements
2. The information axiom: Minimize the information content

From these axioms and other basic knowledge theorems, design rules are formulated (Shu 1990). The axioms, the theorems and the design rules guide designers in the design process. The process is described as a simple loop where the design is compared with the specification of the design and improved in an iterative manner until a good enough design is achieved. The methodology has a clear product focus and is of a prescriptive nature and is classified to be in the upper left quadrant in Figure 1.

The Theory of Technical Systems (TTS) describes the design as a system having an input and an output with a transformation process in between (Hubka & Eder 1988). The transformation process is dependent on the technical system, the human system and the active environment. The TTS is of a descriptive nature and focuses on the product. It is therefore classified to be in the lower left quadrant of Figure 1.

The process oriented branches all describe sequential product development processes of different kinds. Typical steps are the ones described by Pahl & Beitz, who divide the process into four main phases:

1. Planning and clarifying the task
2. Conceptual design

3. Embodiment design
4. Detailed design

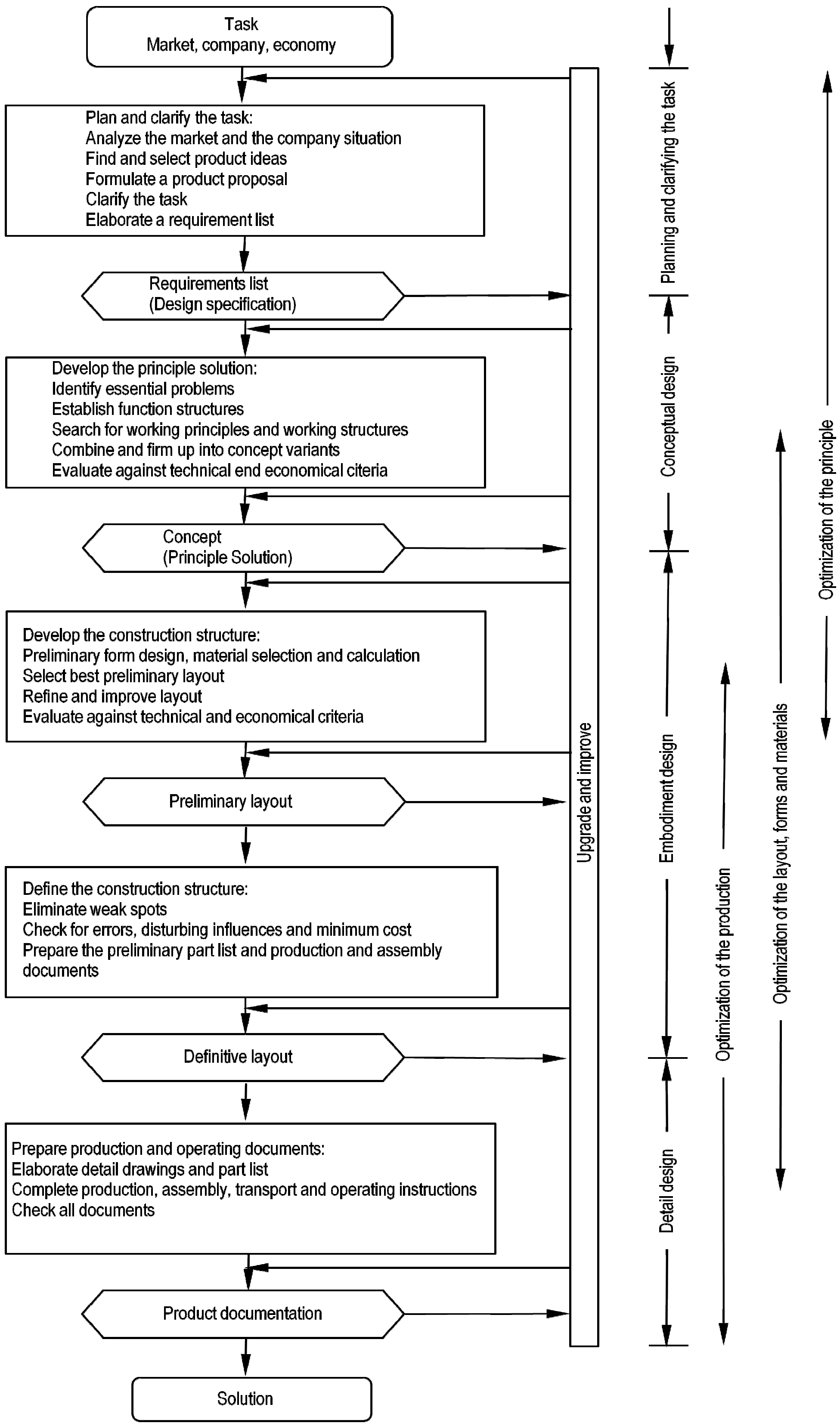

Figure 2. The product development process according to Pahl & Beitz (1996)

SD has a clear focus on the process but also provides advice on the product to be developed. The description is of a prescriptive nature. For this reason SD is classified to be in the left part of the upper right quadrant in Figure 1.

Ulrich & Eppinger (2012) divide the process into the following sequential steps (see Figure 3):

1. Planning
2. Concept development
3. System level design
4. Detail design
5. Testing and refinement
6. Production ramp up

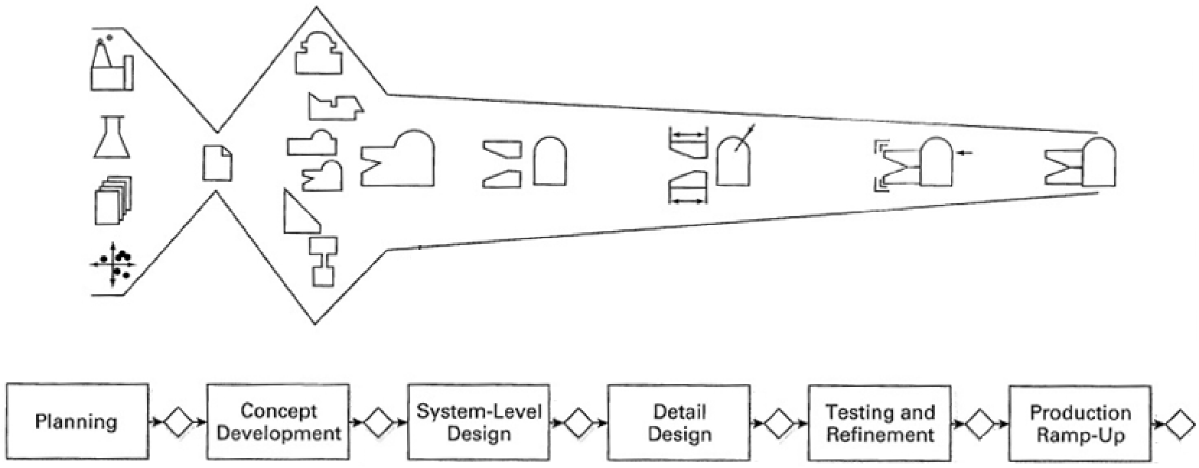

Figure 3. The product development process according to Ulrich & Eppinger (2012)

These resemble the steps of Pahl & Beitz but also include the start of production (Production ramp-up).

The Systems Engineering (SE) model described by Blanchard & Fabrycky (2006) puts a system perspective on product development. The product realisation process as described encompasses the total life cycle of the product. Four coordinated life cycles are mentioned: Product life cycle, production life cycle, maintenance and support life cycle, and Phase out and disposal life cycle. The product realisation process described needs to be tailored to specific product development programs. Blanchard & Fabrycky (2006) mention the waterfall model, the spiral model and the Vee model as possible system engineering processes. Figure 4 shows the Vee model.

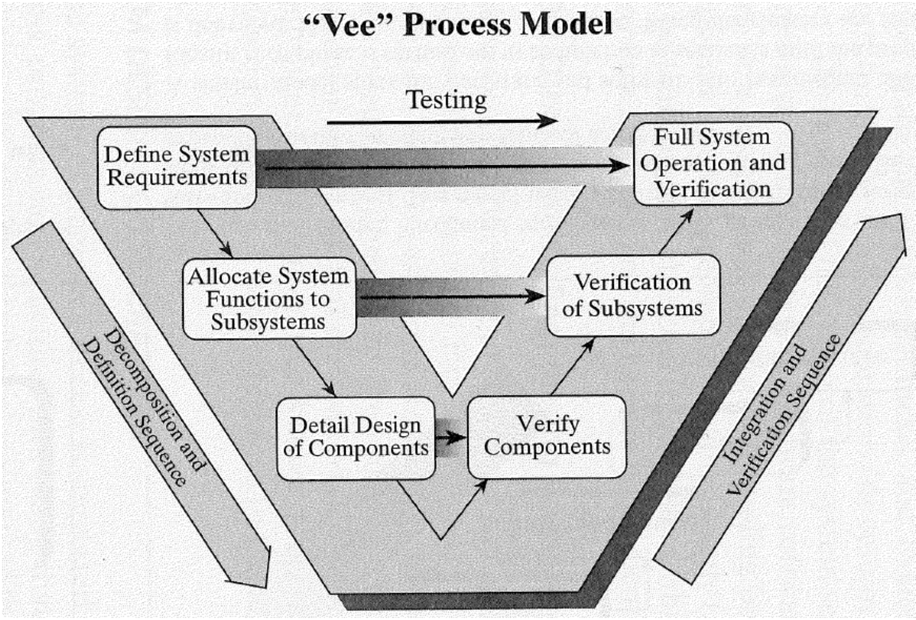

Figure 4. The Vee-model is one of many possible process models for systems engineering according to Blanchard & Fabrycky (2006).

In systems engineering, subsystems of the product are developed, tested and then integrated.

A variant of the sequential view is the one by Andreassen & Hein (1987). They describe the process by using a matrix with parallel tracks (see Figure 5) that are executed in an integrated manner. The name of this model is Integrated Product Development (IPD). The tracks correspond to the activities performed by the marketing function, the design function and the production function. In Figure 5 the top track is the activities of the marketing function, the middle tract represents the design function and the bottom track displays the production function (whereas the approach by Pahl & Beitz focuses more on the product development process that corresponds to the middle track in Figure 5). *The need* that is the prime driver to start the design process is represented as a cloud at the beginning of the tracks.

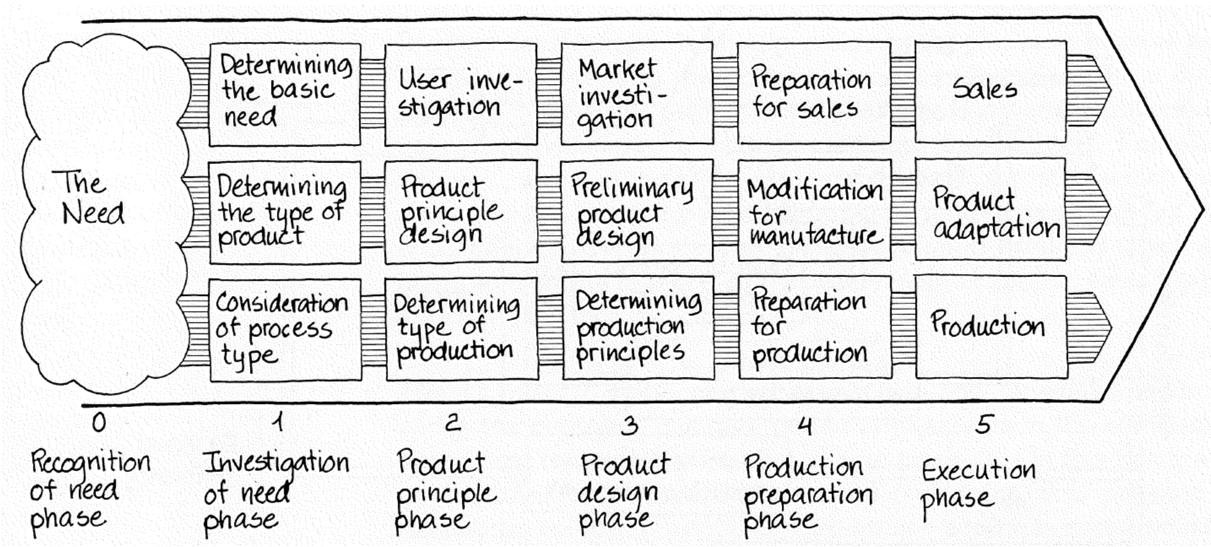

Figure 5. Integrated Product Development (IPD) according to Andreassen & Hein (1987).

The parallelism of the IPD model enables better communication between different activities compared to the linear step by step model by Pahl & Beitz. In IPD, a cross functional team works together to solve the overall task. One idea of the IPD model is to shorten lead time by executing activities in parallel instead of sequentially. IPD is in the above sense similar to concurrent engineering, where activities of different functions are executed in a simultaneous manner.

SE and IPD both have a clear focus on the process, are prescriptive by nature and are hence classified to be in the right part of the upper right quadrant in Figure 1.

Another approach is Lean Product Development described by Ward (2009), who divides the process into two flows. One is the knowledge value flow and the other is the product value flow. The knowledge value flow represents the learning process in the organization. The product value flow represents the steps needed to complete a product realization project. The learning in the project is fed back into the knowledge value flow.

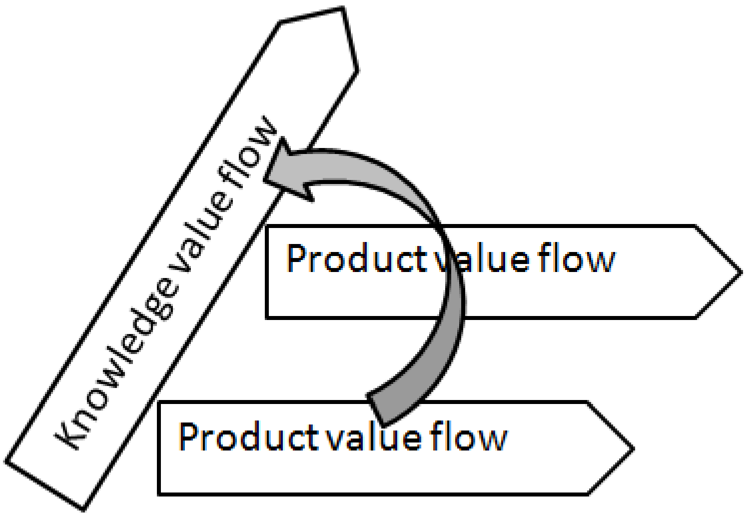

Figure 6. The knowledge value flow consolidates knowledge from the product value flow

Morgan and Liker (2006) describe Lean Product Development as a socio-technical system governed by 13 principles. The system has three main components:

1. Skilled people
2. Tools and technology
3. Process

Both variants of LPD are of a descriptive nature. They focus on the process and are classified to be in the lower right quadrant in Figure 1.

The descriptions by Pahl & Beitz, Andreassen & Hein, Ulrich & Eppinger, Hubka & Eder and Blanchard & Fabrycky originate from the traditions in European and American industry. Descriptions of LPD by Ward (2009) and Morgan & Liker (2006) originate from studies of the product realization process made at Toyota Motor Corporation and some of its supplier's. One of the pioneering papers describing this way of thinking is the one by Ward (1995).

2.1 Components and features of Lean Product Development

Some of the characteristic features and components are described in the following.

2.1.1 Principles of LPD by Morgan & Liker

There are several efforts to group a set of principles in the lean domain. One example is Sobek (1999) which describes three principles of Set-Based Design (see section 2.1.5), and was elaborated on and tested by Raudberget (2012). Another set of principles is described by Liker (2004). His set of 14 principles is applicable at the firm level, while a third set that is geared towards product development was designed by Morgan & Liker (2006). Their set of 13 principles imposes working methods to be used in the design process. One of these principles imposes the use of Set-Based design. This principle (Principle 2 of the 13) is not in conflict with the principles of Set-Based design mentioned above (Sobek 1999). The 13 principles of lean product development by Morgan & Liker (2006) are as follows:

1. Establish customer-defined value to separate value added from waste.
2. Front-load the product development process to explore thoroughly alternative solutions while there is maximum design space.
3. Create a leveled product development process flow.
4. Utilize rigorous standardization to reduce variation, and create flexibility and predictable outcomes.
5. Develop a chief engineer system to integrate development from start to finish.
6. Organize to balance functional expertise and cross-functional integration.
7. Develop towering technical competence in all engineers.
8. Fully integrate suppliers into the product development system.
9. Build in learning and continuous improvement.
10. Build a culture to support excellence and relentless improvement.
11. Adapt technology to fit your people and process.
12. Align your organization through simple, visual communication.
13. Use powerful tools for standardization and organizational learning.

These principles are described in detail in Morgan & Liker (2006).

In the following some of the components of LPD are described. Each component corresponds to one or several of the principles above.

2.1.2 Visual planning

Visual planning is used to visualize the state of an ongoing set of activities to all involved in or having an interest in the outcome of the activities. On whiteboards resources are planned towards the activities to be done within a specified time frame. The layouts of the boards are often adjusted to suit the needs of the organization using them. Two common layouts exist. In one, time is on the horizontal axis and resources on the vertical axis. The rows on the board (see Figure 7) represent individuals and each column represents a unit of time (Söderberg 2012). In the intersections between columns and rows sticky notes are placed to describe a task to be carried out during the unit of time that the column represents.

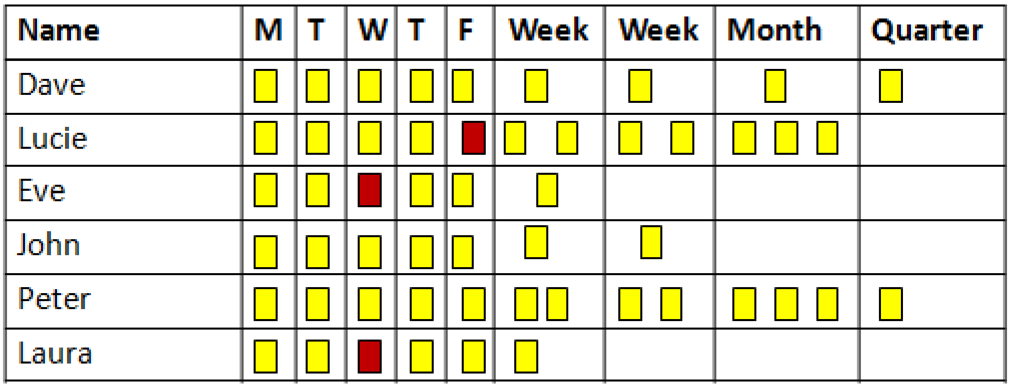

Figure 7. ***An example of a visual planning board. Yellow sticky notes represent work tasks and red represent tasks where there is a problem..***

Typically project groups have recurrent meetings in front of the board to plan activities in the time frame denoted by the marking on the horizontal axis of the board.

Another layout is to have resources like departments or functions on the horizontal axis and projects on the vertical axis (see Figure 8). The intersections represent the state of a project activity handled by the department of that column. The intersection can be marked with something having colours representing the state. Typically red denotes problems, yellow potential problems and green signals that everything is OK. Marks can be sticky notes or magnets of different colours.

The latter type of board is often used to plan multiple projects where achievements are made by several departments in the same project and where most departments are involved in more than one project.

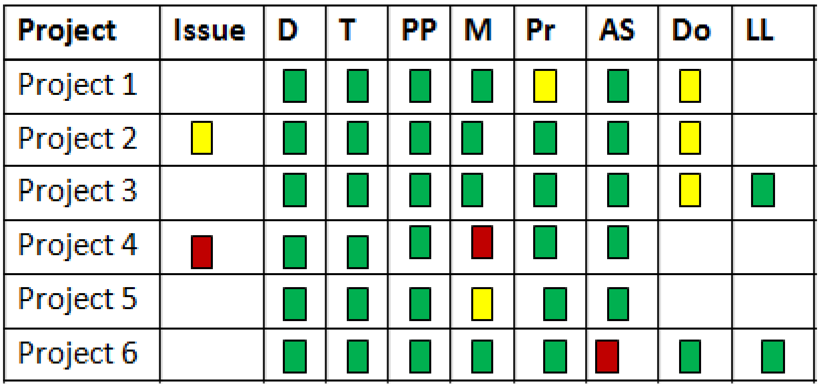

Figure 8. Visual planning on projects versus functions. Green sticky notes represent normal conditions. Yellow represent a small problem and red a severe problem

2.1.3 Structured problem solving

Structured problem solving in lean product development is often done by using a process in the form of a loop. Figure 9 shows two of the problem solving loops most often used in LPD. To the left is the LAMDA loop and to the right is the PDCA loop. The capital letters in LAMDA stand for: Look, Ask, Model, Discuss and Act (Ward 2007), see Table 2.

Table 2. The steps of the LAMDA loop

Letter	**Meaning**	**Anticipated activity**
L	Look	Go to the place or source of the problem and see it for yourself. Do not rely on second hand information.
A	Ask	Ask others about the problem. Ask five why to deepen the analysis
M	Model	Make a model to better understand the problems. Models can be simple such as a sketch on a piece of paper
D	Discuss	Use collected information and the model(s) and discuss the problem with others
A	Act	Decide what to do and act according to the findings. Test, evaluate and go back to Look

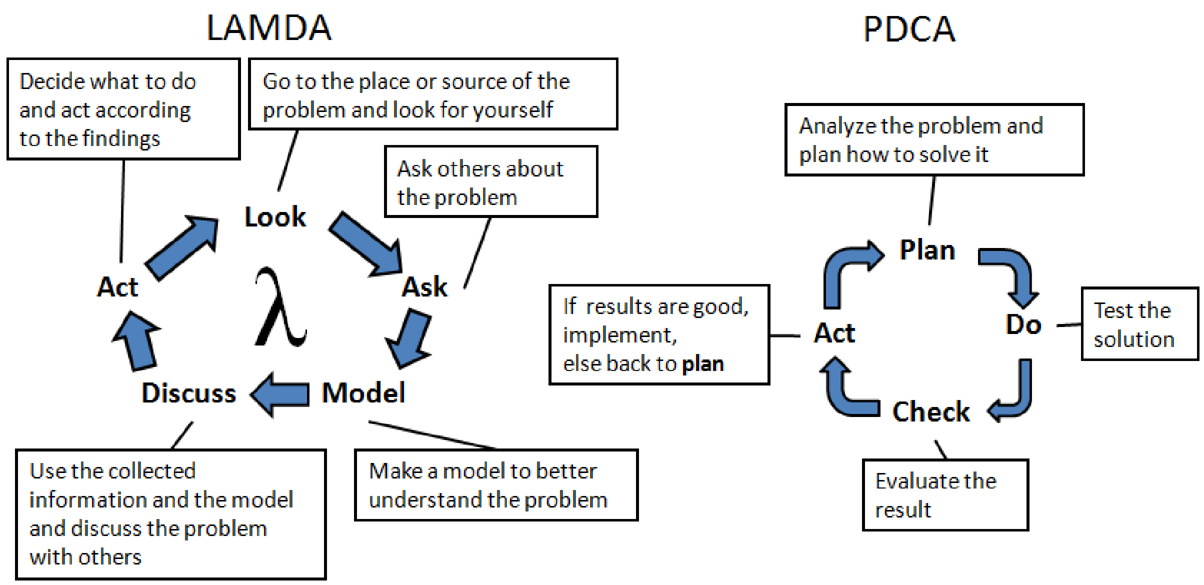

Figure 9. The LAMDA loop (Ward 2007) and the PDCA loop (Sobek 2008).

The PDCA (Plan, Do, Check, Act) has its origins back in the 1950's. One of the recent descriptions is made by Sobek (2008). PDCA resembles the LAMDA loop in many ways. It is however more geared towards production but can be used in a similar way to the LAMDA loop. The steps Plan, Do, Check and Act are given an extended meaning in the applications of PDCA. Table 3 describes the steps of the PDCA loop.

Table 3. The steps of the PDCA loop

Letter	**Meaning**	**Anticipated activity**
P	Plan	Analyse the problem, ask five why to deepen the analysis, plan how to solve the problem
D	Do	Test the solution
C	Check	Evaluate the result
A	Act	If the results are good implement else go back to plan

2.1.4 Trade-off and limit curves

Trade-off and limit curves have a long history in engineering design. The concept has been brought forward by the lean product development currents. One typical example of a trade-off curve is a Wöhler curve describing the relation between the number of load cycles and the stress amplitude of the load when the object reaches its endurance limit (see Figure 10).

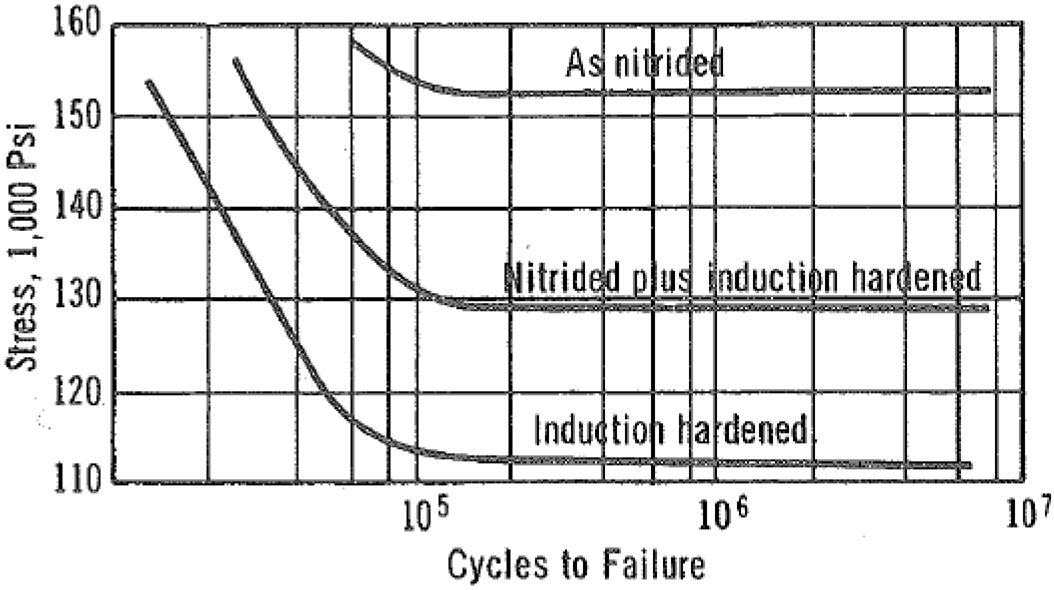

Figure 10. A Wöhler curve is an example of a trade-off curve (Boyer 1986)

A Wöhler curve can be used as a trade-off curve. Tradeoffs can be done to achieve more load cycles by using more material to lower the stress. Often trade-off curves are the result of extensive testing of a solution to explore the limits of a particular design regarding a parameter that is important to the customer experience of a product. For a car it could be top speed versus fuel consumption.

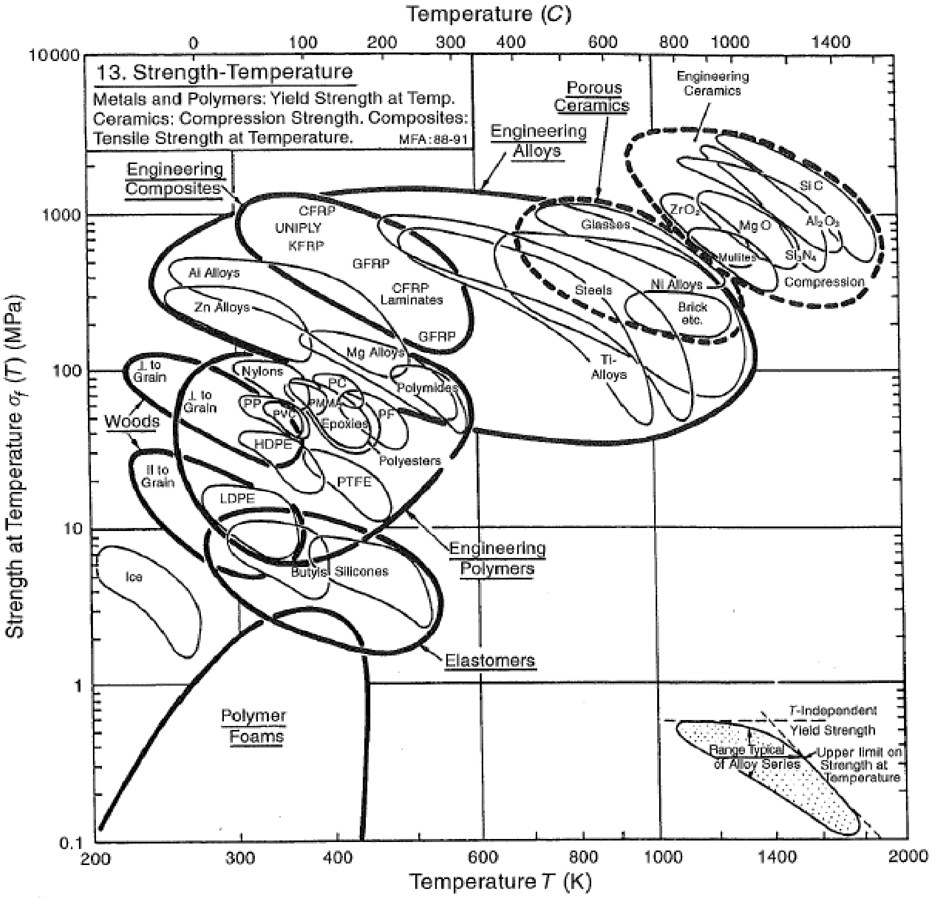

Figure 11. The diagram shows the limit of strength of different materials at different temperatures, from (Ashby 1999)

Figure 11 shows a collection of limit curves for the yield strength of different materials at different temperatures. It denotes the maximum temperature for an application using any of the material types in the diagram. The diagram can also be used to do tradeoffs. Either a stronger material can be selected or the components can be made thicker to decrease the tension.

2.1.5 Set-based design

Set-based design is an approach where multiple solutions or sets of solutions are explored. The design space of each set is explored to find the design limits according to the design intent. When knowledge about the solutions or sets of solutions is gained, less feasible solutions or parts of the sets of solutions are deselected (Ward 1995, Raudberget 2012, Sobek 1999). The process hopefully converges to one solution (see Figure 12).

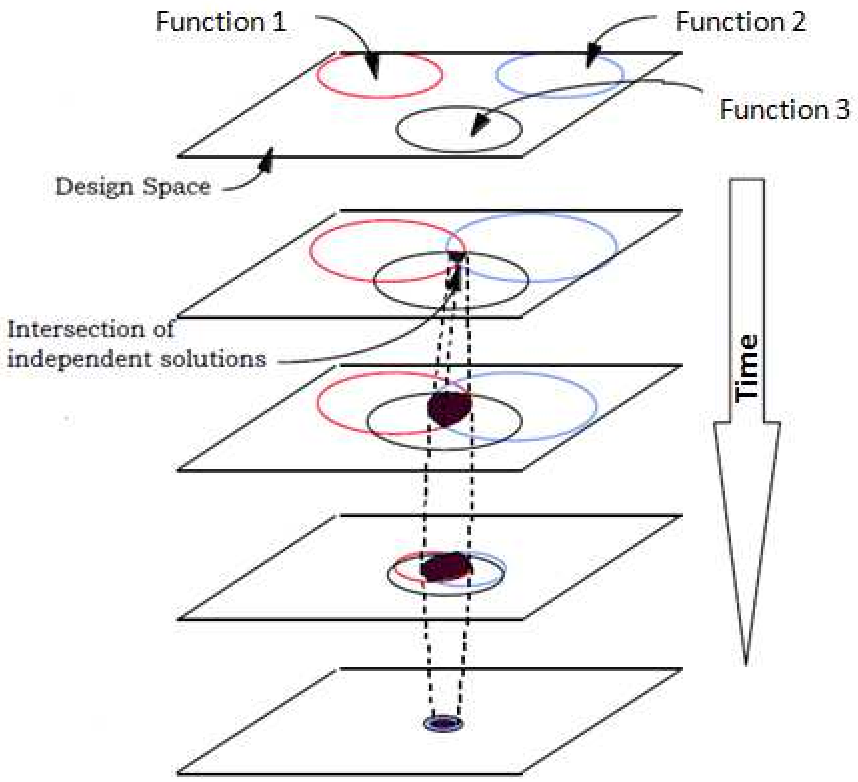

Figure 12. Set-Base design adapted from Bernstein (1998)

Set-Based design is governed by three principles (Sobek 1999):

No	Principle	Description
1	Map the design space	Test different solutions and gain knowledge in which regions of the design space that they are feasible according to customer interests. Do trade-offs between different solutions. Communicate sets (intervals) of possible solutions based on knowledge from exploring the capability of the sets of solutions.
2	Integrate by intersection	Integrate subsystems by using sets of solutions that have overlapping feasible regions. Abandon the least feasible solutions.
3	Establish feasibility before commitment	Always explore the capability of design solutions and assure that the solution is feasible before making commitments towards others like customers, downstream functions etc.

In Set-Based Design, sets of solutions are explored and the least feasible parts of the sets are abandoned as the design process progresses. Feasible intervals of the sets are communicated within the product realization process and narrowed until they have converged towards one solution. This is in contrast to the design methodologies (SE, SD, IPD, TTS) where the most feasible solution is selected from a set of solutions early in the process and then explored. If this solution is found not feasible it is iterated on and another solution is selected. In contrast to Set-Based Design this is often referred to as Point-Based Design. The descriptions of SD and IPD have a more thorough description of the early phases in the PD processes such as planning and identifying the design task and developing the principal solutions.

2.1.6 Waste

Waste is a human activity that consumes resources without creating value. The first definition of waste was given by Taiichi Ohno of Toyota (Womack & Jones 1996) who defined seven types:

1. Defects in production
2. Overproduction of goods not needed
3. Inventories of goods awaiting further processing or consumption
4. Unnecessary processing
5. Unnecessary movement (of people)
6. Unnecessary transport (of goods)
7. Waiting (by employees for process equipment to finish its work or an upstream activity)

Womack and Jones (1996) added to this list:

8. Design of goods and services that do not meet user´s needs

Since waste by its definition is unproductive one objective in LPD is to minimize the amount of it in all engineering processes. The first of Morgan & Likers 13 principles state:

Principle one: Establish customer-defined value to separate value added from waste

2.2 The Engineering Change Process

2.2.1 General

In this thesis engineering changes mean changes made to assembled products that are designed and manufactured in an industrial context. Examples of such products in general are cars, heavy vehicles, rock drilling equipment, automotive components, white goods, airplanes and other mechanical or electromechanical products. Usually the documents or other sets of information which describe the product are modified, which results in a change of the actual product. An example could be that a mechanical component is not performing well and that its design has to be changed to make it perform better. VDA 4965 states the following reasons which regularly motivate the wish to initiate changes:

1. Legislative changes
2. Changes to market conditions or the competitive situation
3. Internal inadequacies in development, planning or manufacturing
4. Quality or safety problems

5. Exploitation of additional optimization potential

When the new design has been decided the documents (drawings, part lists, etc.) describing the new design are communicated to all departments concerned in the company and in particular to departments purchasing and/or manufacturing the product (VDA 4965). Figure 13 shows a flow chart of the EC process according to VDA 4965.

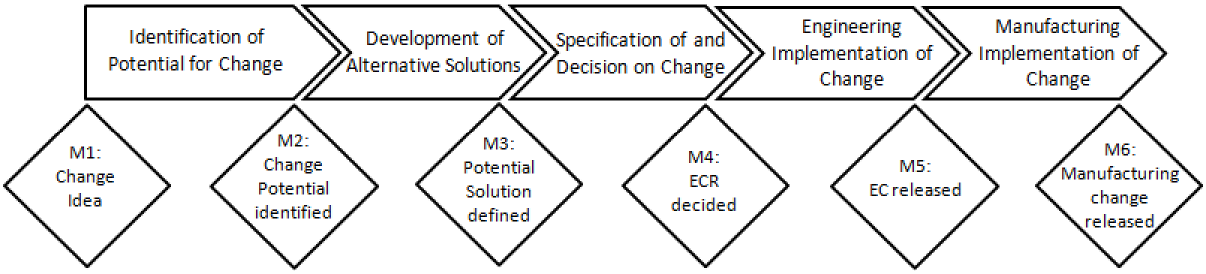

Figure 13. The EC-process. M1 to M6 are milestones of the process.

Engineering changes are sometimes desired and planned but just as often unplanned or unwanted. Typically in cases when the reason for change is either of:

1. Internal inadequacies in development, planning or manufacturing
2. Quality or safety problems

it is likely that that the change is unplanned, unwanted and implemented under harsh time constraints.

In the following sections, the nature of engineering changes will be described and it will be explained why EC needs to be subject to research work.

The engineering change process is often divided into two main phases. These are:

1. Engineering change request (ECR)
2. Engineering change order (ECO)

During the engineering change request phase the reason for change is captured, described and analyzed. The consequences of the change are investigated. If the change is found feasible it is decided to be implemented. In the Engineering change order phase, the documents describing the product are changed and communicated to concerned departments.

The engineering changes process resembles the product development process in many ways (VDA 4965). Table 4 shows a comparison between the main phases of the EC process according to VDA 4965 and the main phases of the SD process of Ulrich & Eppinger (2012).

Table 4. A comparison between SD (Ulrich & Eppinger 2012) and VDA 4965

SD	**VDA 4965**	**ECR**	**ECO**
Planning	Identification of potential to change	X	
Concept development	Development of alternative solutions	X	
	Specification of and decision on change	X	
System-level design	Engineering implementation of change		X
Detail design			
Testing and refinement			
Production ramp-up	Manufacturing implementation of change		X

The difference between the development of a new variant of a product and an extensive engineering change of a product can be subtle. The engineering change process will have a new variant of a product as its output and because of this there are reasons to put the similar demands on the engineering change process as on the product development process

2.2.2 Product complexity and EC

Many of today's products are complex. They often contain a large number of parts based on different kinds of technologies. Products based on multiple technologies will require expert knowledge and multiple view of information to change them and to understand the consequences of the changes (Keller et al. 2005). This, in turn, will increase the number of people affected by the change and needed interaction during the change process. Pure mechanical parts can still be complex if they contain several parts. If a part is used in several product variants or in several different products a change in that particular part might cause changes in several other assemblies. Dependencies between different parts in a product can also cause consequential effects when the part is changed (Eger et al. 2007).

If the product architecture is made up of standard modules with interfaces between subassemblies and modules, it is likely that a change inside a module or subassembly will not affect, or propagate to, other modules or parts of the product as long as the interface of the module or subassembly is unchanged.

If the change propagates to other parts and several parts are affected, which are produced and handled at different sites, the production and logistic facilities at those sites will also be affected.

2.2.3 Consequences of Engineering Changes

As mentioned in the text above, due to dependencies between parts and systems a change can cause undesired consequential effects. A change in one part can propagate to other parts, systems and products.

If the changed part in its changed condition has kept the same fit, form and function as in its previous condition the practice is to classify it as fully interchangeable (SS-EN ISO 11442:2006). If it is fully interchangeable, it is usually sufficient to change its version number and keep the part number unchanged (if the version and part numbers are used in the organization managing the change). If one or several of fit, form or function of the part is affected by the change, the practice is to classify the changed and the unchanged parts as not fully interchangeable. If the parts are not fully interchangeable it is of utmost importance to give the changed part a unique identity that can be used in production and in the logistic flow. This usually means that the part will be assigned a new part number different from the number of the unchanged version. If the part is injection-moulded it can be wise to engrave the part number inside the cavity of the injection moulding tool in order to mark the new part with the new part number. This makes it easier to distinguish the changed part from the unchanged one.

As part of the EC administration work the team managing the EC has to decide about the consequences of the change. Usually a part is changed because of some malfunction or a possibility discovered to improve the part or produce it more cheaply (see above for a more complete list of possible reasons for changes). The consequence of this is often that unchanged versions of the part in the logistic flow and in stock, should be replaced by changed versions. Common practice is that the consequence of the EC can be classified in levels such as those shown in Table 5 (Ström 2008):

Table 5.

Consequence	**Explanation**
Change when suitable.	(Usually) the change will be made when all old versions of the part or material in stock are used up. The old version of the part is working well and the shift to the new part is often done for economic reasons.
Scrap all parts in production and use them as spare parts.	The old version of the part works sufficiently well and can be used as a spare part to replace the unchanged version, but it cannot replace the

Consequence	Explanation
	changed version.
Scrap all parts in production and all spare parts.	This means that it is desirable that no parts of the old version reach the customer. Only the new part should be delivered.
Scrap all parts at the customer’s.	This alternative is used when there is a serious malfunction of the part. No more parts should be delivered to the customer (often an OEM). The supplier has to collect all old parts at the customers and scrap them.
Recall all parts delivered.	This alternative is used when the malfunction of the part is so severe that it can cause serious damage and jeopardize the health of the user.

The logistic flow has to be managed and the remaining stock dealt with. If more of the unchanged version of the part is needed for production or as a spare part, the size of the last production batch or purchase order has to be decided.

The change can also affect the tooling and the production equipment. When the change is released the team managing the change must decide if any changes to equipment or tools are needed.

From the above it can be concluded that the EC-process has an impact on

1. The environment of the product subject to change such as logistic flow and production
2. The design of the product and consequently quality and cost of the product
3. The time to market of the product

According to Ulrich and Eppinger (2012), characteristics of successful product development are

1. Product quality
2. Product cost
3. Development time
4. Development cost
5. Development capability

It is obvious that the performance of the EC process is likely to affect the characteristics of how successful the product development activities are of an industrial firm.

This fact, together with the resemblance of the EC process to the product development process and the resulting impact on the product development activities justifies that research is carried out on how to better perform ECs and use similar (LPD) principles for control and improvement as are used for the PD-process.

Table 6 contains an elaboration on some of the problems often associated with ECs and why means of lean product development can probably mitigate them.

Table 6. Problems in the EC process motivating research on how LPD can be used to improve the situation.

Problem	**Components of LPD that are expected to mitigate the problem**
ECs due to ill performing products in the market represent, in some cases, the voice of the customer.	In lean product development, customer value shall be defined to separate value adding activities from waste.
ECs are often made late in the product development process and are in that sense a potential reason for delay of the launch of the product.	In LPD the design space shall be thoroughly explored while there is time. If that is not done, it is likely that a less feasible solution is selected close to the launch of the product.
Late execution of ECs means that they have to cope with dependencies inside the product and to the environment of the product such as manufacturing equipment created in the proceeding parts of the development process.	Same as above and also cross functional integration in the work force and visual communication is important to enlighten dependencies affecting the outcome of the EC.
If an EC is not synchronized with the PD project affected by the EC, the overview of the PD project is lost, potentially resulting in cost, lead time or quality problems.	The same lean principles applicable to PD-projects are probably applicable to the EC process. Synchronization by using visual aids for communication is probably worth investigating.

The above-mentioned reasons motivate an investigation into the lean principles of Morgan & Liker (2006) to find out if they can be used as a guide to improve an EC-process.

3 Research approach

Research in product development can be carried out in many different ways. Product Development is a highly multidisciplinary domain (Blessing & Chakrabarti 2009) and to try to find a general method that supports efficient research in this domain as a whole is a task too difficult to incorporate in this work. The type of product development that we focus on has to be described in order to be able to narrow down the number of research methods that are reasonable to choose from. The technical framework in Chapter 2 of this thesis frames the part of the total product development domain that we focus on. Also, the delimitations in Chapter 1.2 state that we focus on development of assembled mechanical and electromechanical products which are characterized by containing physical parts made of different materials and sometimes also electromechanical subsystems.

With this view on product development, the type of research methods can be narrowed down. When searching for methods some of them stand out as being more tested, more established and also being subject to scientific review. The following methods were found to fulfil these criteria:

1. Design Research Methodology (DRM) by Blessing and Chakrabarti (2009)
2. Scientific Work Process by Jörgensen (1992)
3. Case study research by Yin (2009)
4. Action research
5. Process mapping by Ström (2008)
6. Literature surveys
7. Interviews
8. Questionnaires
9. Other methods for data collections
10. Transcription of interviews

The process mapping method FLEXmap (Ström 2008) was developed and described to have a tool suitable for the mapping of engineering processes. It evolved from work in several projects. FLEXmap was described in a report (Ström 2008) in conjunction with the work on papers A, B and C as a means of communicating how to use FLEXmap.

In the following these methods are briefly described.

3.1 Design Research Methodology (DRM)

The intention behind this methodology is to help researchers to become more efficient and effective. DRM has a clear focus on acquiring knowledge on how to be more successful in designing products. The design of industrial products is a complex and multi-faceted activity. Several different methodologies, not geared towards product development, were used to carry out research in this domain, causing a risk of poor validity of the results (Blessing & Chakrabarti 2009). DRM was created to minimize this risk and provide a reliable method dedicated to research in product development. The main components of the DRM framework are (see Figure 14):

1. Research Clarification, RC
2. Descriptive Study I, DS I
3. Prescriptive Study, PS
4. Descriptive Study II, DS II

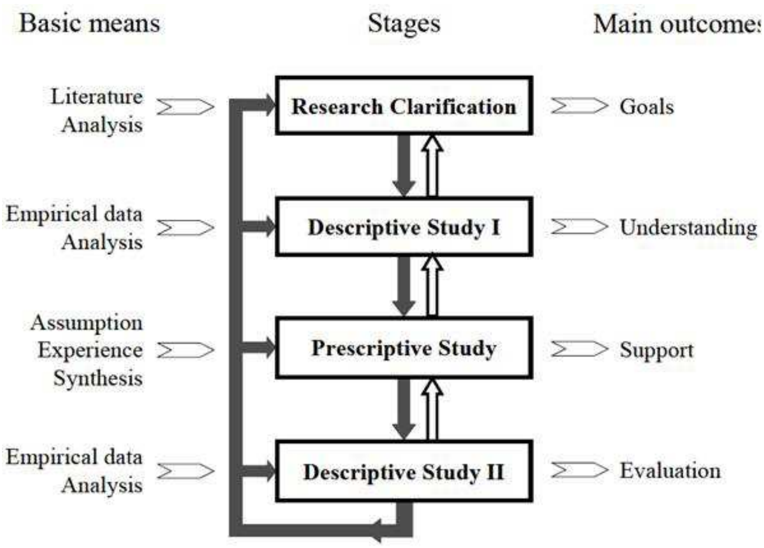

Figure 14. The DRM framework.

In the RC the research work is prepared and clarified. The researchers set the goals and focus of the research. Research questions and hypotheses are formulated and other preparatory measures are undertaken. In the DS I stage relevant literature is reviewed and the current situation is investigated to achieve a better understanding of what has an impact on the situation that we want to improve. In the PS stage supporting measures of the current situation are developed based on the findings from DS I. Also means and plans on how to evaluate these measures are developed. In DS II the suggested measures from the PS stage are evaluated and necessary improvements of the supporting measures are suggested (Blessing & Chakrabarti 2009). As indicated by the arrows in Figure 14, iterations can be made between the different stages in the DRM model to develop better support in the PS stage and evaluate this in the subsequent DS II stage.

3.2 Scientific Work Paradigm

The approach of the Scientific Work paradigm (SWP) is divided into two consecutive parts. The first part is a research part and the second part is a development part. The research part has two flows; one problem oriented and one theory oriented (see Figure 15). The problem oriented flow starts with an empirical study and analysis of a problem resulting in a diagnosis followed by a synthesis resulting in new scientific insights. The theory oriented flow starts with a synthesis of pieces of theory into a model. The model is then analyzed regarding validity, consistency and usefulness resulting in scientific insights. In the development part scientific insight from the two flows are combined in a knowledge transfer activity where practical results are assumed to be achieved through implementation.

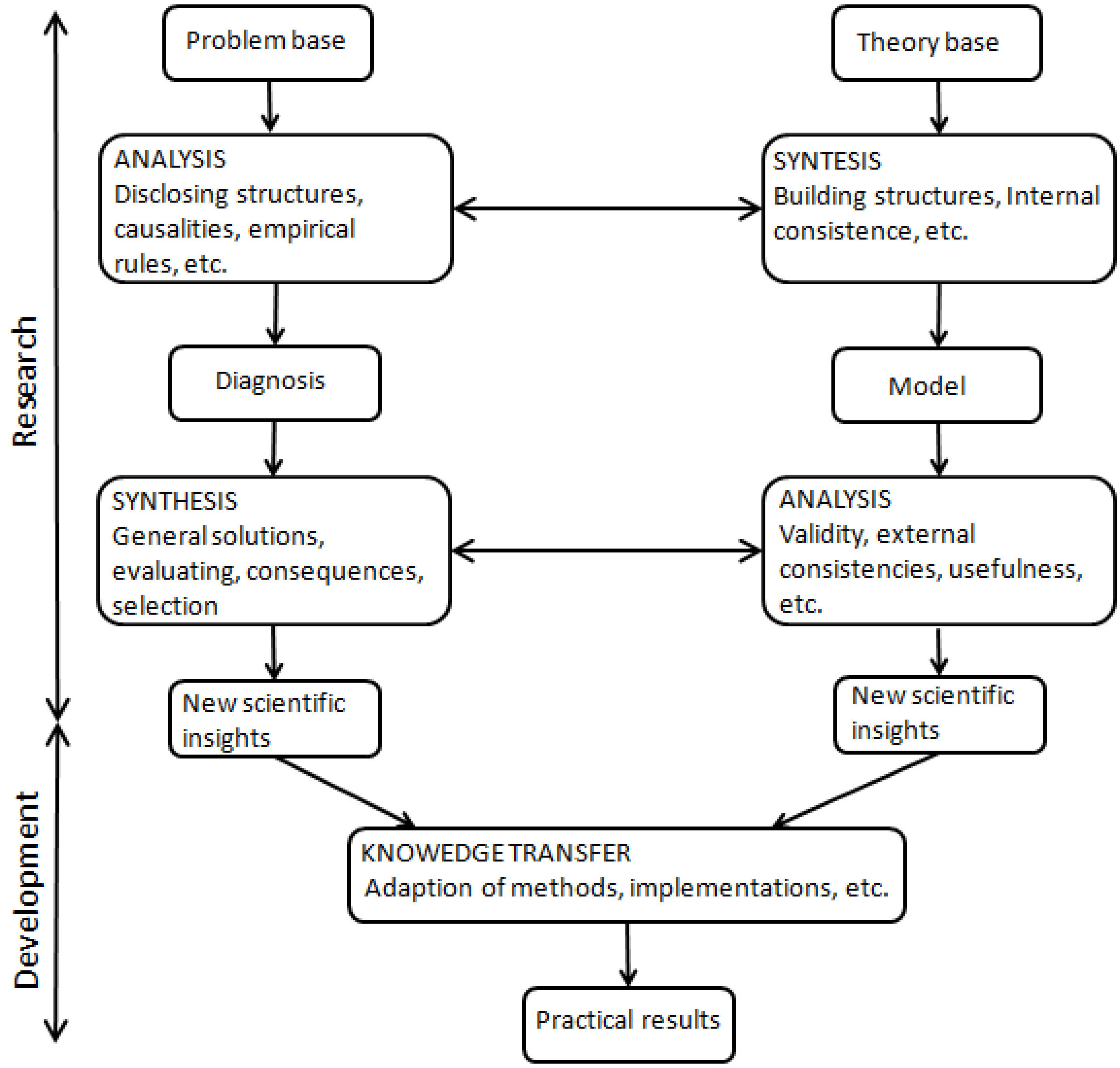

Figure 15. Scientific work paradigm (Jörgenssen 1992).

3.3 Case study research

A case study is an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context. Often the boundaries between phenomenon and context are not clearly evident. The case study methodology is suitable to study technically distinctive situations in which there will be many more variables of interest than data points. To support the results of a case study, multiple sources of evidence are used. As data is collected the results of a case study shall support a converging conception of the phenomenon studied. The study, data collection and analysis are often guided by a theoretical proposition developed prior to the study.

Case studies can be a multiple case study investigating more than one case of similar nature or a single case study investigating only one case (see Figure 16).

Some common components of a case study are:

1. Research questions to be answered
2. A study proposition (similar to an anticipated result of the study)
3. Unit of analysis
4. Logical links between data that will be collected and the anticipated result of the study
5. Criteria on how to interpret the collected data

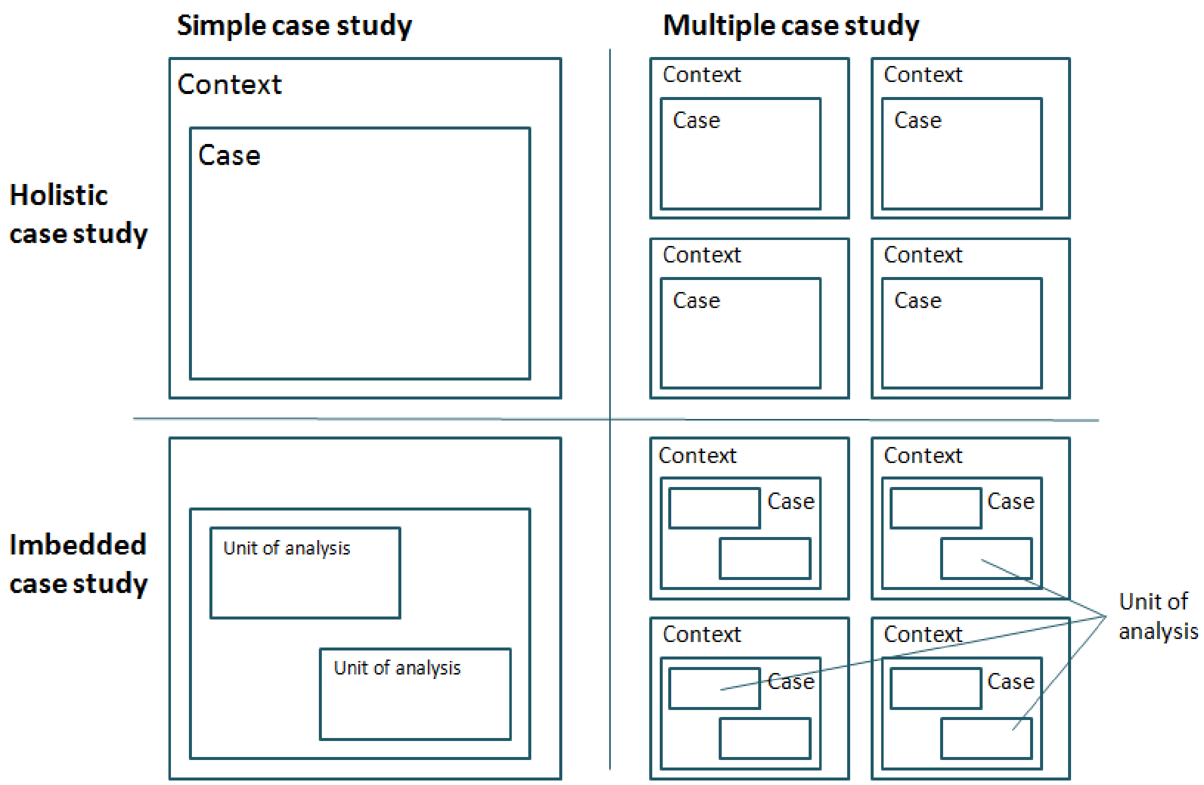

Figure 16.*   *Principle view of different variants of case studies.

Prior to a case study the literature is often consulted to provide a framework for a theoretical understanding of the cases. The framework can be of help when interpreting the collected data in the case study and when formulating the study proposition.

3.4 Action research

Action research is an approach where the researcher participates in the action subject to research in contrast to many other approaches where the researcher is required to have a detached role as an observer (Williamson 2002). Action research is done in a cyclic manner. The researcher participates in an action part of a process and collects data to be analyzed from the same process. The action research cycle can be described as in Figure 17.

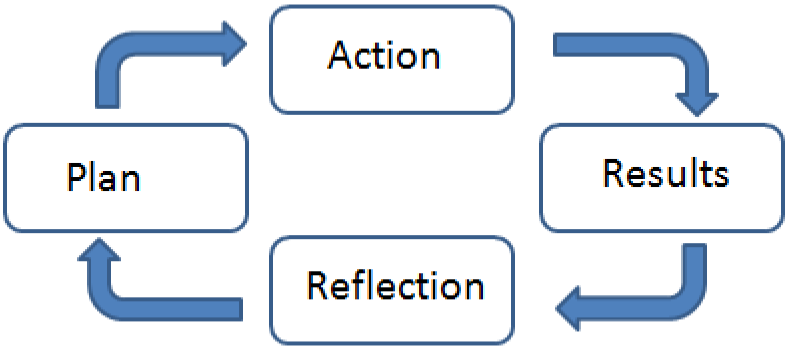

Figure 17. The Action research cycle (Williamson 2002).

Action research is suitable for exploratory research to test solutions to practical problems and gain knowledge at the same time. Action research shall be seen as a means for building transferable knowledge rather than generalizable knowledge.

3.5 Process Mapping

When studying an empirical environment having business processes or work processes as significant constituents, it is suitable to use some kind of process mapping method. This can be the case when using a framework based on either DRM or SWP. Several types of process mapping methods exist. Examples are IDEF0 (Integration Definition for Function modeling 1993), Value Stream Mapping (Rother & Shook 1993), Activity Diagrams (UML 2.1.1) and many more. The method used in this work is the FLEXmap method of Ström (2008). Figure 18 shows an example of a map of an integrated view of a section of an EC process created using the FLEXmap method. FLEXmap has views for Activities, Information, Organisation and an integrated view where all the other views come together. The graphical syntax has support to document times in the process and resources used. The method is implemented in MS Visio.

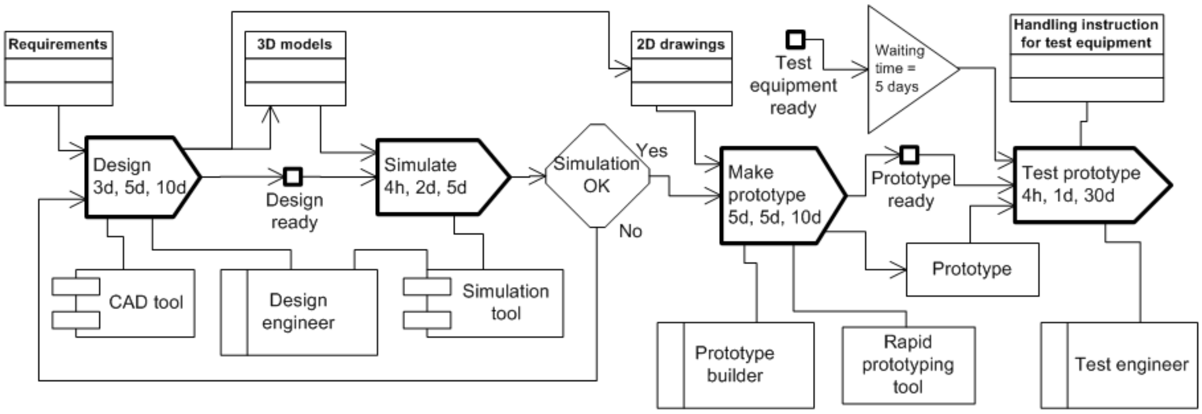

Figure 18. The FLEXmap method developed by Ström (2008), h = hours, d= days.

3.6 Interviews

Interviews can be of different kinds, for examples structured, semi structured and unstructured (Williamson 2002). Structured interviews are suitable when answers shall be compared. In structured interviews all respondents are asked the very same questions in the same order, and it is like a questionnaire conducted as an interview. Semi structured interviews also have a list of prepared questions, but the interviewer is allowed to add questions depending on the answers. In an unstructured interview, the next question is simply generated from the previous answer. Unstructured interviews are therefore suitable for explorative research.

3.7 Questionnaires

Questionnaires are a subtype or tool to carry out surveys. Surveys can be either descriptive or explanatory. One type of questionnaire used in this work to support a descriptive survey is shown in Figure 19. In the leftmost column in Figure 19, worst case scenarios are described from different perspectives, and in the rightmost column there are descriptions of an ideal situation (in this case the project execution process at a firm). In the middle there are five columns representing the current state and the desired state. Respondent's mark how they experience the situation today corresponding to the current state and how they think it ought to be corresponding to the desired state. All answers are summed up and shown as hand drawn histograms for each level. Unfilled staples make up the histogram of the current state and dashed staples make up the histogram of the desired state. Each questionnaire sheet is designed to penetrate a certain topic. The sheet in the figure is designed to support the study of the project execution process. Different sheets can be used for different topics. The sheets are typically posted on the walls of a meeting room and the respondents can walk from one sheet to the next and put their answers on them. When all answers are in, they are summarised and the histogram is drawn by the respondents themselves. We call this a "live questionnaire".

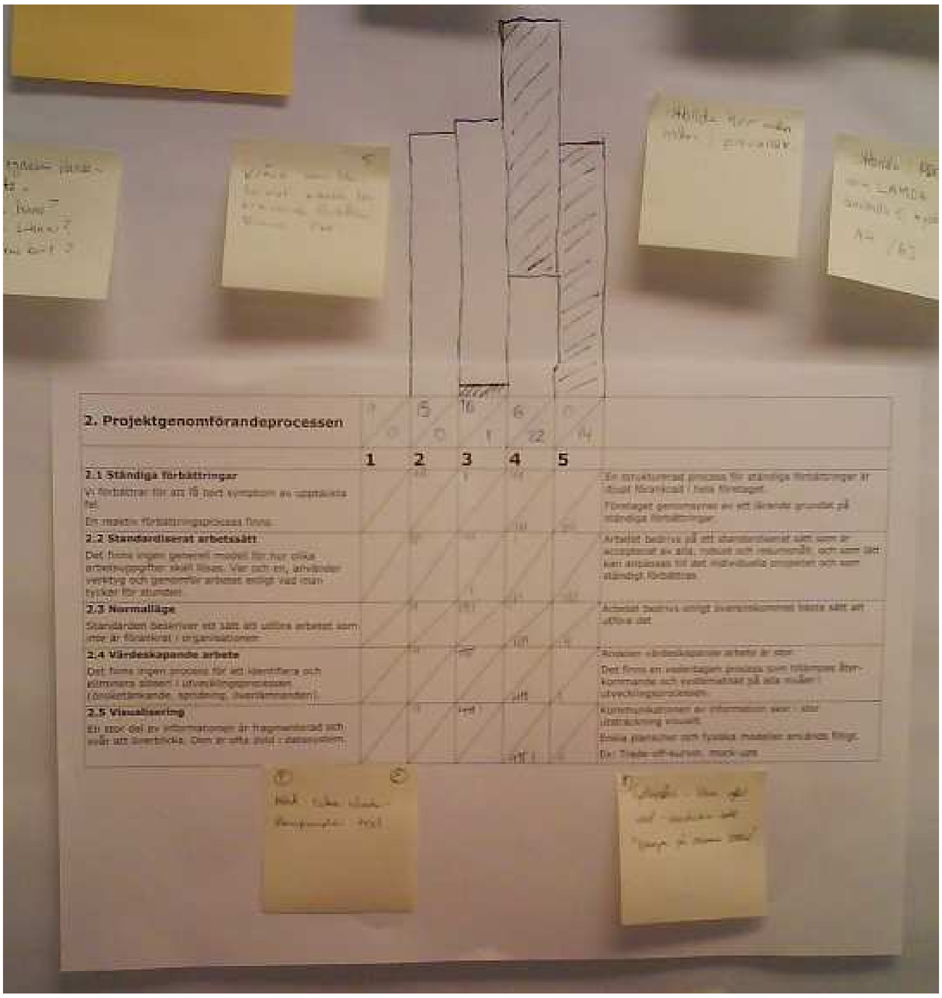

Figure 19. The result from a "live questionnaire". Sticky notes in the figure are suggested measures to achieve the desired state.

Instead of posting the questionnaire on the wall, it can be presented to the respondents in a traditional way on A4 paper size to be filled in sitting down at a desk. The answers can be summarized, analyzed and presented as histograms or spider charts (see Figure 23) by using an office based calculation software. We call this a “traditional questionnaire”.

3.8 Other methods for data collection

Data was also collected through observations on site, by participating in meetings as an observer, collection of narratives such as documents of different kinds, copies of e-mails, records in databases and notes in diaries.

3.9 Transcription and computer assisted analysis

Interviews can be recorded with e.g. a tape recorder or similar device. It can then be put in writing to provide easy access for different purposes. This process is often referred to as transcribing (Bryman and Bell 2007). The transcribed interviews can be analysed using computer tools, to sort the content according to different schemes (Yin 2009) for detection of patterns, relations etc within the transcribed speech. The final analysis still has to be done by the researcher (Yin 2009).

3.10 Course of studies

Below follows a description of the relations between different studies, papers and firms used as study objects.

3.10.1 The relation between firms and papers

The studies in this thesis are described in papers A, B, C and D, and they were carried out at the following firms (see Table 7):

Table 7. Studied firms and their type of production.

Firm	**Type of operation**
A	Supplier to the automotive industry. Designs and manufactures vehicle components such as gear shifters, seat heaters, cables, drive line components etc. in series production.
B	Designs and manufactures mechatronic products such as measuring instruments, optical media devices (e.g., offline quality assurance testers) in series production.
C	Manufactures rock drilling equipment in short series.
D	Designs and manufactures made-to-order special purpose trucks in short series
E	Supplier to the automotive industry. Designs and manufactures vehicle components, mainly tubing and hose components, in series production.

The involvement of the firms in the studies described in paper A – D is shown in Table 8.

Table 8. Studied firms versus published papers

Firm \ Paper	**A**	**B**	**C**	**D**
A	X	X	X	X
B		X	X	
C		X	X	
D		X	X	
E				X

Data regarding the firm in paper A is input to paper B and C. The study in paper D is independent of the work of the other papers, with the exception that the status of firm A before the transfer to lean product development is to a large extent mapped in the work of paper A.

3.10.2 Methods used for papers A, B and C

Paper A is a single case study of firm A. It was started before the studies of firms B, C and D commenced. At the end of the study of paper A the studies of firm B, C and D were started as a multiple case study. In this study parts of the results of the study of paper A were included since the scope of the studies was identical. The results from the multiple case studies (including firm A, B, C and D) were used in paper B and C.

The DRM and SWP methodologies, and in particular the former, can be used as a framework for the course of the studies. The SWP framework was only partly used in the synthesis of the LIM model in paper C. In Table 9, DRM is displayed as a framework, and the other methods are placed at the steps where they belong. The papers (A, B and C) are listed in the rightmost column of Table 9.

Table 9. Employed methods in papers A, B and C within the DRM framework.

DRM step	**Used methods**	**Paper**
Research clarification	Literature survey and preliminary screening of the problem	A, B, C
Descriptive study one	Process mapping, interviews and exploratory single case study.	A
	Process mapping, interviews, traditional questionnaire and exploratory multiple case study	B, C
	Transcription and computer supported analysis	
Prescriptive study one	Synthesis of a model of the EC process, connected information model and implementation in PLM. The lean principles were used. Program to educate users of the new EC tools. Work done in an Action research manner.	A
	Analysis to test the lean principles against the discovered problems in the EC process	A, B, C
	Synthesis to create the Lean Information Model	C
Descriptive study two	The use of tools was studied and reflected on	A
Prescriptive study two	Improvements were implemented in the EC-process and in the Product Lifecycle Management (PLM) system	A

DRM step	Used methods	Paper
Descriptive study three	The use of tools was studied through interviews	A

After the study in paper A the author of this thesis had close contact with firm A by participating in a training program in LPD there carried out by a consultancy firm.

3.10.3 Methods used in paper D

The work of paper D was done after the work of paper A, B and C. It is a two case study of two automotive suppliers. An explanatory study of the transformation process to LPD at firm A was made, and the coaching during the transformation process was done by the firm's own personnel. At the other firm (firm D) the research team served as coaches during the transformation process and was highly involved in it in an action research manner. The used methodology framework and methods of paper D are described in Table 10.

Table 10. Methods used at one of the case firms in paper D

DRM Step	Steps in the action research loop	Method used
Research clarification		Literature survey and preliminary screening of the situation at the firm.
Descriptive study one		Live questionnaire, interviews and exploratory case study
Prescriptive study one	Action	Education in lean product development and suggestion on how to implement.
Descriptive study two	Results and reflection	Interviews, demonstrations of implementations by the personnel at the firm and exploratory case study
Prescriptive study two	Plan and action	Advice on site on how to adjust the implementation
Descriptive study three	Reflection on results	Interviews, demonstrations of implementations by the personnel at the firm and exploratory case study

3.10.4 Reasons for used research methodology

For all papers a literature survey was used to get access to previously published work.

Paper A: This paper describes the redesign of an engineering process. The study was carried out as a single case study, because this was:

1. A suitable method for studying contemporary phenomena
2. A suitable method for answering 'how and why' questions related to the study
3. Suitable for incorporating data collection methods such as observations, process mapping, interviews, collection of narratives and participation in meetings

The process mapping metod FLEXmap (Ström 2008) was used to get a picture of the process subject to redesign, because:

1. Process mapping was found suitable for building a current state map and also a future state map of the EC process
2. The process maps were a convenient means to communicate both the current and the future state of the process
3. The process mapping method can document lead time data which came in handy as part of the study was to explore lead times during the EC process

As part of the process mapping, several unstructured and semi structured interviews were conducted as a complementary method for data collection. The reasons for using semi structured Interviews were that:

1. The preparation work of semi structured interviews assured that the interview resulted in the answers needed.
2. The possibilities to add follow up questions, since answers to one question lead to new questions.

Narratives such as e-mails, records in administrative systems, process descriptions and diary notes were collected since:

1. They were an excellent means to determine when in time steps were taken in the mapped process

The redesigned process was communicated to the firm through an extensive education program by the researcher before the final evaluation of the results. This step included action research. The reasons for using this were that:

1. It was suitable at this stage because it allowed the researcher to observe the implementation of new tools, draw conclusions, learn from observations and suggest improvements at the same time.
2. Improvements of the new EC process could be made in each iteration between education occasions, allowing for new observations on how the improved process was received by the users.

Paper B and C: The engineering change process was studied in four firms. For this purpose a multiple case study was found suitable (Yin 2009) to answer the question how and why engineering changes are performed. The reasons for using a multiple case study were that:

- It is suitable for answering ‘how and why’ questions
- It offered good possibilities to compare results from the cases. Cross case checks could be made to assure validity to some extent
- Tools such as process mapping, traditional questionnaire, and interviews were used for data collection in the case studies. Multiple sources of information made it possible to triangulate from data and draw more secure conclusions

Paper C: This paper uses the same data as paper B. The paper has a synthesis where an innovative solution is suggested. For this reason parts of the SWP framework by Jörgenssen (1992) was used since it supports synthesis based on previous analysis and theory. The path of this framework was very suitable for this synthesis.

Paper D: This paper has an ambition to describe and compare the transformation process to lean product development of two similar, but also contrasting, cases. To answer the question how LPD can be introduced and what experience is gained, a multiple case study was found suitable (Yin 2009). The reasons for using that were that it:

1. Offered good opportunities to compare data and draw conclusions
2. Allowed the researchers to get close to the firms subject to study
3. Offered a possibility to study contemporary phenomena at the firms

Data was collected through a live questionnaire. The reasons for using this were that:

1. The questionnaire is very transparent to all respondents
2. The analysis and the results are instant and transparent for all respondents.
3. The instant results encourage the respondents to go along with the intention of the research work.
4. The results from the live questionnaire shows areas having a potential for improvement
5. The results from the questionnaire served as a good starting point for the coaching activities in the study

Action research activities were used at one of the firms, because:

1. They offered a good way to get close to the firm and introduce improvements and follow up the results
2. New knowledge could be taught to the people at the firm involved in the study

Semi structured interviews were carried out to collect data. The reasons were that:

1. They offered a good way to follow up the implementation of LPD at the firms
2. They could be used during the coaching event when there was time available
3. The possibility to ask follow up questions was a natural way to deepen the data collection

4 Results

In the following, the results of all studies performed are summarized and described in four papers that are attached to this thesis as appendices A-D. The results are described paper by paper. At the end of this chapter there are some comments on them.

4.1 Paper A: REDESIGN OF THE ENGINEERING CHANGE PROCESS OF A SUPPLIER IN THE AUTOMOTIVE INDUSTRY

This paper describes the research conducted on the redesign of the engineering change process of a tier one supplier in the automotive industry. The results are divided into three main sections. These are:

1. Analysis of the situation before improvements were introduced
2. Design of improvements
3. Evaluation of improvements

Section one and section two are intertwined in the sense that the sequence of the new, improved process is compared with the process map of the state before improvements were introduced. The aims of paper A as described in the paper are to:

1. Provide empirical data on the engineering change process in a firm
2. Evaluate the applicability and utility of waste and lean product development principles when redesigning an engineering change process
3. Evaluate the benefits of automating the engineering change process in a PLM system, essentially to reduce lead-times for information transfer

4.2 Analysis of the situation before improvements were introduced

The analysis section is divided into four parts depending on the approach of the analysis. We use the following approaches:

- Process mapping, interviews and documentation
- Lead-time data analysis
- Categories of waste analysis
- Lean principle mapping

4.2.1 Analysis based process mapping interviews and documentation

The process mapping approach begins with interviewing people working in the process which is the subject of the analysis. From the result of the interviews, a graphical representation of the process was drawn by using a predefined graphical syntax (see Ström 2009).

The results from this analysis are problems in the operation of ECs that are detected by using this approach. The general EC process was mapped as well as three explicit EC issues. In conjunction to the process mapping interviews were carried out and documentation on EC issues was studied. Table 11 lists the problems that were detected.

Table 11. Problems found related to ECM by using process mapping, interviews and EC documentation

No	Problem
A1	Lack of overview of an EC issue affecting more than one part due to a one-to-one relationship between the existing EC document and the changed part.
A2	Communication in the firm made more difficult due to that seven different EC documents were used at different sites of Supplier A for the same purpose
A3	Difficult to coordinate the introduction of parts when several parts are changed
A4	Lack of EC status information due to a lack of formal signal from production when the change was implemented
A5	Lack of visibility of EC status for all involved and affected actors
A6	Time consuming physical handling of documents
A7	A lot of paper work in production even for small changes
A8	Long lead-time for approval of drawings when customers are involved
A9	The use of paper documents imposes a serial manner process instead of a parallel process with shorter lead-time
A10	Information transfer takes time, manual routines are used
A11	No way to capture and reuse knowledge gained in the process
A12	Process was too focused on the release of the change specifications in contrast to a more front-loaded process
A13	The relation to the current process for product development was weak
A14	Unclear roles in engineering change process

The process mapping approach, created as a means for this analysis, was also used in the subsequent analysis.

4.2.2 Analysis based on lead-time data

This assessment was done by looking at the process map of the old informal process created in the preceding data collection. The old process was mapped from start to implementation and closure of the EC with the aim of describing a general case of EC. It was done at one site of the firm. The activities in the map showed signs of the process having 7 sequential phases as shown in Table 12. The map was then brought to a second site where people working with EC issues were asked to scrutinise the mapping. Only one small correction was needed. Lead time data and delays of activities from the old informal process were collected by asking people at the second site working with EC issues to assess the shortest and the longest as well as the average time for each activity in the process.

Lead time data were also collected through retrospective studies of three explicit EC cases (not general as above) completed at the time of this study. Methods employed were interviews, studies of personal agendas and records in the PLM-system. The lead time from the general process and from one of the explicit processes was then plotted in a coordinate system, see Figure 19, with time in days on the vertical axis and the main phases of the old general process in chronological order on the horizontal axis. The design of the new tentative process was based on the same main phases found when mapping the general case.

Table 12. Informal phases of the old general EC process.

Step	**Explanation**
Awareness	Awareness of the need or wish for change
Analysis	Analysis of the consequences of the change
Decide	Decision to implement the change or not
Perform	Implement the change on the documents describing the product
Release	Release the changed documentation, internal release and customer approval of release
Implement	Implement the change in production and/or at supplier including distribution of documentation
Close	Close the issue and document lessons learned

The data collection of lead time data of the general EC process only comprises the first five phases. The collection of lead time data of the explicit EC issue comprised all phases. In Figure 20 only the first five phases are included.

The three cases (shortest, average and longest time, see Figure 20) of the general process are drawn with thin lines and the explicit case is drawn with a thick line. The plot of the longest process differs from the other two general cases. The exceptional increase in lead time during the release phase originates from very slow customer approval activities. The explicit case has an exceptionally long activity during the analysis phase, which originates from a long-time testing activity of a material. This particular material was then taken off the market and was thereafter not available. To be able to process the EC issue, another material was chosen that did not need the same type of testing. In the explicit case it is quite clear that the testing could be classified as waste. Principle one of Morgan & Liker (2006) was violated.

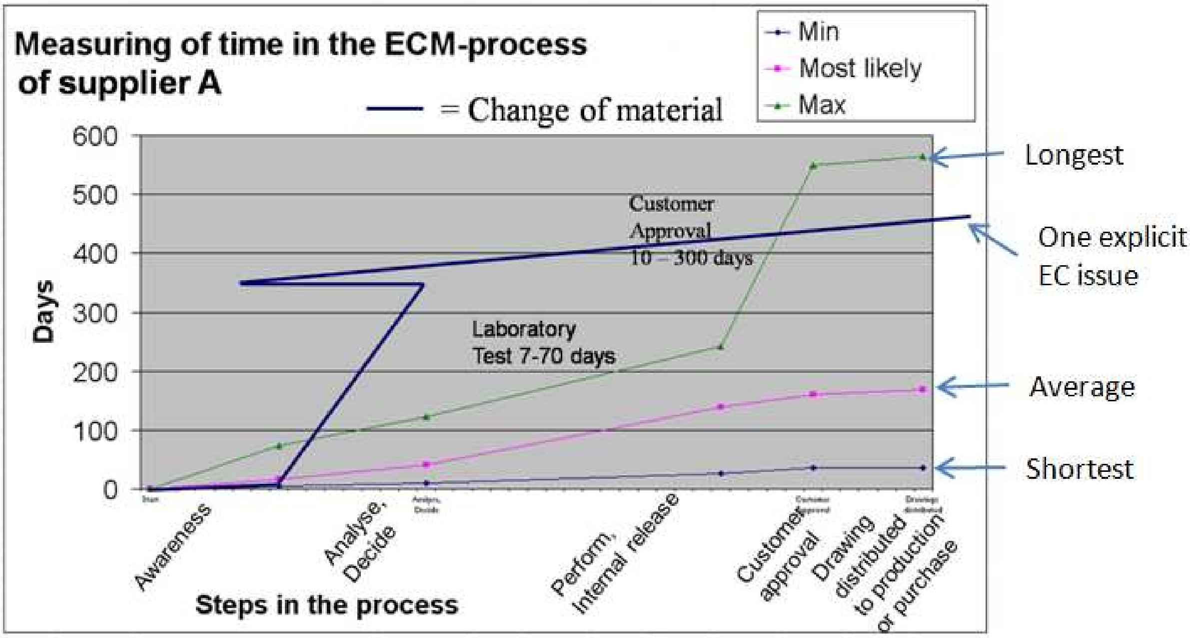

Figure 20. Lead time data of a general case (thin lines) and a particular case (thick line)

The problems shown in table 13 were identified by means of this analysis

Table 13. Problems found related to ECM by using lead time data

No	Problem
B1	Lead times on EC can sometimes be too long due to time consuming testing or late customer approval of drawings
B2	Unwanted rework and loopbacks exist
B3	It is difficult to follow a linear process due to loopbacks

4.2.3 Analysis based on categories of waste

To further penetrate the old EC process the waste categories and waste drivers proposed by Bauch (2004) were used. The following types of waste listed in Table 14 were found in the process.

Table 14. Problems found related to ECM by using waste analysis

No	Problem
C1	Work efforts due to rework
C2	Waiting due to busy people
C3	Work due to process redundancy

No	Problem
C4	Waiting because of poor information transfer
C5	Time spent on finding information about the change
C6	Time spent on unnecessary coordination because of lack of information
C7	Physical handling of documents
C8	Knowledge is scattered and sometimes lost when the EC issue is closed
C9	The EC process was also strongly affected by loopbacks

The waste (C1-C9) was found by comparing detected problems from the subsequent analysis with the waste categories and classifying them according to these.

4.2.4 Analysis based on mapping lean principles and detected problems

In order to better understand how to improve the EC process, the problems found in the investigations were compared with the lean principles of Morgan & Liker (2006). If a principle was violated it was used as a guide to improve the EC process.

Table 15. Problems and imposed changes grouped according to the lean principles

Lean Principle according to Morgan & Liker	Change imposed by the principle	Problem
LP1: Establish customer defined value to separate value from waste	Information shall be gathered in the first step of the process to be able to focus the work on customer value	B2, C1
LP2: Front-load the product development process to explore thoroughly alternative solutions while there is maximum design space	Front load the EC process, use an early analysis, design and test loop	A12
LP4: Utilize rigorous standardisation to reduce variation, and create flexibility and predict outcome	Process steps that are the same or very similar in the EC process and the regular PD process are harmonized. One set of documents is used in the EC process instead of seven different variants of documents	A2
LP6: Organize to balance functional expertise and cross-functional integration	The process description of the new EC process states that a cross functional team shall be part of each EC mission.	A4
LP8: Fully integrate suppliers into the	The process description of the new EC process states that a cross functional team	A8

Lean Principle according to Morgan & Liker	Change imposed by the principle	Problem
product development system	shall be part of each EC mission. This includes the purchase function, which can include suppliers.	
LP11: Adapt technology to fit your people and process	Use some kind of powerful tool to manage ECs. An implementation to support the EC process was done in the PLM system of the firm. A new information model was introduced	A1, A4, A5, A6, A9, A10, A11, C5

The way to draw conclusions from the improvements by contemplating the problems and the lean principles is based on common sense and good engineering practice. The research team discussed each problem and compared the problem with the principles. Each lean principle is of an imperative nature for the organization which is trying to work according to the principle.

The analysis in paper A revealed that the old process was too focused on the release of the change specification. One consequence of this is that the early phases of the EC process were not performed thoroughly. This lead to that the reason for change and the stakeholder behind the requested change were not thoroughly investigated and consequently not always communicated to the designer performing the change and the team approving the change. Because of this lack of the origin of the change, the EC was not always successful. At the time of release of the changed documentation the objective of the EC needs to be known to assess if these objectives were fulfilled by the change and the documentation could be released.

The lean principles 1 and 2 state:

LP1: Establish customer defined value to separate value added from waste

LP2: Front load the product development process to explore thoroughly alternative solutions while there is maximum design space.

Following these principles it is natural to suggest that information shall be collected early in the process to enable an early analysis and a thorough investigation of alternative solutions. This resulted in improvement I7 (see Figure 21).

4.2.5 Design of improvements

The introduced improvements are divided into main improvements, which in turn are decomposed into the sub improvements illustrated in Figure 21.

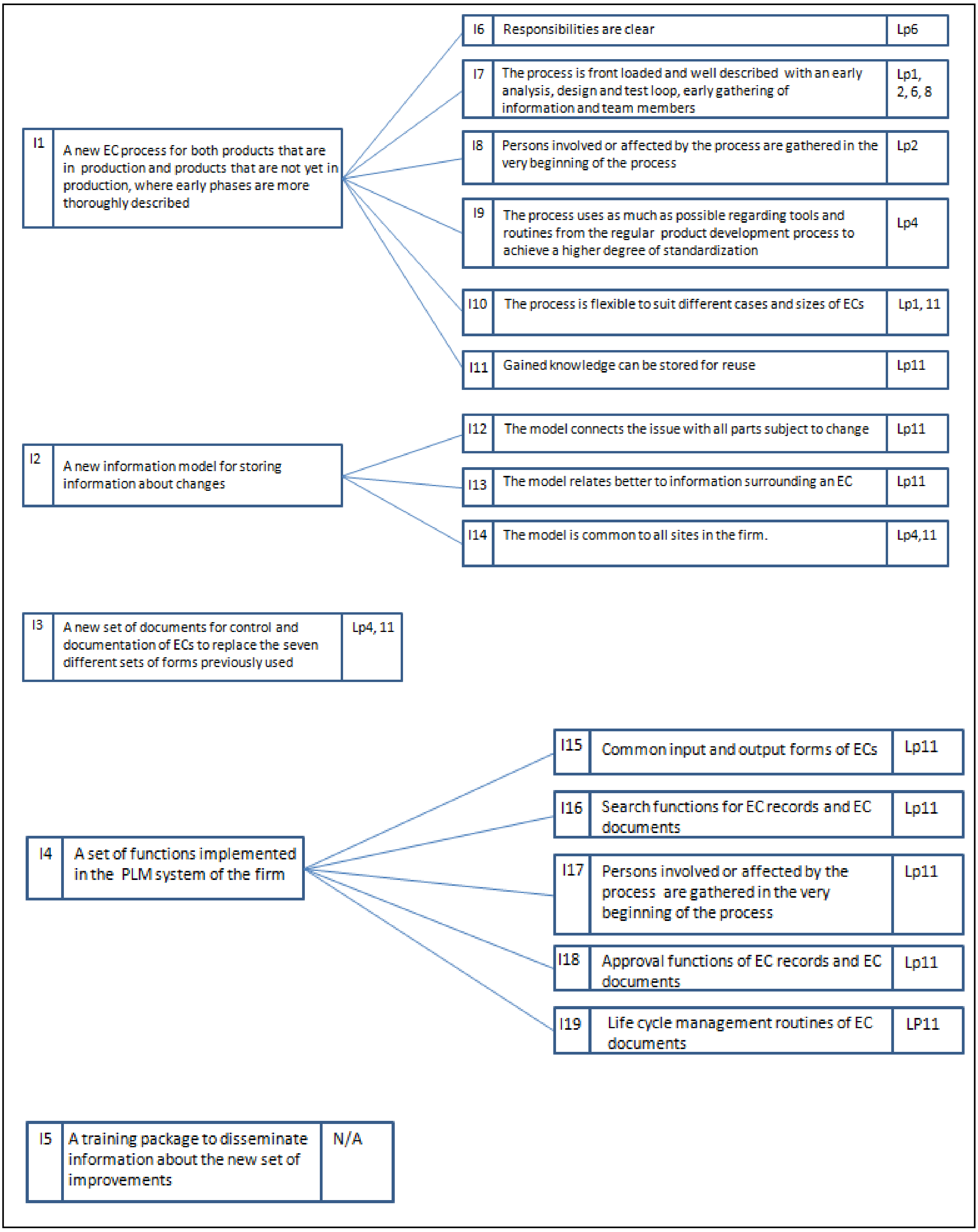

Figure 21. ***Implemented improvements are in the boxes to the left. To the right are decompositions of three of the main improvements. The lean principle imposing the improvement is stated in some of the boxes in the right section***

4.2.6 Experience from use of the new process and the new tools

The new process and the new tools were well received at the firm at the time of introduction and have been used with some success. They provide a better overview of an EC issue, and lead-times for information transfer were also decreased. Some users felt that the new process was more bureaucratic compared with the previous one. The time to release drawings has increased because of lack of skill among managers on how to do this in the PLM system. A conclusion that can be drawn is that the need for education on how to release drawings in PLM was overlooked in the efforts to improve the performance of EC handling.

4.2.7 Lean principles in relation to experienced improvements

Among the principles that are mentioned in Morgan & Liker (2006), principle 1, 2, 4, 6, 8 and 11 are the ones that are most useful in this case. Improvements, experienced by the firm, related to those principles were:

- A better overview of the EC issue and surrounding information
- Decreased time for information transfer

These two features are of fundamental importance in ECM. In Figure 22 the suitable guiding lean principles are connected to the experienced improvements through a chain of the actual improvement measures and in some cases a decomposition of the improvement measures.

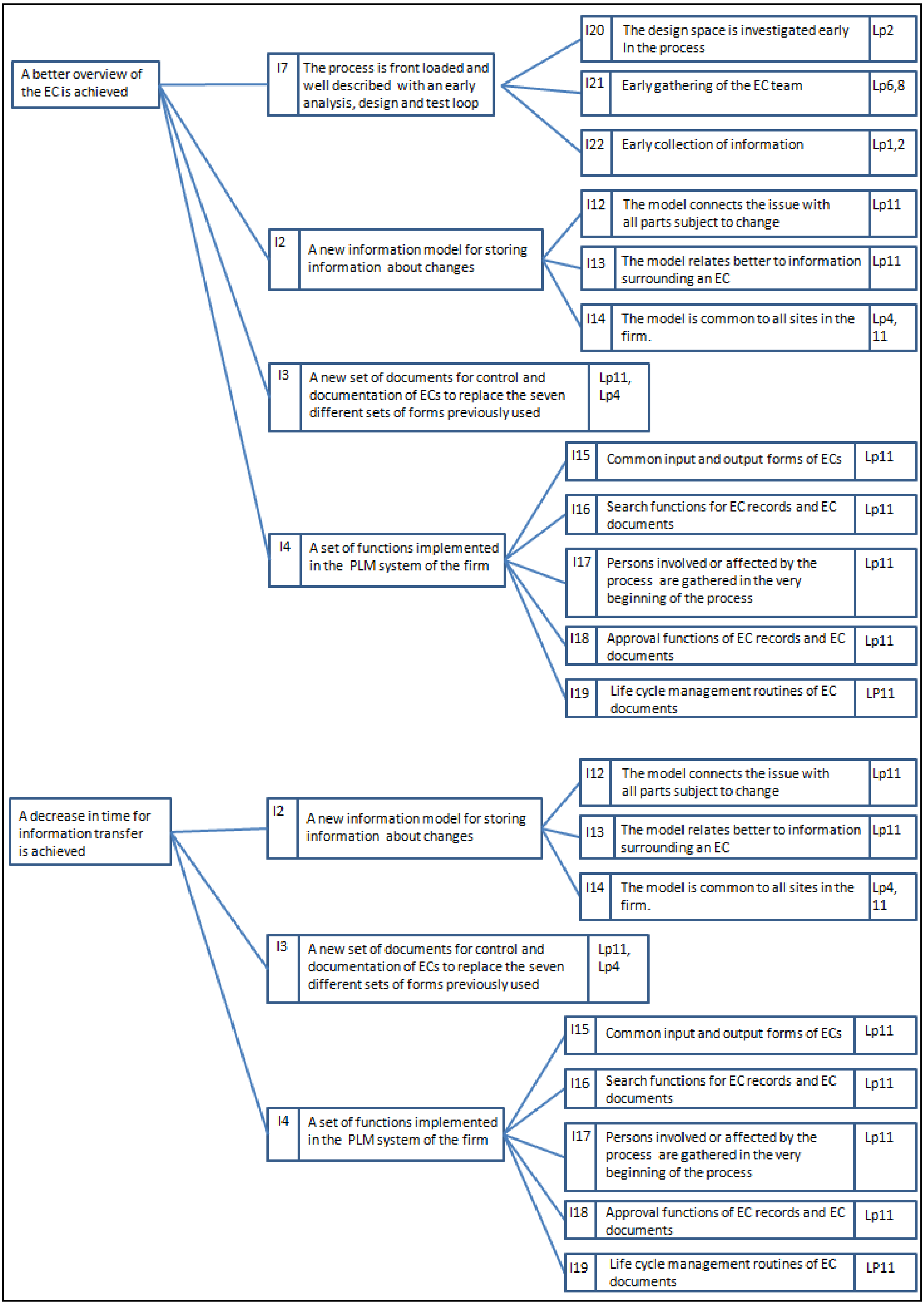

Figure 22. ***The relation between experienced improvements, implemented measures and lean principles. The experienced improvements are the two boxes to the left and improvements are to the right.***

Paper A shows that the lean principles can provide guidance when trying to make improvements in an engineering change process. However, the principles did not explicitly provide guidance to suggest more education for design managers on how to release drawings in the PLM-system of the firm.

4.2.8 Participants from firm A in the study

Process mapping interviews were conducted at the three different divisions of Supplier A. Between 5 and 15 persons were interviewed at each division. The study of lead time data (see section 4.2.2) involved 15 persons from two divisions.

4.3 Paper B: Lean Product Development Point of View to Current Challenges of Engineering Change Management in Traditional Manufacturing Industries

This paper describes a multiple case study of ECM in four firms in heavy machinery, mechatronics and automotive industries in Sweden and Finland. The study includes parts of the results obtained in the study in paper A, which is one of the four cases in paper B. The study in paper A started as a single case study. Later there was an opportunity to extend it to a multiple case study, which was done. The study in paper A was in this way also extended in time (see chapter 3.10.2 regarding research methodology used in this work). The results are obtained using:

1. A self assessment method (see Figure 23) where 18 different parameters of an EC process are studied
2. Interviews
3. Process mapping of EC processes

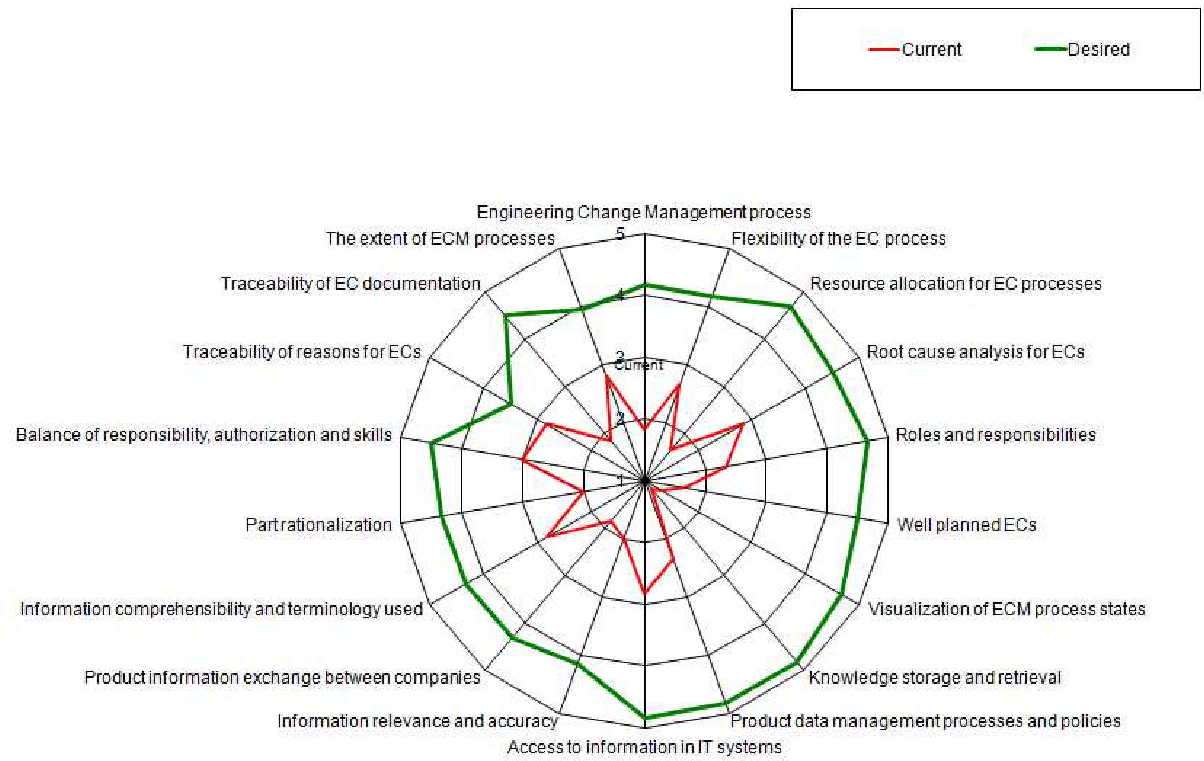

Figure 23. Self-assessment result in one case firm

The self assessment (see Figure 23) shows desired state and current state of the 18 parameters. Current state is the red line (inner, irregularly broken line) and desired state is the green line (outer, irregularly broken line) in the spider chart in Figure 23. The scale on the radial axis is from 1 to 5 beginning in the middle of the spider diagram with 1 and 5 at the outer circumference. The assessment was done as a questionnaire in which the respondents, assigned grades from 1 to 5 for each parameter,. The levels have qualitative descriptions in the questionnaire where level 1 is described as the worst state and level 5 is described as the optimal state regarding each parameter. Each respondent state both the current and desired levels regarding each parameter in the ECM process of the firm where he/she is employed. The average of all answers was calculated and plotted in the diagram. For further explanation please see the methodology section of this thesis.

4.3.1 Analysis of the current situation

In total we found 28 challenges, some of which were common all firms in the study:

1. Roles and responsibilities are unclear – notifying others and reacting to an EC was often delayed, because it was not clear whose responsibility it was
2. Status of the EC process is hard to find – managers were not able to tell the status of ECs related to a product
3. Knowledge storage and retrieval did not work: information about ECs is difficult to find – repeating old mistakes, even if similar problems have been solved before; not knowing the reasons for the ECs makes it impossible to make minor adjustments later on in the process

4. Problems with the usability of the IT tools (PDM system) – ECs were not always documented, but instead handled outside the system. Not documenting the changes results in repeating the same mistakes if similar problems occur later on.

Challenge number 4 above was not classified as such in paper A even though the case firm in paper A was part of the study in paper B. However, the secondary effects of this were detected (see paper A). One example of this is Challenge/problem A6 from paper A: Time consuming physical handling of documents.

In addition to these common challenges, we discovered 24 other issues ranging from poor process discipline to physical transport of paper documents. An example of the three major challenges in each department of one of the case companies is presented in Table 16.

Table 16. Challenges in one case firm divided by department

Department	**Biggest challenges**
Design	1. No time to do EC tasks the proper way – process is not well defined and it is not adhered to because there is an urgency to fix the next problem 2. No time or material for training new employees in the design department 3. Setting the actual date of EC implementation is difficult
Production	1. Not clear who should react on EC notifications and how 2. Poor visibility to the progress of the EC process 3. EC documentation is often omitted because of operative urgencies
After sales	1. Causal connection of the reason for and the consequence of a change is not clear 2. Delivered spare part book, user's manual and machine don't match 3. If a problem is discovered in a machine delivered to one customer, it is not known which other customers have similar machines and should be informed of the problem
Documentation	1. Documentation does not correspond with as-built construction 2. Not clear who should realize whether a change affects user's manuals and how 3. Not clear when ECs are implemented in production

4.3.2 Analysis based on mapping of lean principles and identified challenges

All challenges identified in all case companies were classified according to what lean principle they violated. The principles most often violated were LP1, LP3, LP4, LP11 and LP 12. They were related to Processes and Tools & technology (Morgan & Liker 2006). Principles related to Skilled people were not violated quite as often. One firm, however, found a significant amount of challenge in principle number 5: *Developing a chief engineering system*. A graphical representation of the analysis results is shown in Figure 24. In the figure, there is a pie chart showing to what extent the 13 different lean principles are violated.

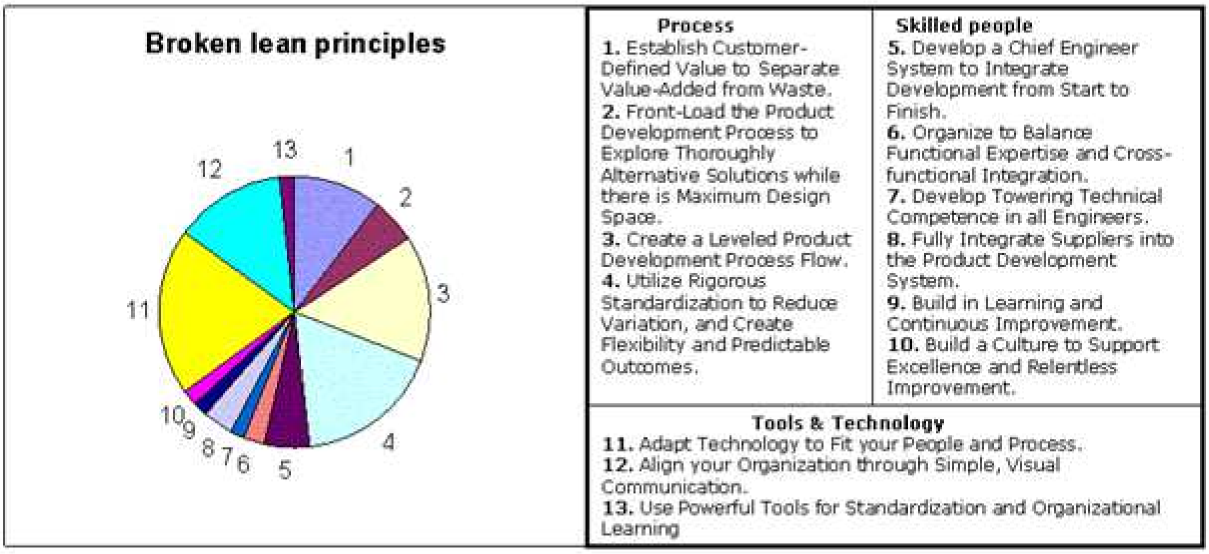

Figure 24. Challenges categorized according to the lean principles (Morgan and Liker 2006) that they violate.

4.3.3 Consequences and implications

The classification of the challenges according to the lean principles provides some guidance on how to best improve the situation regarding ECM in the case firms. The violations of principles 3 and 12 point out the need for some kind of control and communication mechanism that will induce a levelled flow in the EC process as well as provide visual communication. With the results from paper D at hand it is fairly easy to jump to the conclusion that visual planning can be the first feasible step to take. If an introduction of visual planning is successful and frees time, more time can be devoted to PD instead of EC. The next step in a process of continuous improvement could be to fulfil principle 4 by standardizing activities in the EC process and striving for communality at an activity level with the PD process of a firm. The size of the sectors in the pie chart in Figure 24 indicates the need of an improvement of the business process at the firms participating in the study. The first step in such a process could be to fulfil the violated principle having the largest slice in the diagram, provided that this is not too cumbersome to do.

4.3.4 Participants in the study

Forty-two people were interviewed after they had filled in the self-assessment questionnaire, and some additional people were interviewed during the process mapping of the EC process. Table 17 shows the category of the personnel stated for each firm.

Table 17. Type of personnel participating in the study from the studied firms

Firm	**Type of Firm**	**Category of personnel**
A	Supplier to the automotive industry. The firm designs and manufactures vehicle components such as gear shifters, seat heaters, cables, drive	Design (mechanical) Production Purchasing Service & warranty

Firm	Type of Firm	Category of personnel
	line components etc. in series production	Technical documenting
B	Designs and manufactures mechatronic products such as measuring instruments, optical media devices (e.g., offline quality assurance testers) in series production	Design (mechanical & electrical) Production Purchasing IT support Sales
C	Manufacturer of rock drilling equipment in short product series	Design (mechanical) Production Purchasing Test laboratory Project management
D	Designs and manufactures special purpose trucks in short product series and as made-to-order products	Design (electronics, software & hardware) Production Purchasing Service Sales

In one of the companies, the exact duration of two EC cases was measured. For this purpose, another 15 people were interviewed.

4.4 Paper C: Lean Information Management Model for Engineering Changes

This paper has the same starting point as paper B. The same common major challenges among the analysed firms and the same analysis as presented in Figure 24 is used. Paper C further develops the idea of using the lean principles as a means of improving the EC process and associated information management. Some of the 13 lean principles of Morgan & Liker (2006) have an impact on EC management and information management. To better address EC management and information management challenges, the original lean principles of Morgan & Liker were modified. The reason for this was to gear the principles towards the part of the environment in the firm that is supported with IT tools for information management. This way the principles better address the identified ECM and information management challenges. One example of this is the first principle in paper C:

LIM principle 1: Separate value-added from information waste

This is a modified variant of:

Lean principle 1: Establish customer-defined value to separate value-added from waste

In paper C there are 9 modified principles formulated, originating from the 13 lean principles of Morgan & Liker (2006). The principles are of an imperative nature and are used as tools to gear the improvement process. The modified lean principles are categorized into toolboxes for Process, Technical tools and People.

Process tool box

1. Separate value-added from information waste
2. Front load the information exchange process
3. Create a levelled information exchange process flow
4. Utilize rigorous standardization to reduce information exchange channels, establish clear responsibilities and control the transfer of needed information

Technical tool box

5. Support people and processes with adequate technology
6. Use visual communication

People tool box

7. Strengthen teamwork
8. Train employees to be effective informers
9. Strive for continuous improvement

To connect challenges in EC-management and information management with improvement induced by the lean principles, a new model called the Lean Information Management (LIM) model was created (see Figure 25).

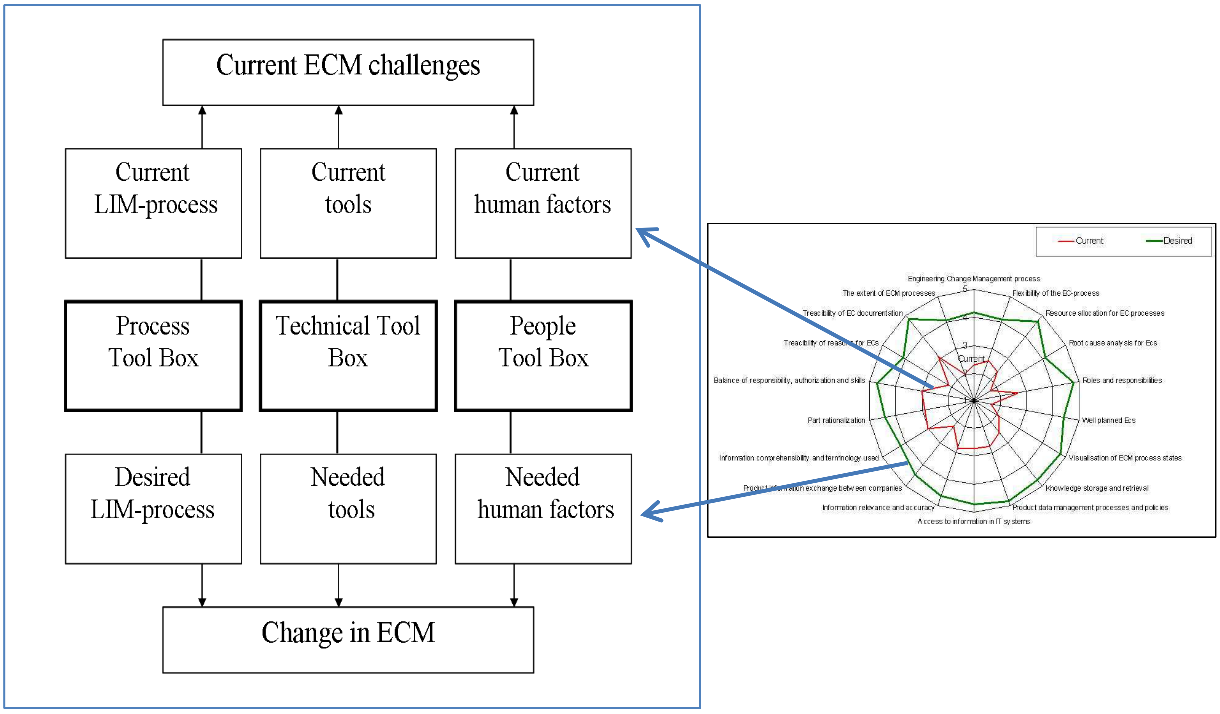

Figure 25. ***LIM model to the left and the spider chart from the self-assessment method to the right. A magnified image of the spider chart is found in paper B and in the chapter describing paper B.***

The tool boxes in Figure 25 contain the modified lean principles. A firm using the LIM model can, when gaining more experience, add this to the tool boxes. The LIM model acts in this way as a storage of experience for process improvement measures.

In order to use the LIM model, the desired state and current state regarding ECM and information management need to be identified. This can be done by using the self-assessment method described in paper B, i.e. process mapping and interviews. The self assessment method identifies the current state and the desired states of the ECM and information management process for ECs. Secondly, the challenges connected to ECM and information management are mapped. One starting point for this mapping can be to utilize the difference between current state and desired state. Thirdly, guidance from the tool boxes can be used to select suitable means to achieve the desired changes in ECM and information management in order to reach the desired state. An example of how the LIM model can be used is shown in Table 18.

Table 18. An example of how the LIM model can be used.

Challenge	**Current tools**	**Tool box of modified lean principles**	**Change in the ECM process**	**Original lean principle**
		Process tool box		
People have to go through irrelevant EC notices	People send the EC notice according to wide mailing lists	Separate value added from waste	Information about ECs is targeted to relevant people	LP1
Manual makers are not informed of EC	Manual makers try to get information about ECs through information channels	Utilize rigorous standardization to reduce information exchange and to control transfer of needed information	Defined role in the EC process: who is responsible for informing manual makers of the ECs	LP4, LP6
		Technical tool box		
Poor visibility of EC progress	EC issues are typically handled outside the system and not documented afterwards	Align your organization through simple visual communication	White board is used for visualizing progress	LP12
Production does not know which component version they should use	No component version information in ERP system	Adapt technology to fit your people and processes	Include component version information in ERP system	LP11
		People tool box		
Setting the time of EC implementation is difficult for an individual designer	Time is set but it often changes and causes trouble	Strengthen teamwork	Create a cross functional team that decides on the date of EC implementation	LP6
ECs are not documented	Performance is not followed	Build in continuous improvement	Go through lesson learned after EC projects. This helps to understand if problems occurred in some other department	LP9

The rightmost column in Table 18 is added to the original version of this table in Paper C. In this column, the corresponding original lean principles according to Morgan & Liker (2006) are added.

4.4.1 Consequences and implications

The LIM model is one attempt to develop the use of lean principles further from the results obtained in paper A and paper B. The idea of using the LIM model as a means to improve the operation of a firm and also store gained experience goes well with lean principle 10: “Build in culture to support excellence and relentless improvement” even though this is not mentioned in the paper.

4.4.2 Participants in the study

The basis of the paper is the same as that of paper B. Participants from the studied firms are described in section 4.3.4.

4.5 Paper D: TRANSFORMATION TO LEAN PRODUCT DEVELOPMENT – APPROACHES AT TWO AUTOMOTIVE SUPPLIERS

To get a broader view of how lean product development (LPD) can be used, two case studies were performed. The introduction of LPD was studied at two suppliers in the automotive industry. Both firms introduced LPD in their PD work.

This study comprises the introduction of the following components of LPD:

1. Customer interest A3s
2. Structured problem solving on A3s
3. Visual planning
4. Integration events
5. Knowledge owners
6. Knowledge value stream

One of the firms used a top down approach to introduce LPD and the other a bottom up approach. This affected the transformation process to LPD. The top down approach represented a stronger larger ambition to achieve change compared to the bottom up approach. The top down approach however, encountered larger resistance to change compared to the bottom up approach.

In conjunction with this study we also made semi-structured interviews regarding characteristic success factors of design projects. The main result from these interviews was that good communication is essential to success in PD in the supply chain of the automotive industry.

Other results were that structured problem solving, A3s, visual planning and integration events are possible to introduce into the operations of the two case companies. To fully establish the “Knowledge value stream” and “Customer interests” on “A3s” is more problematic due to difficulties to get acceptance for this among the engineers who participate in the study. One reason is the lack of time to learn and test the methodology. Some positive results are however noticed.

The corresponding lean principles that can give guidance in a case like this are shown in Table 19.

Table 19. Tested LPD component connected to lean principles.

LPD component	**Success**	**Lean principle**
Structured problem solving on A3s	TP, AC	LP13
Visual planning	TP, AC	LP12, LP11
Integration events	BT, TP	LP6
Customer interest A3s	BT, AC	LP1
Knowledge value stream	TP, AC, DI	(LP7)
Knowledge owners	DI, BT	(LP6), (LP7)

TP = Tests are Promising, AC = Accepted as new working method, BT = Being tested, DI = Difficult to Implement.

Table 19 summarizes the success of the introduction of the lean components. In this assessment TP = “Tests are Promising” means that the component is proven to be successful in practical tests. AC = “Accepted as new working method” means that the component is found feasible and is formally accepted as a new working method, BT = “Being tested” means that the component´s feasibility is tested and DI = “Difficult to Implement” means that the component was tested and difficulties were encountered. Prentices in the right column of Table 19 principles indicate that the lean principle within the brackets provide a weaker support.

How to introduce the role “Knowledge owner” in the PD organisation is not clear. Some attempts were made but without success during the time of the case study.

4.5.1 Participants in the study from the studied firms

From firm D, in total 15 people from design, production, purchasing, marketing and management participated in these studies. From firm A, in total 18 people from functions such as design, software, electronics, management, production, quality, test, production and project management participated. Earlier, the previous PD model had been examined in a single case study involving methods such as process mapping, participating in meetings of best practice groups, conducting semi structured interviews, studying best practice experience records, process descriptions and other relevant documents, conducting a workshop-based questionnaire for self assessment and by assisting during internal training courses. In total 210 people were involved in this study.

4.6 Comments on the results

In this section the results of papers A – D are commented based on a deeper analysis. There are small differences between how IT tools such as PDM systems are used and experienced in the organisations participating in the studies in paper A – D. The result from paper A was that the PDM system helped shorten the time for information transfer and gave a better overview of the EC. In paper B and in paper C, the IT systems are described as not being adapted to suit the people and the processes. Also visual planning is treated differently. In Paper A, visual planning is not mentioned at all whereas it is mentioned in paper C and in paper D. In paper D the introduction and use of visual planning is one of the key findings. This difference between the papers originates from the fact that the case firm in paper A made vast efforts in implementing a global PLM system in their organisation before the study. This system provided means for transfer of information and an overview of an EC issue. There were no similar efforts at the other firms at the time. Due to the existence of the global PDM system at the firm in the study of paper A, visual planning never became an alternative as it did in paper C and paper D. Paper D also included the case firm in paper A, but the study in paper D was done three years later and during the time between these studies the view regarding visual planning was changed at the firm in the study of paper A.

Another observation that can be made is the fact that the lack of competence among design managers to release drawings that was found in the study in paper A indicates that principle 11 was not applied on the technical solution for this purpose.

5 Discussion

In this chapter reliability and validity is discussed, and the research questions and answers to them are described.

5.1 Research questions

RQ1: How do the lean principles match the current problems in ECM?

Paper B shows that seven of the 13 principles could be matched to problems to a larger extent than the remaining 6, but all principles could be matched to some problems found in the case study of paper B.

RQ2: How can the lean principles provide guidance on how to improve an EC process?

In paper A, 23 unique problems were found, and of them 13 could be matched to six of the 13 principles of Morgan & Liker (2006) resulting in an implemented improvement. Even though not tested in this study there is nothing found that speaks against using the lean principles of Morgan & Liker (2006) as guidance to find improvements to mitigate the rest of the detected problems.

RQ3: How can the lean principles provide guidance in a transformation process to LPD?

In the subsequent analysis of the results of paper D, it is shown that guidance on how to implement the following components of LPD could be supported with lean principles: Structured problem solving on A3s, Visual planning, Integration events and Customer interest A3s. The implementation of Knowledge owners and a Knowledge Value Stream could be supported, but the relation to a lean principle was not as obvious as for the other components mentioned above.

5.2 Remaining knowledge gaps

The following are some detected knowledge gaps that were not investigated:

5.2.1 Usability of administrative IT-systems for managing ECs

The following knowledge gaps were detected but not fully investigated in the study of paper A and paper B:

- In paper A it is reported that there were difficulties to release drawings in the administrative system of the studied firm
- In Paper B it was reported that there were difficulties to manage EC in PLM systems

How and if the lean principles can be used to improve the management of ECs in administrative systems such as PLM regarding usability of the administrative system was not investigated. Nor were the IT systems capable of contributing to fulfil all lean principles fully investigated. The reason for not investigating this was that resources for doing practical implementations were limited.

5.2.2 The use of visual aids in the EC process

Visual aids such as visual planning (Söderberg 2012) were not tested as a means of improving the performance of the EC process, because the policy of firm A prioritized other developments of their way of working, at the time of the study.

5.2.3 The capability of the LIM model

The LIM model of paper C remains to be tested in practical applications. The reason for not having done this is limited resources and time.

5.2.4 Mapping of the transformation process towards lean principles

In the study of paper D, all steps of the transformation process and all implemented components were not fully mapped to the lean principles of Morgan & Liker (2006). The purpose of the study was originally to follow the transformation to LPD at the firms participating in the study. In this thesis, Morgan's & Liker's principles are compared with the results of the study but not actively used when the study was carried out. It remains to investigate how the lean principles can be used actively in the transformation process from traditional product development to LPD. The reason for not having done this was the limited time available when the study was carried out.

5.2.5 Longitudinal study of the transformation process towards LPD

In the study of paper D, the transformation process was studied during a limited time. The long time effects of the transformation process to LPD were not studied. The reason for this was the limited resources and time available for the research team.

5.3 Reliability

Regarding papers A, B and C, observations were made by four different researchers. Collected data was scrutinized by all four. Multiple sources of evidence such as interviews, process mapping, and narratives such as mails, data records and process descriptions were used. Published results were reviewed by representatives of the studied firms. In the lead time study of paper A, the results of the process mapping was scrutinized by other representatives of the firm than the ones participating in the mapping. The accuracy of the process maps was found to be very good. The lead time data collected was of a reliable type such as dates on mails, dates of meetings confirmed by more than one participant and dates of records in administrative IT systems. There were no contradictions between the collected data.

Regarding paper D, observations were made by four researchers in one of the cases and by two of them at the other firm. On some occasions there was only one researcher. The latter condition could cause a weaker reliability in this particular case. However, observations were communicated frequently with a representative of the case company which probably to some extent compensated for this fact. The results were reviewed by representatives of the studied firms.

Enough information is provided in this thesis and appended papers to aid other researchers to repeat the studies and compare results.

The above-mentioned circumstances strengthen the reliability of the collected data.

5.4 Validity

Regarding papers A, B and C, data was collected using different methods, and also multiple sources of data were used. The studies leading to these papers were compared in a multiple case study and very little inconsistency was discovered. Key informants have reviewed scientific publications based on the findings. This strengthens the validity of the results (Yin 2009), as does the fact that the problems and circumstances found regarding ECs were similar to the results of many other studies. The results were also found to be supported by other studies (Huang 1999) and Pikosz & Malmqvist (1998). Pikosz & Malmqvist (1998) studied changes of aircraft components, which are subject to rigorous safety regulations. Their work describes a thorough investigation of design solutions which is carried out early in the EC process. This is in line with the improvements suggested in paper A, and it also conforms well with the lean principles. In paper A, the focus is on lead time and in the aircraft case of Pikosz & Malmqvist (1998) the focus is rather on lowering risk. Risk reduction is a clear intention in LPD (Raudberget 2012), and it is also implicitly supported by the lean principles of Morgan & Liker (2006). In the study of Huang (1999), a list of influential factors of ECM is presented. The most significant barriers to successful ECM listed are poor communication and late problem discovery resulting in quick fix solutions. This is very similar to the results of paper A and B. In the studies of Eger (2007) and Keller (2005), the change propagation is highlighted. This is not highlighted in the studies in this thesis, however, it can be seen from the results in paper A that there is sensitivity to unexpected impact resulting in rework. According to Eger (2007), the product development process and its environment should be regarded as a system, involving product, process and people, where impact in one end can cause undesired effects at the other end. This agrees very well with the results from both paper A and paper B, even though change propagation as a phenomenon was not highlighted in these papers. The collected data also have great resemblance with standards describing the EC process (ECM Recommendation Part 0, VDA 4965) and standards describing the document management process (SS-EN ISO 11442:2006).

Regarding paper D, the results were compared across cases in the multiple case study and communicated to key informants. Rival explanations were used. Several individuals at the case firms were interviewed, and in that sense different sources of information were used.

Table 20. Criteria of what is valid design research according to Cross (2007) and fulfilment in the presented work.

Criteria by Cross	**Fulfilment**
***Purposive* –** based on identification of an issue or problem worthy and capable of investigation	**Paper A, B and C:** ECs often have a great impact on the capability of a firm developing and manufacturing products. Lean principles seem to have a potential to be of guidance when trying to improve EC process performance
***Inquisitive* –** seeking to acquire new knowledge	**Paper A, B and C:** Knowledge about the feasibility of lean principles applied on EC is sought **Paper D:** Knowledge about the transformation to LPD was sought. Measures and objectives in the transformation process were compared with the lean principles
***Informed* –** conducted from an awareness of previous, related research	**Paper A, B, C and D:** Studies of research in EC and LPD has preceded the conducted research. Also studies of design theory were carried out
***Methodical* –** planned and carried out in a disciplined manner	**Paper A, B, C and D:** Scientific research methods such as DRM and case studies methodology etc. are used
Communicable - generating and reporting results that are testable and accessible by others	**Paper A, B, C and D:** Four scientific papers have been published

The criteria in Table 20 are fulfilled, which contributes to the validity of the results.

The fact that the results were accepted by representatives of the studied firms also enhances validity. Buur (1990) suggests the following criteria of validity of design theories through verification by acceptance:

- Statements of the theory (axioms, theorems) are acceptable to experienced designers
- Models and methods derived from the theory are acceptable to experienced designers

The dominant portion of firms in the study comes from the automotive, truck and vehicle section of the Scandinavian industry. That, the abovementioned reasons and the fact that the studies mainly concern assembled mechanical and electromechanical products, makes the results valid for these types of firms and products in a Scandinavian context.

6 Conclusion

Given the results mentioned in earlier chapters and the reliability and validity of the results, the following can be concluded regarding the lean principles of Morgan & Liker (2006):

- There is a good match between the problems connected to ECs at the studied firms and the lean principles.
- Lean principles can be used as guidance when improving an EC process in the industrial context of this research.
- There were no contradictions found between improvements of an EC process and the lean principles.
- Lean principle one, six, eleven, twelve and thirteen explicitly and principle seven implicitly support transformation to Lean Product Development at a supplier of mechanical and electromechanical products in the vehicle industry.
- A better overview of ECs and a reduction of the time for information transfer are achieved when an EC process is designed according to the lean principles.

7 References

Andreasen, M. M. & Hein, L. (1987) Integrated Product Development, ISBN 0-948507-21-7, IFS Publications Ltd, Bedford, UK.

Ashby, M. F. (1999) Materials Selection in Mechanical Design, ISBN 0 7506 4357 9, Butterworth-Heineman, Oxford, UK.

Bauch, C. (2004) Lean Product Development: Making waste transparent, Technical University of Munich, Germany.

Bernstein, I. J. (1998) Design Methods in the Aerospace Industry: Looking for Evidence of set Based Practicies, MIT, Cambridge, MA. USA.

Blanchard, B. S. & Fabrycky, W. J. (2006) System engineering and analysis, Pearson Prentice Hall, NJ, USA.

Blessing, L. & Chakrabarti, A. (2009) DRM, a Design Research Methodology, Springer, London, UK.

Boyer, E. H. (1986) Atlas of Fatigue Curves, American Society for Metals, ISBN 0-87170-214-2, Carnes Publication Services, Inc., USA.

Bryman, A. & Bell, E. (2007) Business research methods, ISBN 978-0-19-928498-6, Oxford Univerity Press Inc., NY, NY, USA.

Buur, J. (1990) A Theoretical Approach to Mechatronical Design, Department of Engineering Design, Doctoral Thesis, Technical University of Denmark, Lyndby, Denmark.

Cooper, R. (1994) Perspective, Third Generation New Product Processes, Journal of Product Innovation Management, 11:3-14, Elsevier Science Inc, NY, NY, USA

Cross, N. (2007) From a Design Science to a Design Discipline: Understanding designerly ways of knowing and thinking in R. Michel (ed.) Design Research Now, Birkhauser, Basel, Switzerland, ISBN 978 3 7643 8471 5, pp. 41-54.

ECM-Recommendation Part 0, VDA 4965 - Part 0 Version 3.0, issued Jan. 2010, Verband der Automobilindustrie, Pro-Step IVIP, SASIG, http://www.prostep.org/fileadmin/freie_downloads/Empfehlungen-Standards/VDA/VDA_ECM_Recommendation_-_Part_0__ECM__V2.0.3.pdf , Accessed on 2013-02-20.

Eger, T., Eckert, C. M. & Clarkson, P. J. (2007) Engineering Change Analysis During Ongoing Product Development, ICED´07, 28 - 31, Cité Des Sciences Et De L'industrie, Paris, France.

Garza, A. L. (2005) Integratin Lean Principles in Automotiv Product Development: Breaking Down Barriers in Culture and Processes, MIT, MA, USA.

Hicks, B. J. (2007) Lean information management: Understanding and eliminating waste. International Journal of Information Management 27, p. 233–249. Elsevier Ltd.

Horikiri, T., Keiffer, D. & Tanaka, T. (2008) Oobeya - Next Generation of Fast Product Development, http://leansi.wp.institut-telecom.fr/files/2009/11/Oobeya-article-2009.pdf, Accesed on 2013-02-24.

Huang, G. Q. & Mak, K. L. (1999) Current practice of engineering change management in UK manufacturing industries, International Journal of Operations & Production Management, Vol 19 No 1. pp. 21-37, MCB Univeristy Press.

Hubka, V. & Eder, W. E. (1988) Theory of Technical Systems, ISBN 3-540-17451-6, Springer-Verlag Berlin, Germany.

Integration Definition for Function modelling, (1993) FIPS Pub 183, National Institute of Standards and Technology, USA.

Johannesson, H., Persson, J. -G. & Pettersson, D. (2004) Produktutveckling – effektiva metoder för konstruktion och design, ISBN 91-47-05225-2, Liber AB, Stockholm, Sweden.

Jörgensen, K. A. (1992) Videnskabelige arbejdsparadigmer, Aalborg University, Aalborg, Denmark.

Keller, R., Eckert, C. M. & Clarkson, P. J. (2005) Multiple Views to Support Engineering Change Management for Complex Products, CMV '05 Proceedings of the Coordinated and Multiple Views in Exploratory Visualization, pp33-41, IEEE Computer Society Washington, DC, USA.

Kennedy, M. N., Minnock, E. & Harmon, K. (2008) Ready, Set, Dominate, Oaklea Press, Richmond, VA, USA.

Måhede, D. & Collin, M. (2007) The Use of lean principles in product development, University of Borås, Borås, Sweden.

Modig, N. & Åhlström, P. (2012) Detta är LEAN, ISBN 978-91-86797-07-2, Stockholm School of Economics Institutes for Research, Stockholm, Sweden.

Morgan, J. M. & Liker, J. K. (2006) The Toyota product development system, Productivity Press, NY, NY, USA.

Pahl, G. & Beitz, W. (1996) Engineering Design – A Systematic Approach, Springer-Verlag Limited, London, Great Britain.

Pikosz, P. & Malmqvist, J. (1998) A Comparative Study of Engineering Change Management in Three Swedish Engineering Companies, Proceedings of ASME DETC 98, Paper No DET99/CIE-9006.

Raudberget, D. (2012) Industrial Experience of Set-Based Concurrent Engineering – Effects, results and applications, Licentiate Thesis, Chalmers University of Technology, Gothenburg, Sweden.

Rother, M. & Shook, J. (1998) Learning to See - Value Stream Mapping to Add Value and Eliminate Muda, The Lean Enterprise Institute.

Scheer, A. W. (1999) ARIS-Business Process Modelling, Springer Verlag, Berlin, Germany.

Siyam, G., Kirner, K., Wynn, DC., Lindemann, U. & Clarkson, P. J. (2012) Relating Value methods to waste types in lean product development. In: 12th International Design Conference (DESIGN 2012), Dubrovnik, Croatia.

Sobek, D. K., Ward, A. & Liker, J. (1999) Toyota's Principles of Set-Based Concurrent Engineering, Sloan Management Review, 36:p. 67-83.

Sobek, D. K. & Smalley, A. (2008) Understanding A3 Thinking: A Critical Component of Toyota's PDCA Management System, Productivity Press, Boca Raton, FL, USA.

Sobek, D. K. & Jimmerson, C. (2004) A3 Reports: Tool for Process Improvement, Proc. of the Industrial Engineering Research Conference, Houston, TX, USA.

Söderberg, B. (2012) On the Use of Visual Planning in Teams, Chalmers University of Technology, Licentiate Thesis, Gothenburg, Sweden.

SS-EN ISO 11442:2006, (2006) Technical product documentation — Document management, SIS

Ström, M. (2008a) A flexible method for business process mapping – FLEXMAP, Swerea IVF Report 08004, ISBN 978-91-89158-92-X, Mölndal, Sweden.

Ström, M. (2008b) The Engineering change process at a tier 1 supplier in the automotive industry, Swerea IVF-report 08006, ISBN 978-91-89158-94-6, Swerea IVF AB, Mölndal, Sweden.

Suh, N. P. (1990) The Principles of Design, MIT, Oxford University Press, NY, NY, USA.

Ulrich, K. T. & Eppinger, S. D. (2012) Product Design and Development, McGraw Hill Companies Inc, NY, NY, USA.

Unified Modelling Language ver 2.1.1, Object Management Group, www.omg.org. Accessed on 2008-06-10

Ward, A. C. (2002) The Lean Development Skills Book, Ward Synthesis, Inc, Camas, WA, USA.

Ward, A. C. (2009) Lean Product and Process Development, The Lean Enterprise Institute, Cambridge, MA, USA.

Ward A., Liker, J. K., Cristiano, J. J. & Sobek, D. K. (1995) The Second Toyota Paradox: How Delaying Decisions Can Make Better Cars Faster, Sloan Management Review, Vol. 36, No. 3.

Williamson, K. (2002) Learning to see, ISBN 1 876938 42 0, Center for Information Studies, Wagga Wagga, NSW, Australia.

Womack, J. P & Jones, D. T. (1996) Lean thinking: banish waste and create wealth in your corporation, ISBN 0-684-81035-2, Simon & Schuster, NY, NY, USA.

Yin, R. K. (2009) Case Study Research - Design and Methods, SAGE Publ. Inc., Thousand Oaks, CA, USA.