CHALMERS

TOWARDS EFFICIENT PRODUCT DEVELOPMENT PLANNING
- EVALUATION OF TWO METHODS FOR INCREASING UNDERSTANDING OF THE DEVELOPMENT PROCESS

MASTER OF SCIENCE THESIS

BJÖRN RASK
CAROLINE SELANDER

Department of Product and Production Development
Division of Product Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2012

MASTER'S THESIS

TOWARDS EFFICIENT PRODUCT DEVELOPMENT PLANNING

- EVALUATION OF TWO METHODS FOR INCREASING UNDERSTANDING OF THE DEVELOPMENT PROCESS

BJÖRN RASK
CAROLINE SELANDER

Department of Product and Production Development
Division of Product Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2012

Towards efficient product development planning
- Evaluation of two methods for increasing understanding of the development process

BJÖRN RASK
CAROLINE SELANDER

© Björn Rask and Caroline Selander, 2012.

Department of Product and Production Development
Division of Product Development
Chalmers University of Technology
SE-412 96 Göteborg, Sweden
Telephone + 46 (0)31-772 1000

Printed by Chalmers Reproservice
Göteborg, Sweden 2012

ABSTRACT

This master thesis has been carried out at Volvo Aero, a company which is developing aircraft engine components. As in many other product development companies, similar to Volvo Aero, the development process is highly complex due to the high number of involved companies, risk of requirement changes etc. This contributes to uncertainty within projects. However, to have efficient plans it is not possible to plan for all thinkable changes. The purpose with this master thesis has been to investigate if studying distribution of man-hours and simulation can increase the understanding of the effects of disturbances and support planning.

The method which included the study of distribution of man-hours, both planned and actual results, gave a clear picture of the difficulty of planning complex and long projects. It also showed that there are a lot of unexpected events that occur during the work. Although it may not be profitable to plan for changes it is important to know that they occur and be prepared for how to deal with them.

In order to take the study a step further, after identified that there are difficulties with the planning of projects, a second method was applied which included simulation of a small part of the development process to see how specific disturbances affect the process. This has been done with the software Simul8, where selected disturbances were simulated to clarify how they affect a project in terms of time and cost.

Both methods have shown great utility when it comes to improving the awareness and understanding of how disturbances and uncertainties affect projects and can provide a good support when planning projects. In order to get the best result when using these methods extensive knowledge and understanding of the process is required.

Keywords: disturbances, project planning, project normalization, product development process simulation

PREFACE

This report is the result of our work during the spring of 2011 which has involved an investigation of two methods with purpose to improve planning of development projects and increase the knowledge about the process's behavior. The project has been performed at Volvo Aero in Trollhättan together with the Department of Product and Production Development at Chalmers University of Technology. The report is the final part of our education in Mechanical Engineering and the Master program in Product Development at Chalmers University of Technology.

We would firstly like to thank our supervisor Anders Sjunnesson at Volvo Aero who has made this project possible and provided support and guidance throughout this time. We would also like to thank Professor Johan Malmqvist, our examiner at Chalmers, who has given us supportive feedback.

Further, we would like to thank the persons involved in our regular steering group meetings at Volvo Aero; Mats Leijon, Ola Isaksson, Martin Mandinger and Torgny Almgren. We would also like to thank Yvonne Månsson, Joakim Svantesson and Martin Lindström who have been incredibly helpful by providing us with knowledge and information about the projects and support during the simulation. There have also been several interviews with other Volvo Aero employees, who we want to thank for their time and for providing us with a better insight in Volvo Aero and how they run projects.

Göteborg, June 2011

Björn Rask
Caroline Selander

TABLE OF CONTENTS

LIST OF TABLES, FIGURES AND EQUATIONS

TABLES

FIGURES

EQUATIONS

1. INTRODUCTION

This chapter gives an introduction to this master thesis by providing a background of the problem and current situation in the product development of aircraft engine components. A problem discussion is included to give an insight of some difficulties that lead up to and justify the purpose of the thesis. The purpose and aim of the report is then presented. Also the delimitations of the thesis project will be discussed. Finally an outline of the report will be presented to guide the reader through the rest of the report.

1.1 BACKGROUND

The development and manufacturing of a new commercial aircraft is a large and expensive undertaking, too large for any company to manage alone. An aircraft is a complex product with millions of individual components and many dependencies (Harrison, 2003). The development and manufacture require involvement and coordination of hundreds of companies from a range of industries for a few years, thus the development process can also be categorized as complex. (Wynn, 2007, p. 2) The challenging regulations regarding safety and environment impact from regulatory organizations and authorities also contribute to the difficulty of developing an aircraft (Scott et al., 2006)

Airframers such as Airbus and Boeing develop and manufacture airframes to civil aircraft. The engines to these aircraft are developed and manufactured by the engine Original Equipment Manufacturer (OEM)[1], such as Rolls-Royce, General Electric, Pratt and Whitney, and their three joint ventures. Engine design and airframe design are in these days integrated in order to take full advantage of new technologies. A new engine design can lead to substantial cost savings since the relationship between engine performance and aircraft performance is highly dependent. Aircraft sales are handled by the airframers, however since there often are multiple engine choices to an aircraft the operator negotiates with both airframers and engine companies to get a low price.

The increasing product complexity and cost of aircraft engine programs, and consequently also risk, has made engine OEMs to go from developing all components on their own to let suppliers develop some of the components. The Risk and Revenue Sharing Partner (RRSP) relationship means that suppliers fund a fraction of the engine program and in exchange receive a fraction of the revenue and also stay as supplier for the whole program. Suppliers always compete to be part of new OEM engine programs. To be competitive, these companies must have abilities to reduce noise, reduce weight, become cost efficient, create successful relationships and get financial support. (Scott et al., 2006)

An aircraft engine consists of many interdependent components and the whole engine must be tested a number of times during the development phase to make sure that all parts work together. Before an aircraft engine can be used in operation it must also pass different certification tests. The companies involved in the engine development must therefore synchronize their development processes with the OEM's to synchronize the delivery of hardware needed to test the engine. For the engine program not to be delayed it is critical that all suppliers deliver on time.

---

[1] An Original Equipment Manufacturer (OEM) manufactures complete products or sub-assemblies that later on become integrated parts of the end products, for example an aircraft engine of an aircraft. (Business Dictionary, 2011)

Planning of large and complex projects, as airframe and engine programs, is a complex task. Planning of somewhat smaller projects as engine component development projects is also difficult. This is largely due to the complexity of each component and the dependency to other engine components which make unplanned changed requirements and technical challenges likely to occur, which in turn lead to more work than anticipated. (Wynn et al., 2006) If plans are made without buffers of time and budget an unforeseeable event may bring undesirable consequences to a project. On the other hand, having too large buffers lead to inefficiency if the project is completed without any major disturbances. (Flanagan et al., 2005)

As airframers constantly strive to produce better aircraft, in shorter time and to lower costs, suppliers are all the time pressed to make improvements to stay competitive (Pardessus, 2004). To accomplish these objectives technical advancement is often not enough, the development processes within companies must also be improved. Developing more robust plans, introducing better procedures and new tools are ways to improve the process, but to achieve any of those a good understanding of the process and its likely behavior is needed. (Wynn et al., 2006) One part of understanding the process and how to improve it, is an understanding of how uncertainty affects projects and how the process can be made less sensitive to the effects of uncertain events (Chalupnik et al., 2009).

Volvo Aero is a first-tier supplier to civil aircraft engine OEMs and also faces the challenges described above. They gave an opportunity to study their process in order to shed light on and evaluate their process in relation to project uncertainty and disturbances, which this report is a result of.

Historically, Volvo Aero has mostly developed and manufactured components to military aircraft and space engines, but from early 1990s they are mainly developing and manufacturing static components to civil aircraft engines. Even though Volvo Aero is relatively new to developing components to civil aircraft engines they have managed to stay competitive and are part of most of the OEMs' engine programs. (Volvo Aero Corporation, 2007) Their development projects have been completed with good technical results but also with resource utilization and cost exceeding initial forecast. This demonstrates the difficulty of planning such projects and hence the need of a better understanding of the development process to be able to make better predictions of future projects.

1.2 PROBLEM DISCUSSION

There have been a number of studies on how to make development projects more cost efficient and how to be able to make more realistic plans, but due to that different projects and processes have their own prerequisites and requirements different methods are needed to accomplish this. Each company has to find their own way to improve their process and the methods suitable for the situation. Joglekar and Ford (2005), say that the two important improvement fields to make better plans and follow them are to make the process more efficient and to understand the allocation of resources within the projects. This is often a problem because of the complex projects and the amount of iterations that occur. When it comes to foreseeing the resource need, it is important to know how previous projects have performed and how the work-load was distributed.

Even though the processes and allocation of resources are known improvement fields it can be a challenge to locate where and how to progress. There are many factors that come into play and affect the process in one way or another. In order to predict and plan development of parts to aircraft engines, deep knowledge is required in many different areas. For example knowledge about how an unexpected event affects the project in terms of resource need and duration of rework. Many of the disturbances, especially external, are difficult to avoid which makes it more necessary to know how to handle these situations which at the same time are difficult due to that the processes are affected by several actors.

Another approach to facilitate the planning and better predict the effects of changes within processes is process simulation (Yan et al., 2003). By using simulation, the possibilities increase to analyzing different scenarios with a reliable outcome and see the effects of unexpected events. This could be beneficial when analyzing: activity durations, resource usage, the order of activities and how beneficial parallel work streams are. Other advantages simulation provides, are the possibility to discover bottlenecks and investigate whether a change in the workflow or resource usage provide an improvement or not. Simulation is more suitable to predict outcome, before process or tasks are undertaken, instead of verifying how the process went (Löfstrand & Isaksson, 2010).

1.3 Purpose

The purpose of this master thesis is to investigate if studying distribution of man-hours and simulating the process are useful methods to increase aircraft engine component suppliers' understanding of their process to more accurately predict future projects.

1.4 Aim

The aim of this report is to evaluate whether the tested methods are suitable for these types of processes and their conditions. The results will also go into what each approach can contribute with.

1.5 Research questions

To get a clearer idea of what answers this master thesis should provide to fulfill the purpose four research questions have been formulated.

RQ 1. What are the patterns of outcome and plan of man-hours in Volvo Aero's projects, and how do the patterns differ?

RQ 2. What is the variation between projects, and to what extent can project data support planning of new projects?

RQ 3. What methods can be used to simulate product development processes?

RQ 4. How can simulations of available resources, work mode change and occurrence of uncertain events increase the understanding of the process and support planning of projects?

1.6 Delimitations

This case study only includes Volvo Aero's situation and information, but as there are many other companies in similar situations the goal is to provide a general discussion and methods suitable not only for Volvo Aero. With this said, the data collected in this thesis project is taken from Volvo Aero only.

Since the development process is more critical, both in terms of time and costs, after the contracts are signed by the parties involved it was chosen to focus on the process after the contract signing. This was due to that the activities before the contract signing, the predevelopment phase within Volvo Aero, often last for several years and are more flexible when dealing with various disturbances.

In this report, different simulation models are described and their suitability for development processes are investigated, but despite several simulation models has only one simulation program been tested and evaluated. The simulation program Volvo Aero uses today is Simul8 and has also been used in this study. The reason why only one simulation program has been used is the expensive licenses for simulation programs and that Volvo Aero already is familiar with Simul8.

The simulations made in this thesis project only take into account one specific part of the development process. The reason for this is that the whole development process would be too large and complex to simulate in order to see small effects and investigate if process simulation is a suitable tool for analyzing effects of changes and disturbances. Due to the complex situation as a development process involves, some assumptions and simplifications have been made.

1.7 REPORT OUTLINE

The report is structured as follows. After this introduction chapter a description and review of the methods used, in order to achieve a good result in the end of this study, are presented. The report continues in Chapter 3 with a summary of relevant theory to be able to continue the study with the right focus and more knowledge about the chosen area. Chapter 4 gives the reader a better understanding of how projects are carried out at Volvo Aero and the risks they are exposed to.

The result part of the report is divided in two chapters. The results involving a broader perspective of work-load distribution are presented in Chapter 5. Here is an investigation and analysis made of the comparisons between plan and the actual outcome and how this can contribute to a deeper understanding of the process. In Chapter 6, it is investigated if process simulation is suitable for development processes and what questions can be answered with simulation. At the end, there is a discussion on the thesis project and the conclusions drawn from it.

2. METHODOLOGY AND USED METHODS

This chapter will elucidate what methods have been used and how the research process has been carried out in order to fulfill the purpose of this master thesis. Since the purpose covers a broad area it has been broken down into four research questions, which also simplifies the process of finding suitable research methods. Each method aims to deliver a result which will ultimately contribute to fulfilling the main purpose. The chosen research strategy is shown in Figure 1, where the left column of boxes visualizes used methods and in which order they were executed, and in the right column the expected results from each method are shown.

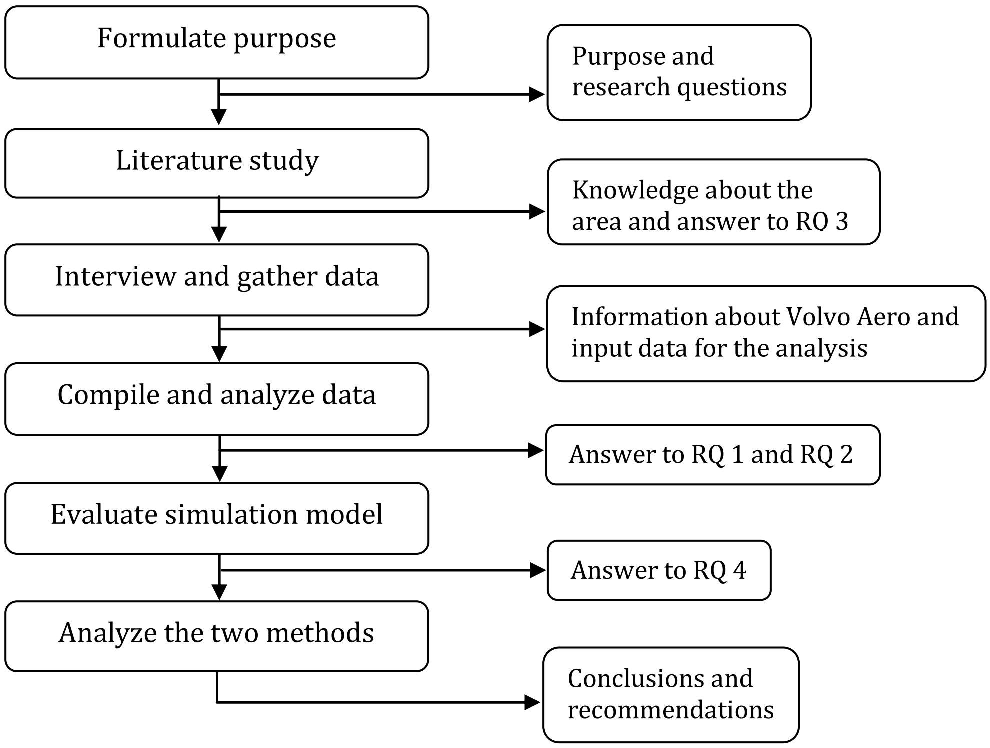


Figure 1. Methods used in the master thesis and the expected results

The research started with a literature study phase to increase the knowledge about project planning, product development management and product development process simulation. With information from the conducted studies on process simulation, Research Question 3 (RQ 3) was answered. The following phase consisted of 20 interviews with personnel at Volvo Aero to understand their product development process and risks that their projects are subjected to.

Together with the outcome from the literature study and the interviews the remaining work was planned, including gathering data and analyzing the studied methods. Data from projects was collected and analyzed with the expectation to see patterns in projects regarding distribution of man-hours. The result from examining planned man-hours with the outcome of man-hours had as purpose to answer RQ 1 and RQ 2. RQ 4 has been answered by simulating a specific part of the process to explore how disturbances and changes in the workflow affect the process. It has also been tested how resources and cost are connected in order to make better plans and understand the process's behavior better.

2.1 DATA COLLECTION

The data collection in this report involves both primary and secondary data. The primary data, regarding information about the development process, comes mainly from interviews with personnel at Volvo Aero. Input data for the analysis was received from data bases. The secondary data concerns mostly the literature study where similar studies and theory from various kinds of literature were found. The next sections look at these two types of data in more detail.

2.1.1 LITERATURE STUDY

The literature study was focused on increasing the knowledge in areas related to product development such as project planning and product development management but also suitable approaches to simulate product development processes.

The search for literature on the subjects was done primarily using the search engine Google Scholar where electronic publications are relatively easy to find and to which Chalmers University of Technology has access to. A complementation of the article research was done when it came to project planning and product development management in form of studying textbooks with relevant content. The reason for this was to get a broader view of information and gather both research and theory.

Secondary data has the benefit of providing work that has already been done which often results in a timesaving search in comparison to collecting primary data. Collection of secondary data can also provide a broader view within the area of study, but on the other hand the disadvantage of using others' work is the uncertainty of the reliability and methods used. (Sørensen et al., 1996) The benefit of having more than one source is the awareness of several opinions and results of previous researches, but there is a risk of missing important qualifications and assumptions made in articles.

When searching for a paper the importance of knowing what to look for and narrowing down search words in order to get more relevant hits are high. A variety of documents was looked through to determine the usefulness of each and to be sure of finding useful information covering all product development process simulation approaches. Thereafter, a more careful study of the documents and a compilation of the approaches were done to deepen the knowledge on the subject and to form a good foundation for the ongoing work.

2.1.2 INTERVIEWS AND COLLECTION OF RAW DATA

In order to collect information about Volvo Aero's process and company, interviews with personnel at Volvo Aero, for example project managers, design leaders, production manager, purchasing manager, have had a central role. These interviews and meetings have been performed to gain more knowledge about how projects are carried out, what difficulties there are and the relations between Volvo Aero, their suppliers and the OEMs.

The interviews have been conducted in a semi-structured way. Open-ended questions were prepared in advance with the purpose of gathering as much information as possible about Volvo Aero and their way of working. That included; get an insight of how the projects are implemented, possible changes and risks during projects. 20 persons have been interviewed and the interviews lasted between 60 and 90 minutes. The reason for using open-ended questions was to invite to a discussion, with prepared questions, and still give an opportunity for the interviewee to talk more freely about the subjects.

A semi-structured interview aims at gathering as much information within the current topic and provides a possibility to get knowledge about issues which have not been thought of by the interviewer. There are often questions prepared but they do not have to be asked in a specific order or be exactly the same in each interview. This structure allows the interviewee to take the lead in a greater part of the interview. It is important to be aware of the possibility of a high pace of changing topics and the risk of losing track of the purpose of the interview. (Sommer & Sommer, 1997)

Open-ended questions cannot be answered with only a "yes" or a "no", instead it forces the interviewee to think through before answering and give a more descriptive answer. This type of questions often leads to follow-up questions and a deeper knowledge is provided to the interviewer. (McQuarrie, 2006)

When gathering and using primary data it is important to think through what answers are sought. A risk with interviews is the possibility of partiality and that the received answers only reflect what the interviewed person think or has experienced the situation.

2.2 COMPILATION AND ANALYSIS OF DATA FROM THE PROJECTS

The raw data about how the projects were planned and the outcome was acquired through extensive communication with employees at Volvo Aero, both through the informal interviews and through email conversations. Man-hours were extracted from data bases and data of gates were found in project schedules and told by employees.

In order to use and analyze the input data from the different projects, both planned and outcome, Excel has been used as a tool. Bar charts have been developed, with normalized figures, to view the different patterns and the difference between planned man-hours and the outcome. The differences between the completed projects have been analyzed further by using standard deviation and mean value to give a clearer picture of how the variation between projects is.

2.3 TEST AND EVALUATION OF SIMULATION SOFTWARE

From the result of the literature study, different product development simulation methods have been found and evaluated. This was done in order to provide an increased knowledge about simulation models but also to have a firmer foundation when using the computer software in order to simulate Volvo Aero's product development process. Since Volvo Aero already uses Simul8 for logistics simulation it was found appropriate to use also in this purpose. To ensure the appropriateness of the program; the usability, presentation of result, how rework is handled, possibility to export data result to Excel among other things were investigated.

For the simulation part in this master thesis the network of activities, data on activity durations, rework probability and learning effects were estimated and provided by engineers responsible for the area. Evaluation of the program has been done with help from skilled personnel, within this area, at Volvo Aero and by taking into account the conditions for the simulation and expected outcome.

The result of each simulation has been evaluated and analyzed with help of histograms and probability distribution of the likelihood that the process is completed at a given time. Histograms were used in this matter to see the frequency of different values in different intervals and to calculate a probability curve.

3. FRAME OF REFERENCE

The chapter presents the framework of the master thesis. Concepts relevant for the thesis within project planning, product development management and product development process simulation are described. This will provide a good basis on which the results will be analyzed.

The first two sections include theory about project planning and product development management and point out what is important when planning and implementing projects and give an additional aspect when analyzing the answers to RQ 1 and RQ 2. The third section about simulation models provides a deeper understanding about simulation and suitable simulation models, and answers RQ 3. Selection of simulation model, for the upcoming simulation to answer RQ 4, is also made. Last in this chapter is the used simulation program introduced.

3.1 PROJECT PLANNING

In order for a project to be successful; i.e. fulfilling criteria of time, cost, performance and client acceptance, it is important that the project plan is feasible (Pinto, 2010, p. 35). If the initial plan shows not to be feasible the project will be delayed unless the criteria of performance and client acceptance are lowered or the resources and hence costs are increased. However, project delay often also results in increased cost because some of the resources are assigned longer to the project.

There is always some kind of uncertainty in projects. Because of the uncertainty, which is the basis for project risk, it may be difficult to predict the outcome of projects. Project risk is any event that negatively can affect the project and can be categorized as financial risk, technical risk, commercial risk, execution risk, and contractual or legal risk. Financial risk relates to the capital investment made and the uncertainty about its return. Technical risk relates to implementing unique technical elements in products or use unproven technology and the uncertainty about how this will affect the project. Commercial risk relates to the uncertainty about the product's success on the market. Execution risk relates to exceptional conditions or uncertainties that negatively can affect the execution of the plan. (Pinto, 2010, pp. 221-225)

Cost overruns in projects may thus be due to poor planning or to occurrence of unfavorable events. Some of the most frequent reasons for cost overruns are: low initial estimates, unexpected technical difficulties, lack of project definition, specification changes and external factors such as shortage of raw material, and economical and political factors.

When a new project is to be undertaken there are two different approaches, top-down and bottom-up, that can be used to plan the project and its individual activities regarding resources, durations and costs. In the top-down approach it is thought that the top management has experience from similar projects and can provide good estimates of future projects. The top management makes estimates on the overall project level and for the major work packages. These estimates are then passed down the hierarchy where the project gets broken down into work packages and tasks. This method gives top management control of the decision making process and research says that when the top management makes estimates of project costs they are in many cases quite exact. Bottom-up planning on the other hand begins on the lowest level in the project hierarchy. First, estimates are made for the activities and then these estimates are summed all the way up through the hierarchy to the overall project level. This method consequently requires a detailed view of the project from the beginning. (Pinto, 2010, pp. 262-264)

Parts of the project planning process that are challenging, and may give a project different preconditions depending on how they are done, are the estimation of resources, durations and costs, which also are closely connected to each other. To estimate activity resources a list of the activities to undertake, their individual scope of work and the dependencies them between must be defined. To estimate activity durations the amount of work required to complete the individual activities and the amount of resources to be assigned to the activities must have been estimated. (Project Management Institute, 2008, pp. 141-146) The processes of deciding activity resources and activity durations may be iterated to achieve a reasonable project plan that either meets time constraints, resource constraints, or mixed constraints (Pinto, 2010, pp. 375-376). The different activity estimates also decide the project's overall resource need, duration and cost. Although resources may be people, material, equipment and supplies, the focus of this master thesis is on the people.

To estimate resources, durations and costs there are a range of tools and techniques available; including expert judgment, analogous estimation, parametric estimation and three-point estimation. Analogous estimation means that parameter data from previous similar projects are used as basis to estimate new projects, and if there are known differences in project complexity this can be dealt with. The advantage of using this method is that it is normally less costly and time consuming than other methods, but it is also less exact. Parametric estimation means that the sought estimate is calculated using a statistical relationship between historical project data and another variable of the project. For example, if a company building railway tracks knows it takes 1 day to complete 25 meters, a calculation would give that to complete 1000 meters would take 40 days. If the model is reliable this method can give high accuracy estimates. Three-point estimation takes estimation uncertainty and risk into account, and can thus give more accurate estimates. Probability distributions of duration or cost are described by estimates of most likely, optimistic and pessimistic duration or cost. However, even the average of three values may give a more accurate estimate since the uncertainties of estimates are taken into account. (Project Management Institute, 2008, pp. 149-150)

3.2 PRODUCT DEVELOPMENT MANAGEMENT

In the early phases of a product development project it is possible to change the final characteristics of the product without resulting in high costs. As the project progresses the cost of changes increase exponentially while the uncertainty and risk decrease. This is illustrated in Figure 2 below. (Project Management Institute, 2008, p. 17)

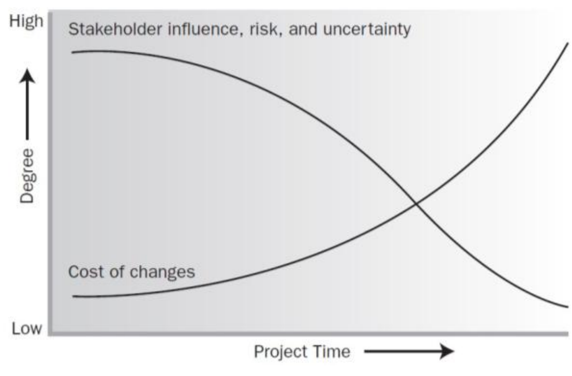


Figure 2. Impact of different variables based on project time (Project Management Institute, 2008, p. 17)

Although all above is recognized, a problem many projects have are that made decisions are shown to be wrong and they must solve problems late in the process, called firefighting. Instead of rushing through the process and end up firefighting, engineering teams should spend enough time upfront to completely understand the problem, define what knowledge is needed to evaluate alternative designs and make most appropriate trade-offs. Product development is an iterative process of learning and covering knowledge gaps, and one method that supports learning and knowledge sharing in the early phases of development is set-based engineering. The idea is to make a big effort in the beginning of the development to understand the trade-offs on a set of solutions before deciding what design to go further with. (Stackpole, 2011) Another term with the same purpose, with the addition to solve anticipated problems at the root cause early, is front-loading the product development process, one of the process principles of lean product development (Liker & Morgan, op.cit). Set-based engineering and front-loading thus encourage doing more work in the beginning of projects to enhance the probability of making good decisions. However this does not mean that the amount of resources assigned to the project peak in the beginning. Usually the resource demand looks like a bell-shaped curve with few resources in the beginning, reaching the peak around halfway into the project when designs are being completed and then decreases to almost zero as serial production starts (Liker & Morgan, op.cit).

3.3 PRODUCT DEVELOPMENT PROCESS MODELS

To simulate product development process behavior a model of the process is needed. The literature study revealed different approaches to model development processes. In these approaches, the focus and thus the idea of what determines process behavior differ. The approaches may be activity-focused, information-focused or actor-focused. Task network models are activity-focused and represent processes as a set of tasks that are undertaken individually. The information required and produced by each task determines the order in which tasks are undertaken. However, the information flows are not seen as driving process behavior. Queuing models represent a process as many separate stations processing and transferring information. The stations have information waiting to be handled, and when handled sent to the queue of another station. Queuing models are thus information-focused, but may also include an activity-focused part. Work-queuing models, often used to describe manufacturing systems and supply chains, are on the other hand actor-focused. Multi-agent models are both actor- and information focused. It is viewed that decision-makers collaborate and act depending on the information received from another decision-maker, without having a picture of the whole system. System dynamics models are also information-focused. The process is viewed as a work-processing system where the feedback and feed forward of information about the current process condition decides system behavior. (Wynn, 2007, pp. 36-38)

The remainder of this chapter focuses on the different task network models suitable to simulate product development processes. Some task network models can only be used in a descriptive purpose and are thus left out. The reason for leaving out the queuing, multi-agent and system dynamics modeling approaches are that they are not as commonly used as task network models to describe product development processes due to that they are either on a too high level or too abstract to get a detailed understanding of process behavior. Queuing situations can however appear in task network models where there is a limitation in resources, but in these models it is the information flows instead of resource constraints that limit what tasks that can be done in parallel (Wynn, 2007, p. 56).

3.3.1 PETRI NET

Petri net is a graphical method that describes the logic network of activities. Vertical bars represent activities and circles denote places where information can be. The vertical bars and the circles are connected with arrows. Tokens, solid dots, are carrying the information and forwarding it from activity to activity. An activity cannot begin before all required tokens have been received from previous activities. The transition of tokens over an activity is illustrated in Figure 3. (Wynn, 2007, p. 44)

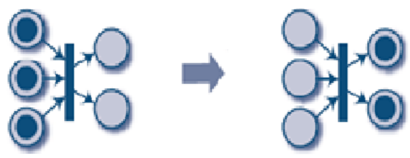


Figure 3. Transition of tokens over an activity in a Petri net (Wynn, 2007, p.44)

In Petri nets it is possible to set limits on certain activities, for example conditions for an activity when to begin. Compared to other similar simulation methods the major distinction is the use of tokens (Kumanan & Krishnaiah, 2006). The graphical network and the use of tokens make the simulation state and movement of tokens visible to observers.

The fact that Petri net can handle iterative flows is an advantage when product development processes are to be simulated, but a major limitation is that it cannot handle time. Another limitation with this model is that there is no weighting between the activities which leads to that all activities are equally important (Smith & Morrow, 1999). For the Petri net to be useful, the activities in the process and the order of them must be clear.

3.3.2 PROGRAM EVALUATION AND REVIEW TECHNIQUE (PERT)

The Program Evaluation and Review Technique model, also called Network diagram, represents a project as a series of activities. Before an activity can start results from all predecessors must have been acquired. In the PERT chart a project is built up of nodes and arrows. Most common is to let nodes denote activities and arrows define precedence, but the opposite is also used. (Eppinger et al., 1992) In Figure 4 an example of a PERT chart can be seen. In this figure, arrows represent activities with respective duration, and nodes represent milestones.

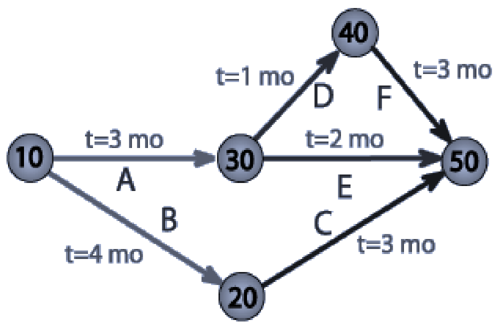


Figure 4. An example of PERT model

The PERT model is often used when planning projects to order activities and to get an overview of the duration of activities (NetMBA, 2010). The Critical Path Method (CPM) is similar to PERT. The only difference them between is the way activity duration is estimated. In CPM one estimate is used to decide activity duration, in PERT however, uncertainty of estimation is taken into account by using three estimates, which reflect a probability distribution, to decide activity duration. Since the models are very similar they are often referred to as PERT/CPM.

Using PERT/CPM the longest path, commonly named the critical path, can easily be found. A delay in any of the activities on the critical path directly prolongs project duration. However, if a change to the process is made or an activity off the critical path gets delayed another path may become critical. (Pinto, 2010, p. 286)

Even though PERT is a good method when simulating a product development process in view of time, the method has several shortcomings. For example, lack of possibility to simulate iterations which usually occurs many times during a product development project (Smith & Morrow, 1999).

3.3.3 Graphical Evaluation and Review Technique (GERT)

The Graphical Evaluation and Review Technique model is an upgrade of PERT, which can handle some of PERT's limitations. GERT can include iterations, which may be due to disturbances, and the probability of them to occur. The durations of activities can be described with probability density functions. (Wynn, 2007, p. 46). The right image in Figure 5 shows how it is possible to use different parameters and requirements with this model. The left image shows an example of what a GERT diagram can look like and how the parameters affect the diagram.

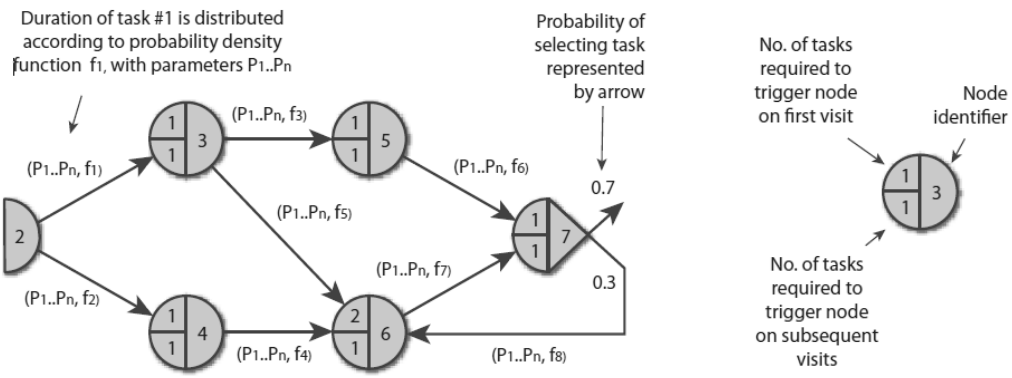


Figure 5. An example of a GERT activity diagram (Wynn, 2007, p.46)

3.3.4 Design Structure Matrix (DSM)

The Design Structure Matrix is more of a structuring tool than a simulating method. It is used to analyze the dependency between tasks and it shows if it is possible to have tasks in parallel in order to find the most efficient order of tasks.

DSM is a square matrix, and the off-diagonal is used to specify the relation between tasks and in which direction the information is moving.

In Figure 6, which shows a small DSM, each letter represents an activity and the matrix is read as follows: the row for each activity indicates where the input is coming from and the column shows where the information is sent. (Karniel & Reich, 2009) When the dependencies have been deployed, the activities should be organized, if needed, to have all marks below the diagonal.

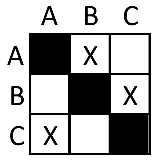


Figure 6. An example of a small DSM

This model does not include resource need and availability, but it is useful when the most efficient way of structuring tasks is searched for and it gives information about the relationship between tasks (Yan et al., 2003).

DSM can be used for simulation of processes. In numerical DSMs it is possible to include iteration scenarios with probability of rework. Thereto, the task durations can be described with probability distributions and learning effects can also be included. (Cho & Eppinger, 2005)

3.3.5 WORK TRANSFORMATION MATRIX (WTM)

Work Transformation Matrix is an upgrade of the original DSM and takes into account rework factors and each activity's expected duration. The left image in Figure 7 shows the rework factor which affects a task's duration when an iteration appear and the right image shows activities' duration the first iteration (Eppinger & Smith, 1997). This method requires an iterated process and the outcome is the total finished work which is summed from the iterations (Smith & Morrow, 1999). This method can be used as an aid when investigating how relations between different tasks affect task duration (Licht et al., 2007).

Figure 7. Work Transformation Matrix (Eppinger & Smith, 1997 p 276)

3.3.6 SIGNPOSTING

Signposting differs from Petri net, PERT and GERT in the sense that the task ordering is not explicitly captured, and from DSM and WTM that task connectivity is not directly represented. Instead, suitable tasks to undertake next are identified based on the confidence to the product solution under development. An activity can be undertaken first when specified levels in confidence of input parameters are reached, and when an activity is finished the confidence of the parameters usually increase. Signposting thus gets round the need of having an overview of the process, which in many cases can be difficult to have and iterations are easily handled. Matrices are used to describe what levels of parameter confidence each task needs in order to be undertaken and what the confidence will be when the activity has been finished.

The original model has been extended with probability density functions for task durations, needed resources, how quality of input parameters affects output parameters etc. (Wynn, 2007, pp. 52-54)

3.3.7 SELECTION OF SIMULATION MODEL

The previous subsections aimed at providing a better knowledge of simulation models and to answer RQ 3, about which simulation models are useful in simulation of product development processes. This discussion will compare the various models and clarify which simulation model that will be used later in the report and why.

All the above presented models can be used when simulating product development processes. However, as they describe processes in different ways, the most appropriate model to use for simulation of a specific product development process depends on what answers the simulation aims to provide and what knowledge there is about the process.

If the process can be described with a network of ordered tasks Petri net, PERT and GERT make it possible to present this graphically and an overview of the process can be obtained. If the order of tasks is not of interest but the dependencies between activities are, DSM and WTM make it possible to organize and present these dependencies. If both order of tasks and dependencies them between is not to be studied, signposting can be used to describe a process where activities are undertaken depending on the confidence to the product being developed.

Based on the presented information above about the models, simulation of product development processes can give answers to activity durations and total project duration when probability density functions for activity durations are used. As activity durations are determined by the activity resources, the amount of resources can also be elaborated in a simulation. If the amount of resources is limited some activities may not be attempted as planned and the project may get delayed.

Product development processes are characterized as iterative in nature, thus in order to fully explore the dynamics of a development process a model that takes iteration into account is needed. Signposting can easily handle iterations since it is the current state of the project that determines what activities to undertake. Petri net, GERT, DSM and WTM can also handle iterations, but then the order of activities or dependencies between them must be decided in advance. When iterations are included in a simulation model the probability of them to occur is often set. As iteration means activities are undertaken again and that in many cases a reattempt means shorter duration, learning effects may also be considered to capture process behavior.

For the upcoming simulation, in this master thesis, it seems as if GERT is most suitable due to its ability of handle iteration and probability that various activities occur. This cannot GERT's forerunner, PERT, handle and was because of that less suited for the report's purpose. Petri net is another model which can handle iterations and probability but it lacks the ability to manage time in simulation. DSM, WTM and Signposting were decided not to be used as they do not present processes graphically. The decision to use GERT was based on that the main requirements for the selected model were to be able to handle iteration, probability of events to occur and time. These are important features of a model as a development project often is subjected to disturbances which can cause rework and time is always important in these kinds of projects.

3.4 SIMUL8

Simul8 is the simulation program that has been used in this master thesis. This program provides a simulation environment where processes can be visualized and analyzed. It is a discrete event simulation software where activities are undertaken when previous ones are completed. When activities are completed is time-based. It is possible to set resources, probability distributions for durations and probability of activities or iterations to occur. The software has the ability to import and export data from Excel and it is possible to use Visual Basic for Applications (VBA), which is an event-driven programming language. This gives possibility to easier control the behavior and constraints of the simulation. (Simul8 Corporation, 2011)

Even though Simul8 is the software Volvo Aero currently uses for logistics simulation was Simul8 found suitable for the purpose of this report. The selection of simulation program was due to the suitability and because Volvo Aero already is using the program and people with experience of simulating processes in Simul8 easily could be accessed.

4. THE PRODUCT DEVELOPMENT SITUATION AT VOLVO AERO

This section includes a description of Volvo Aero's development process but also the various disturbances that may occur. This is to give the reader a deeper understanding about Volvo Aero's way of working but also some of their difficulties.

The information about Volvo Aero and their development process, which is presented below, is gathered through several interviews with Volvo Aero employees. Volvo Aero's official website and their Intranet have also been used.

4.1 THE PRODUCT DEVELOPMENT PROCESS

Volvo Aero's product development process for the commercial market is not as mature as their development process for military engines, due to they have not gone through as many complete commercial projects. Even if they have a lot of experience of developing aircraft engines to the military industry, they faced many new challenges and different demands when entering the civil market. Volvo Aero was used to develop whole engines which can be compared to just develop components to an OEM. This change means in practice a higher degree of external demands and other disturbances which affect the process in a way that Volvo Aero cannot control but instead have to solve along the way. This together with a tight lead time affect the development process by making it more difficult to plan and creates an increasing need for overlapping activities. According to Krishnan et al. (1997), this is a common trend within many manufacturers in connection with high competition and demands on developing high quality products in a high pace. This improvement of the development process implies that many activities are performed in parallel and requires good communications interactively.

In order for Volvo Aero to cope with the high development pace, several activities are performed in parallel which can have the benefits of reducing cost and time but it is not only a positive way of working. By releasing too immature documents/drawings/ information can lead to later mistakes which in turn can implicate time-consuming rework and cause delays. (Krishnan et al., op.cit)

Volvo Aero's product development process is based on Volvo Group's Global Development Process (GDP), see Figure 8. The development process is divided in different phases, colors, and is separated by technical reviews followed by a gate. As mentioned earlier, this report only takes into account the parts of the product development process which are performed after the contract signing at Gate 3 (G3) and the first phase is then Detailed Development. The phases before Gate 3 are a predevelopment phase where concepts are evaluated and chosen together with manufacturing techniques. In phase G3-G5 the concept is analyzed and proven to meet the requirements. The production is also up and running and after G4 the manufacturing of the first hardware starts in order to prepare for the first engine test. In the Final Development phase, the product is verified and the manufacturing of more hardware is proceeding. After G6 the design should be finished and the production of serial hardware begins. In this phase and forward the production account for the largest part of the work-load. After G7 the product is approved and has passed all certification tests and manufacturing techniques are verified and certificated.

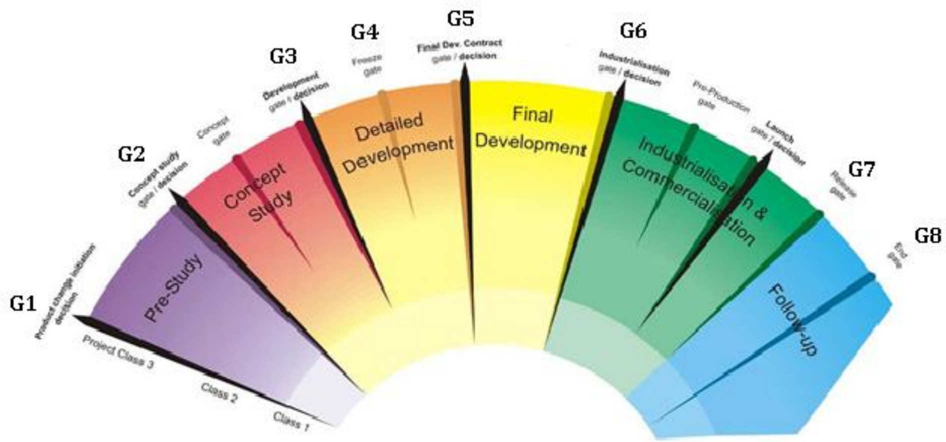


Figure 8. Volvo Aero's GDP (from VAC's Intranet)

The time plan is based on the OEM's time schedule together with the GDP. The schedule made by the OEM, including planned flight and certification tests, is the basis for how Volvo Aero plans their projects and decides when reviews and gates have to be done. The gates and reviews are a control function of how the development proceeds and if the component meets the requirements. For each gate a project goes through, the requirements get tougher as the component gets closer to a final product. Other critical deadlines are the flight and certifications tests which are performed by the OEM. These tests shape the development process in terms of what needs to be finished at what time. For each test the OEM requires a new hardware because of different test objectives and instrumentation used during the test.

4.2 Disturbances and uncertainties

Risk within projects is a big issue for many companies where the uncertainty factor involves time, cost and the product's ability to fulfill requirements. With increasing competition, plans are often made to look optimistic to demonstrate that the project will keep the deadline and budget. A too optimistic project plan is a risk and can contribute to large damage if something goes wrong (Flanagan et al., 2005). Risk taking is about weighting the impact of different risks against possible advantages and find an acceptable balance (Unger & Eppinger, 2009).

There are two types of sources that cause disturbances; external and internal sources. The disturbances caused by external influences are unavoidable but the internal disturbances are possible to reduce and belong to the continuous work to improve Volvo Aero's product development.

Disturbances have different effects on the development process depending on the extent and when they occur.

4.2.1 External disturbances and uncertainties

Possible actors in Volvo Aero's product development process who may come with changes in requirements or other essential elements are suppliers, OEMs and authorities. Due to the many actors who are involved in the process of developing an aircraft engine the risk for external disturbances are high and important to be aware of. For example, design and interface changes are possible reasons for rework but there is also a high risk for new or updated load cases. These and other similar changes are causes for rework and bring an uncertainty into the project planning when it comes to both resources and duration of a phase. In order to reduce the imminent risk it is important to have good knowledge about the process and how the disturbances affect the workflow but also a strategy for how to handle disturbances.

There is also the possibility that contractors become late with supplies of components or materials which in turn makes Volvo Aero late and cannot proceed as planned.

4.2.2 INTERNAL DISTURBANCES AND UNCERTAINTIES

Internal disturbances often arise from rough assumptions when planning projects and too large risks that have been taken in order to keep deadlines, both the OEM's and their own, and may lead to mistakes which in turn lead to rework or increasing lead time.

As previously mentioned, Volvo Aero is working with an overlapping approach, with a close collaboration among different tasks and departments, which may bring a higher risk to projects. Poor communication between design and manufacturing teams could result in that the developed concept's design is not suitable for the developed manufacturing technology and one of the parties have to redo their work. An effect of changing design or manufacturing technology can cause the project to be forced to take a risk in introducing an immature technology that is not fully tested in order to fulfill its commitment.

Aside from large disturbances, there is always an uncertainty that could affect the project. Examples of uncertainties are; absence of personnel, misjudgments of planned development and in project plans when it comes to estimate activity durations. These unplanned events naturally affect the process, but they are often too small to get anything out of evaluating each individual impact.

Other uncertainties that may affect the project are the differences in learning period depending on who performs the task and if it has been done before in a similar way. Uncertainty has to be considered when projects are planned.

5. STUDY OF DISTRIBUTION OF MAN-HOURS IN PROJECTS

As said in the introduction chapter, knowledge about how resources were allocated and how work-load was distributed in previous projects can be useful when planning new projects. This chapter presents the results of using an approach where the distribution of man-hours over projects' phases are studied in order to increase the understanding of the development process with aim to support planning of future projects.

In this chapter the two research questions below are to be answered.

RQ 1. What are the patterns of outcome and plan of man-hours in Volvo Aero's projects, and how do the patterns differ?

RQ 2. What is the variation between projects, and to what extent can project data support planning of new projects?

Next in this chapter, the situation of the development projects at Volvo Aero is described, with focus on the different preconditions for the projects that are analyzed. Planned and actual distributions of man-hours in projects are then reviewed, followed by a section where the variation between projects is defined and where the usefulness of project data when planning new projects is explored. At the end of the chapter there is a discussion about the results presented and the answers to the two research questions.

Twelve projects are studied. Of these twelve, six are completed, one has passed G6 and the remaining five have only completed one phase, G3-G4. The five projects only completed one phase are excluded from charts in Section 5.2 but are taken into account in Section 5.3.

5.1 CONDITIONS FOR THE PROJECTS

All twelve projects studied have more or less different preconditions. There are for instance differences in maturity level of technology at project initiation, number of similar previous projects, relationship to OEM and how the component is built.

Three types of components have been developed: cold structures, hot structures and rotating spools. The projects related to each component type are presented below to provide a clearer picture of the similarities and differences between projects. Thereafter, all projects are summarized in Table 1, to provide a clear overview of the projects.

5.1.1 COLD STRUCTURES

Cold structures are components that are placed in the front part of the engine. They are not exposed to as high temperatures as the components in the rear part of the engine, called hot structures. The demands on cold structures are as a result different than those for hot structures.

In Project A, the component was developed in conjunction with an OEM new to Volvo Aero. This was the first project where Volvo Aero was involved and responsible for the whole development process. The basic design of the component could be made by, to Volvo Aero, known technology but the component also included a complex design which had not been done before. The developed component consists of many parts.

Project D was a sequel to Project A, and similarities existed in many aspects except in the sense of knowledge about the component and process. The engineers could reuse the knowledge gained in the previous project.

Project H develops a component which Volvo Aero has done before, but a new manufacturing method is to be used. When the project started the new manufacturing method had a low Technology Readiness Level (TRL)[2]. The component is extremely complex and contains many interfaces to other components.

Project I and J develop almost the exact same component but for two different aircraft. For this kind of component a new OEM was to be collaborated with, however the design of these two components is simpler than in previous projects.

5.1.2 HOT STRUCTURES

Hot structures are, as said above, exposed to high temperatures. This places high requirements on the material in the components.

Project B was Volvo Aero's first commercial development project for this kind of component. However, they had made a prototype earlier and tested it, and the gained knowledge was brought into the project.

Project E was a sequel to project B and they could reuse much of what they had learnt in the previous project.

Project G develops a component based on previous similar projects but the complexity has been increased by introducing more advanced material and design in order to reduce weight. The TRL level of this technology at project start was lower than in previous hot structure projects. The project also meant collaboration with a new OEM for this kind of component.

Project K and L develop the same component but for two different aircraft. Information and knowledge from previous similar projects could be used, but they have not used the exact same design. These components are also a lot smaller than the previous similar developed components.

5.1.3 ROTATING SPOOLS

Project C could base component design on previous similar developed components not made by Volvo Aero, and the complexity of the component is quite low.

Project F was a sequel to Project C and the component has almost the same design.

[2] Technology Readiness Level is a scale from 1 to 9 which is used to measure how mature a technology is and compare different technologies. TRL 1 = the technology just discovered and at a research level. TRL 9 = the technology is safe and verified (Mankins, 1995).

Table 1. Conditions for analyzed projects

	Project characteristic
Cold structures	
Project A	New OEM, known base design but new complicated feature.
Project D	A scaling of project A, thus very similar.
Project H	Known base design, new unproven manufacturing method.
Project I	New OEM for this kind of component, known base design.
Project J	New OEM for this kind of component, known base design.
Hot structures	
Project B	Volvo Aero's first commercial development of this kind of component.
Project E	A scaling of project B, thus very similar.
Project G	New OEM, introducing new light weight technology.
Project K	Redesigned and smaller than previous similar developed components, no scaling.
Project L	Redesigned and smaller than previous similar developed components, no scaling.
Rotating spools	
Project C	Could use information from previous similar projects not carried out by Volvo Aero.
Project F	A scaling of project C, thus very similar.

5.2 PATTERNS OF WORK-LOAD AND LABOR INTENSITY

To be able to compare distributions of man-hours in projects that have different total duration, and also take into account what type of work being done in the project, the projects are studied per project phase. As described in Chapter 4, projects at Volvo Aero are planned and follow the GDP, and the different project phases represent different type of development work being done. This approach makes it easy to find patterns but also to understand and give some explanation to the result.

The collected project data on man-hours of projects and dates for project phases are the basis for the results presented below. Data on planned man-hours for the projects has been portioned into the planned project phases, and the reported man-hours have been portioned into the actual project phases.

In Figure 9 the outcome of man-hours per phase for the projects that have passed G6 is illustrated. The values of the bars have been normalized against the highest value in the chart. The amount of man-hours per phase represents the work per phase. Examination of the chart gives that the work-load of projects is concentrated to phases G4-G5 and G5-G6, as all projects have their two highest values there. In these two phases, both design and production engineers are working at full speed to be able to deliver a component that meets the requirements and can be serial produced. In phase G3-G4 the amounts of man-hours are much smaller. When G6 has been passed, design is near to be completed and it is to largest part production engineers that are working, which answer the decreasing amounts of man-hours after G6. Except from the two completed hot structure projects the amounts of man-hours in G6-G7 and G7-G8 are small compared to the projects' other phases. The pattern of outcome of work per project phase is bell-shaped, meaning that man-hours increase to a peak and then decrease. Five out of seven projects peak in phase G5-G6 and the remaining two projects peak in G4-G5.

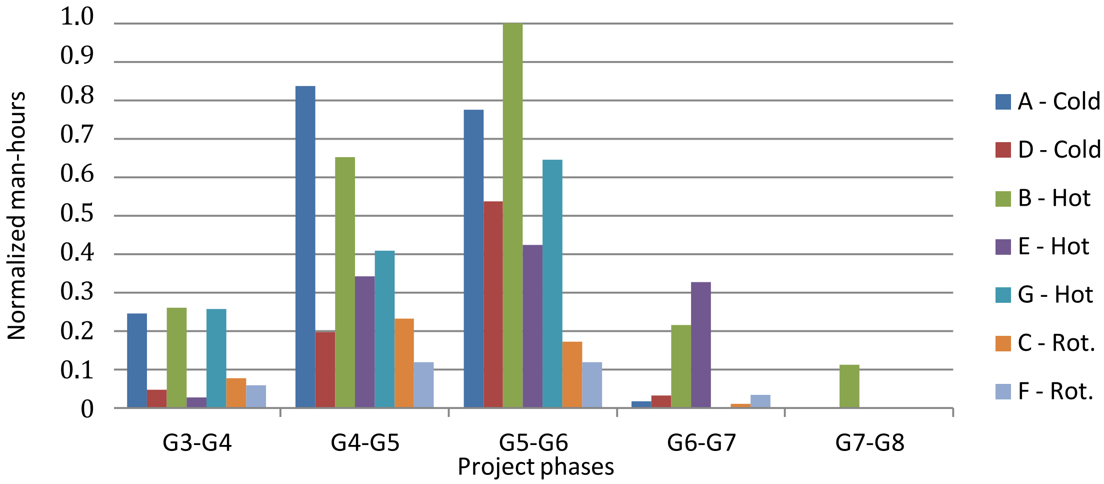


Figure 9. Outcome of work

This pattern of increasing and then decreasing man-hours can also be deduced by studying the slopes in the accumulated outcome chart, Figure 10. The values have been normalized against the highest value in the chart. This chart shows that man-hours per phase increase after G4 and increase or stay almost the same after G5. After G6 man-hours per phase drastically decrease and are close to zero for some projects, but the two hot structure projects have, as said earlier, considerable amounts of man-hours reported.

In Figure 9 and Figure 10, it can be seen that the second time a similar component is developed (D compared to A, E compared to B and F compared to C) the amount of man-hours in each phase is much lower than for the first developed structure. This is what could be expected since these sequels were close to scaled copies of the first components. The values of the third developed hot structure, Project G, on the other hand lie between the first and second hot structures, which can be explained by the conditions for the project.

The amount of man-hours per phase are in general higher in cold and hot structure projects than in rotating spool projects, but these components are also much more complex. The heights of the bars in Figure 9 are thus due to the difficulties of projects, but as the duration of projects' phases differs this also affects the heights of the bars.

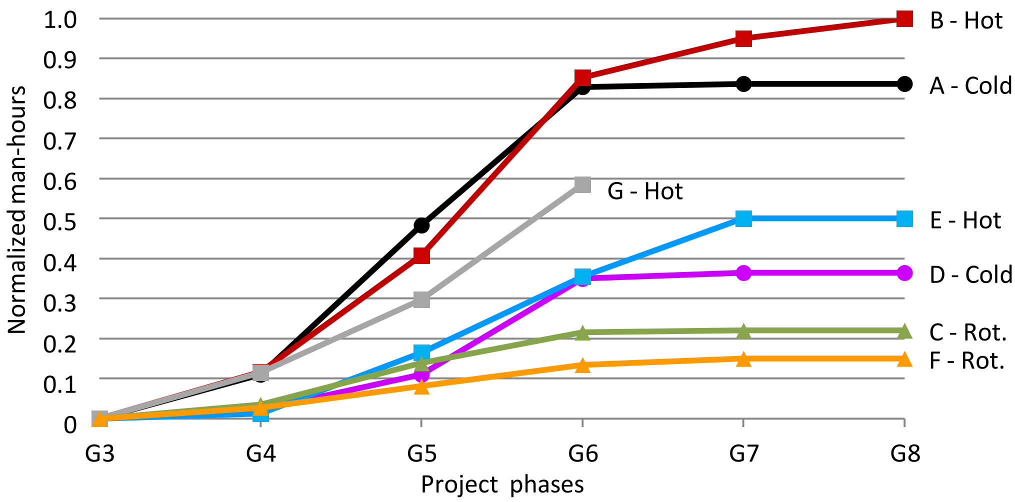


Figure 10. Accumulated outcome of work

In Figure 11 the amount of man-hours reported in a phase is divided with its respective phase duration and a slightly different chart to Figure 9 is obtained. The values of the bars have been normalized against the highest value in the chart. Here amount of man-hours in a phase represent the labor intensity. Even in this chart the bars in phases G4-G5 and G5-G6 are highest, but the bars in phase G3-G4 are now much closer to the following two phases, except from Project D and E which have remarkable low labor intensity. The bars in phases G6-G7 and G7-G8 are almost the same as in Figure 9. The pattern of outcome of labor intensity is bell-shaped and five out of seven projects peak in G4-G5.

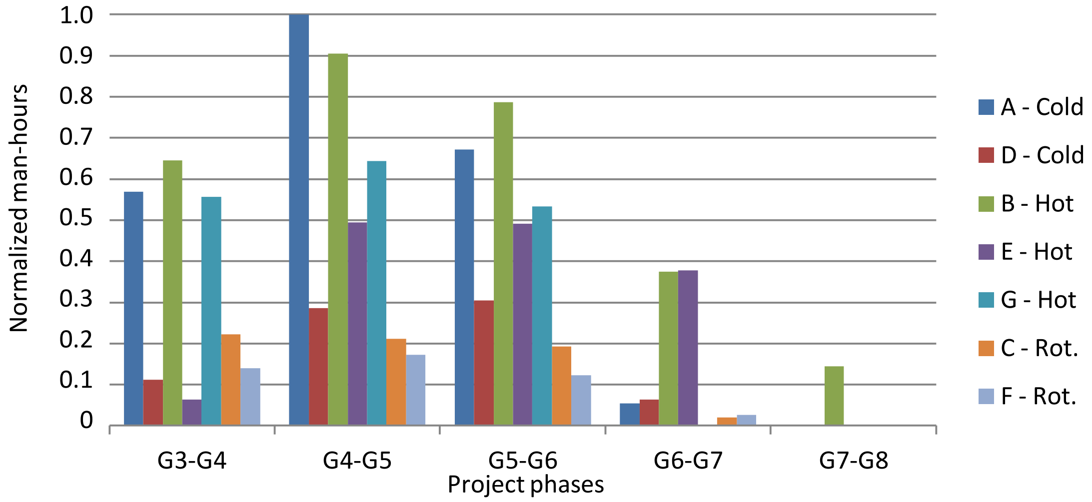


Figure 11. Outcome of labor intensity

All three presented charts show that there is a rather large variation between projects, even within component types. However, to become aware of the need of planning differently, the plan of man-hours and the difference between reported and planned man-hours must be studied.

The patterns of planned work and labor intensity have been studied. Charts illustrating planned work and planned labor intensity are included in Appendix A together with outcome of work, Figure 9, and outcome of labor intensity, Figure 11.

The pattern of plan of work is bell-shaped and six out of seven projects have their planned peak in G4-G5. A comparison of the patterns of outcome and plan gives that although both are bell-shaped the peaks do not match as in most projects reported work peak in phase G5-G6 and planned work peak in G4-G5.

However, the pattern of plan of labor intensity resembles a downhill, meaning that planned man-hours divided with respective phase duration decrease in each phase. Four out of seven projects have their highest value in G3-G4, the remaining three projects peak in G4-G5 but with a value just above the value in G3-G4. Highest labor intensity is thus wanted in the early phases of the development. A comparison of the patterns of outcome and plan of labor intensity thus gives that the patterns are not similar as reported labor intensity is bell-shaped where most projects peak in phase G4-G5. A schematic picture illustrating the difference between a bell-shaped curve and a downhill is shown in Figure 12 below.

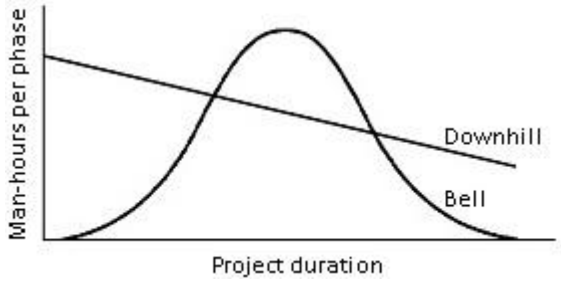


Figure 12. Schematic picture of a bell-shaped curve and a downhill

In Figure 13 the outcome and plan of work in projects' phases are compared. A study of the chart gives that there are large variations between projects' outcome divided with plan. From the chart it can also be seen that in phase G4-G5 all but one project have an outcome higher than plan, and in G5-G6 all projects have an outcome much higher than plan.

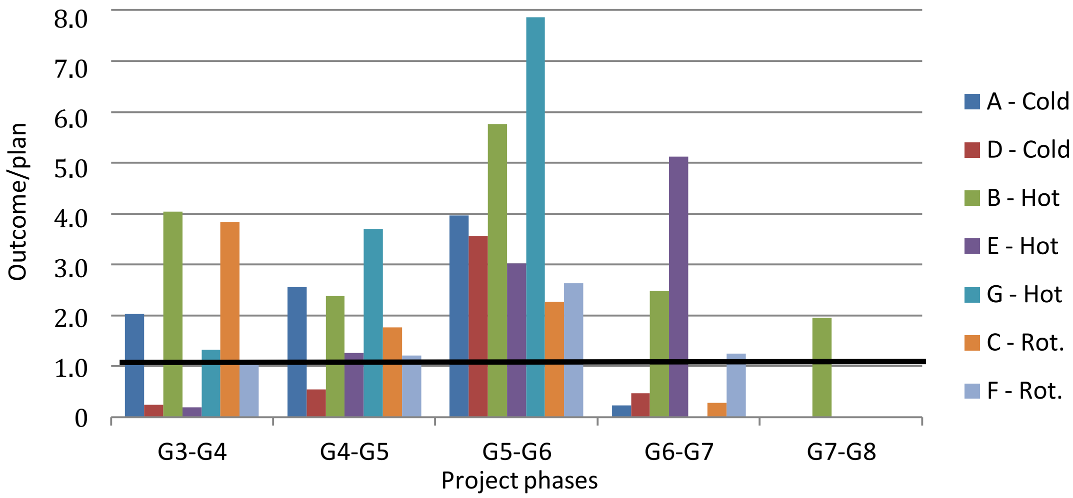


Figure 13. Comparison of outcome and plan of work in projects

This study of patterns of work-load and labor intensity indicates that initial project plans are in most cases not met. The four most important observations are:

- The amount of work in project phase G5-G6 is significantly underestimated in all projects.
- For most projects the work-load peak is planned to phase G4-G5, but is actually in G5-G6.
- For most projects labor intensity is planned as a downhill but is instead bell-shaped. Although highest labor intensity is wanted in G3-G4 the actual labor intensity peak in G4-G5.
- There is large variation between all projects' outcome of work, labor intensity and work divided with plan.

5.3 Variation between projects

In Section 5.2 it was observed that there is large variation in the projects' outcome of workload, even within component types. In this section, this variation between projects is defined and the usefulness of data from previous projects when planning new projects is explored.

In this analysis, all projects mentioned in Section 5.1 are included except for Project K and L in which rare events have led to much more work in G3-G4 than planned for, and would thus distort the calculations if included.

The variation between analyzed projects is presented in Table 2. The values are calculated through division of the standard deviation and the mean of all related projects. The closer a value is to zero, the smaller the variation. This approach of dividing the standard deviation with the mean makes it possible to compare the variation between data sets that have widely different means (UCLA Academic Technology Services, Statistical Consulting Group, 2008). The column G3-G8 is not the sum of the other columns and the row of all projects is not the sum of the other rows. The reason to the two zero values in column G7-G8 is that the projects have come that far but have zero man-hours reported in this phase.

Table 2. Variation between projects expressed as division of standard deviation and mean of projects.

	G3-G4	G4-G5	G5-G6	G6-G7	G7-G8	G3-G8
Cold structures	0.59	0.87	0.26	0.44	0	**0.56**
Hot structures	0.74	0.35	0.42	0.29	1.41	**0.47**
Rotating spools	0.17	0.45	0.25	0.75	0	**0.27**
All projects	0.73	0.65	0.60	1.25	2.45	**0.67**

The table shows that there is large variation between projects, even when grouped by component type. The value of 0.47 for whole hot structure projects means that the limits of one standard deviation are placed 0.47 times the mean of the population away from the mean, both above and below. Project outcomes are assumed to be normally distributed. From the definition of standard deviation and normal distribution, this means that if the mean of hot structure projects is directly used to make an estimate of a new project there is only 68%[3] likelihood that the outcome will be within 0.53–1.47 times the mean of hot structure projects. In this context of planning large development projects with a lot of required man-hours, this wide range of possible outcomes with this likelihood is not good enough for using previous project data to support project planning. A value below 0.1 may perhaps be regarded as good in this context when there is 95% likelihood of having a result within 0.8–1.2 times the used mean.

The value of whole cold structure projects is larger than of hot structure projects, and so is the value of all completed projects. The value of rotating spools projects is lower than of hot structure projects, but 0.27 is still far from what may be regarded as good.

[3] The probability of having a result within one standard deviation plus-minus from the mean when assuming normal distribution is approximately 68%, within two standard deviations approximately 95% and within three standard deviations approximately 99.7%. (Montgomery & Runger, 2006, pp. 122-123)

These results are not surprising as the preconditions for the projects differ a lot, which is described in previous sections. To be able to use data from previous projects to support planning of new projects the different preconditions of projects must be taken into account to have reasonable estimates.

If the projects could be normalized regarding different preconditions the systematic differences between projects would be taken away and only a smaller common variation would persist. An estimate from these normalized project values would then be much better as the range of possible outcomes for one standard deviation would have reduced a lot, and leading to a higher probability for the estimate.

Volvo Aero has, with purpose to compare cost of projects in a more fair way, developed a model that aims to normalize projects with regard to different conditions (Högberg, 2011). This model gives each project a complexity index based on number of pre-series hardware (N_{hw}), number of interfaces (N_{if}), number of parts (N_{part}) and a measure of how large the technology step was in relation to previous projects (N_{Δ}), see Equation . The technology step reflects both knowledge of product design and production method.

Equation 1. Complexity index

$$Complexity\ index = \frac{\frac{N_{hw}}{N_{hw,ref}} + \frac{N_{if}}{N_{if,ref}} + \left(\frac{N_{part}}{N_{part,ref}}\right)^{0,5} + \frac{N_{\Delta}}{N_{\Delta,ref}}}{4}$$

Using the model, one project is set as reference, with the complexity index one, and all other projects' complexity indices are set relative to the reference. The complexity indices of the analyzed projects are displayed in Table 3 below.

Table 3. Complexity indices of projects

Cold structures					Hot structures					Rot. spools	
A	D	H	I	J	B(ref)	E	G	K	L	C	F
1.7	1.48	2.07	1.16	1.21	1	0.82	1.2	1.01	0.97	0.65	0.58

In this report, the complexity indices of projects have been used to normalize man-hours of projects. This should not be that different than normalizing costs as the largest part of project cost is the cost of personnel. Project B was used as reference, and by multiplying Project B's reported man-hours with each project's complexity index a calculated value of man-hours for each project was obtained. For each project the reported man-hours were thereafter divided with the calculated value to get a value of how close the actual outcome was to the complexity index calculated outcome. Using these values were then the mean, standard deviation and standard deviation divided with mean for the component types and all projects found. Table 4 below displays these values of standard deviation divided with mean which represents the variation between projects when complexity indices have been applied. The values in Table 4 are directly comparable with the values in Table 2.

Table 4. Variation between projects when complexity indices are applied.

	G3-G4	G4-G5	G5-G6	G6-G7	G7-G8	G3-G8
Cold structures	0.56	0.81	0.16	0.52	0	**0.47**
Hot structures	0.71	0.35	0.40	0.42	1.41	**0.34**
Rotating spools	0.09	0.38	0.17	0.80	0	**0.19**
All projects	0.56	0.47	0.55	1.30	2.45	**0.58**

An examination of the values in the table gives that the variation between whole projects is still large. A comparison with Table 2 gives that the use of the complexity index has managed to reduce the variation between whole projects by about 0.1. For example has the G3-G8 value of all projects moved from 0.67 to 0.58.

5.4 Discussion

In Figure 13, reported work in projects' phases was compared to planned work. This comparison showed that projects' outcome in most cases not match plan and this gives reason to believe that more tools to support planning are needed.

Uncertainty is always present when executing projects and poor estimates, unexpected technical difficulties and specification changes among other things may lead to an outcome different than plan. Giving specific reasons to why the analyzed projects differ from plan are not the focus of this discussion, and it would require a much more in detail study of all projects to pinpoint exactly all things that happened in the projects. This discussion focuses more on that outcome of projects differ from plan, that this is due to poor planning or occurrence of unfavorable events, and that this difference must be dealt with to have more efficient plans of new projects.

The studied patterns of work-load indicate that planned work-load peak does not match actual peak. For most projects the peak is planned to phase G4-G5 but for most projects the actual peak is in G5-G6. The comparison of projects' outcome divided with plan of work gave that especially in phase G5-G6 the amount of work is significantly underestimated for all projects.

The studied patterns of labor intensity showed that Volvo Aero wants to have highest labor intensity in G3-G4 and G4-G5 and that it should decrease gradually, but this is not how the projects turn out. Instead, labor intensity is highest in G4-G5 and second highest in G5-G6.

The patterns of work-load and labor intensity thus indicate that more work is done and more resources are used than planned for late in the development process, meaning just before G6 where series manufacturing is about to start. This coincides with what Volvo Aero has told about their projects. Often extra resources are introduced late in the development process and many problems are solved at the back end, so called firefighting. This event of introducing extra resources late in a project may have the consequence that not enough resources are assigned to a project in an early development phase, and the consequence of this may be that the project also needs extra resources later in the process.

Although there is highest ability to influence the final characteristics of the product without significantly impacting cost in the beginning of a project, this does not necessarily mean that there must be most work done and highest amount of resources assigned in the beginning of the project. The process should be front-loaded to have just enough resources in the beginning of a project to completely understand the problem and the trade-offs on a set of solutions. If things are done right the first time, costly changes later in the project can be avoided.

In the case of projects at Volvo Aero, perhaps higher labor intensity in the beginning of projects would have made that more problems were solved earlier and that not as many resources were needed just before G6. As Volvo Aero's development is dependent to the aircraft engine OEM's development and customer changes are not uncommon, it is not possible to make a conclusion that higher labor intensity in the beginning would have prevented this. However, if they had been more prepared for requirement changes they could perhaps have avoided to do as much work late in the process.

Using data of man-hours in completed projects is one method to make estimates of new projects, called analogous estimation. However, as was made clear in Section 5.3, the variation between completed projects is too large for using the mean of projects within a component type to make an estimate a new project. The range of possible results would be too wide to be useful. At this time only a few projects were completed and more projects would perhaps have led to a smaller variation, but as the conditions for the projects differ more than what component to develop the variation would still be too large for using the mean of projects as a good estimate of a new project. For the data on man-hours in completed projects to be useful the different preconditions of projects must therefore be taken into account. The use of the complexity index model developed by Volvo Aero aimed at normalizing projects, but as the result showed, the projects were brought only somewhat closer each other and not enough for only using complexity indices and previous project outcomes to make a project estimate. A conclusion can therefore be made that the underlying model of the complexity index cannot reduce the systematic differences between projects enough for estimates, using the complexity index, to be of practical use. A complexity index model better in this purpose to normalize man-hours in projects is therefore asked for.

6. SIMULATION OF THE DEVELOPMENT PROCESS

As mentioned previously in the report, resource allocation and activity durations are important issues when it comes to implementing a development project with positive results. In Chapter 5, the charts illustrate a variation between outcome and plan of work and labor intensity. This indicates difficulties when estimating resources and activity durations. In some cases have, however, unplanned events occurred and forced rework and delays. Hence, the need for better plans and being more prepared to handle disturbances is evident. This chapter presents the results of using simulation as a tool to increase understanding of development processes regarding how disturbances and changes to the process affect, but also how simulation can help planning resources in projects.

In order to be able to answer RQ 4, three additional questions were set up:

1. How do disturbances affect the process in terms of duration?
2. How does a drastic improvement in the duration of an activity impact the overall process?
3. How will number of available resources affect cost and duration of a process?

First in this chapter there is a section about the assumptions made for constructing the model. Thereafter, the results from all the simulations are presented and the questions above answered. The results are presented in the same order as the questions. The chapter ends with a discussion about the simulations made and the simulation program used.

In order to perform a simulation knowledge is required of how activities are related to each other, sequence of activities and other characteristics that are of importance for the simulation such as activity durations. All simulations begin with building a model of the process. As said in Chapter 3, the most suitable model for simulating Volvo Aero's development process is GERT since it can handle probabilities of events to occur and iterations. This is of great importance when disturbances are common in development processes and may cause rework. The simulation model has mainly been used for construction of the process which then has been used as a basis for the simulations. As said earlier in the report, the used simulation program, Simul8, is suitable for this kind of processes since it can deal with probabilities and iteration.

6.1 ASSUMPTIONS AND SIMPLIFICATIONS OF THE PROCESS

Development processes often have a high complexity and are large-scaled, so also Volvo Aero's development process. Because of this and the time limitation, it was selected to simulate a small part of the process. The real process has much more connections and information flows that go back and forth between activities. This has been simplified since it is essentially the method of using simulation which is in focus.

The simulated flow is between G3 and G4 which is an early design phase. That particular part of the process was of interest because there is a recent improvement of the process that could be evaluated while it is a phase that is exposed to disturbances. The simulated improvement is a changed mesh method that contributes to a shorter duration of the mesh activity.

All three questions will be answered using this same process flow as base. The process flow used in the simulations can be seen in Figure 14 and a view of how the process looked like in the simulation program can be found in Appendix B. The process flow contains of six different analyses. All the analysis activities, 1-6, have different durations but consist of similar activities, see Figure 15. The four activities that are referred to as BL in Figure 14 stand for different design activities and the released design baseline. In reality, design engineers are working during the whole process but in order to be able to simulate it has been chosen to model the process as shown below. In the BL activities the design of the component is updated. An assumption made for the simulations is that it is not possible to place more than one resource per activity.

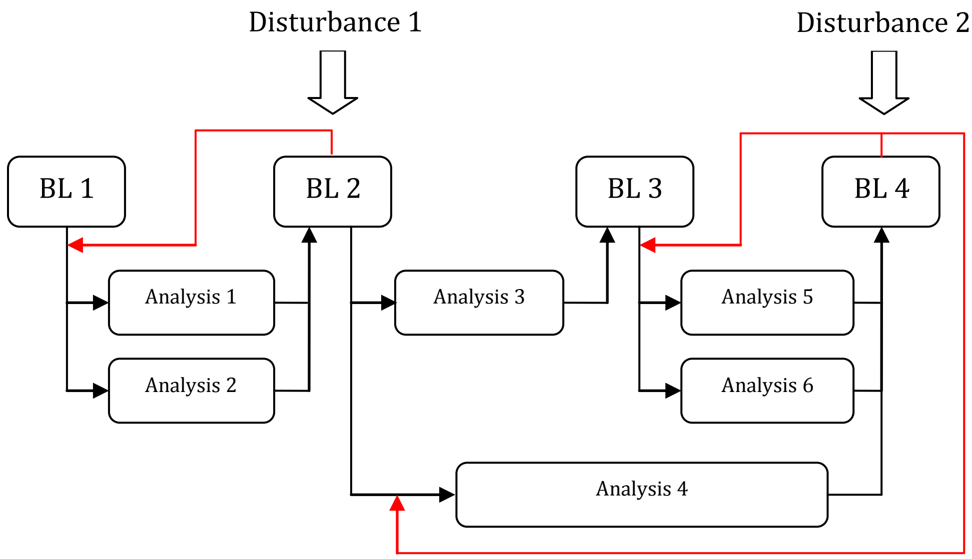


Figure 14. A simplified view of the simulated process

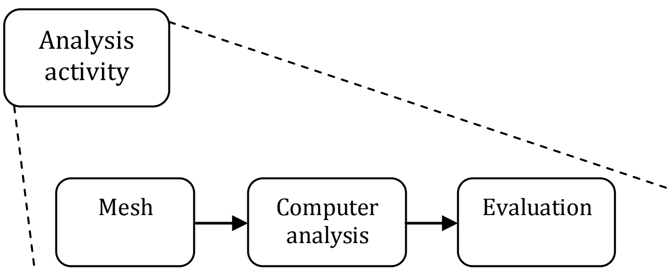


Figure 15. The activities within each analysis

The simulations have been conducted with Monte Carlo sampling[4] and each simulation consisted of 10 000 runs through the process. Two iterations, as result of disturbances, were included in the model and are represented by red arrows in Figure 14. The probability that a disturbance would occur was set to 20%, and as the disturbances lead to

[4] The Monte Carlo sampling is used to randomly generate values from the given distribution for each activity.

rework learning effects has been taken into account through decreasing the duration of an activity for each attempt.

Small disturbances occur quite often in development projects and they have been included by describing activity durations using probability distributions. The distribution used is normal distribution with a standard deviation of 25% of mean.

6.2 Effects of the disturbances and implementation of improvement

In this section the first two questions will be answered by simulating the old and the improved process with and without added disturbances. Both simulations are performed with unlimited number of resources.

In Volvo Aero's development process, there is a high risk of disturbances which made it interesting and relevant to evaluate whether it is suitable to simulate disturbances in order to see how they affect the lead time for the process. Although, it may not be efficient to have too big margins and plan for disturbances, it is important to be aware of them and know how to act when they occur and here simulation may be of help.

The simulations made for answering the first question, the old process is simulated in three different simulation setups. First the process is simulated without disturbances, then with one disturbance and last with two disturbances. The results from these simulations are shown in Figure 16 where the black histograms show the frequency of completed processes within the selected intervals, on the x-axis, and the red lines show the probability of a completed process at a specific time.

The charts, in Figure 16, show that the lead time increases as the disturbances occur, while the probability of a complete process, for example, at 16 weeks decreases markedly. This indicates a higher uncertainty in processes when there is risk of disturbances to occur.

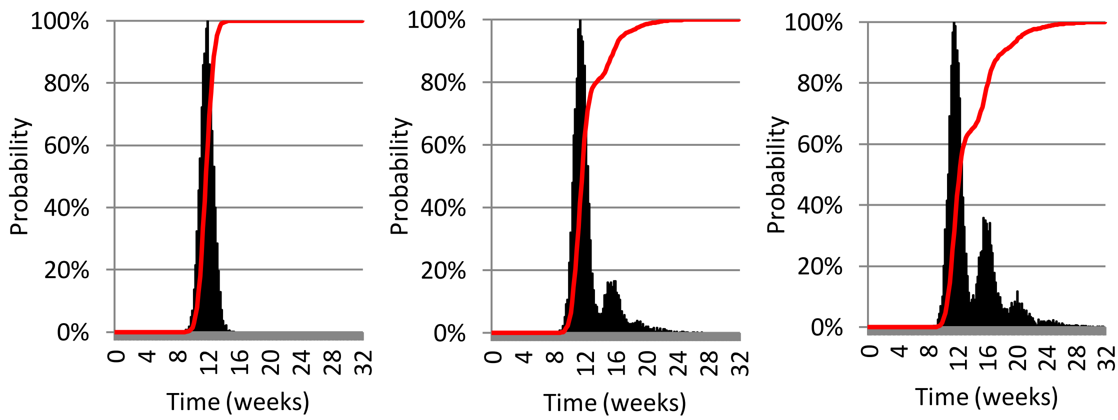


Figure 16. Histogram and probabilities of lead time with and without disturbances. From the left, the old process without disturbances, with one disturbance and last with two disturbances

The improvement, which was chosen to simulate in order to answer the second question, is a new method to mesh where the duration of the mesh activity decreases from 1 ½ week down to 2 hours. The old mesh method was obviously time-consuming and required a lot of preparation but now with the new improved method a lot of the work is automated. The charts in Figure 16 are made with the old mesh-method and are compared with Figure 17 where the results from the simulation of the improvement are shown. The comparison shows a reduction in lead time when simulating the improved process, which is understandable when some of the activities go much faster in the new process. It can also be read out of the charts that the probability that the process is completed at a given time is higher with the improved process. Data have been picked out from the charts and are shown in Table 5. This has been done in order to present the differences and advantages with the improved process in a more clear way.

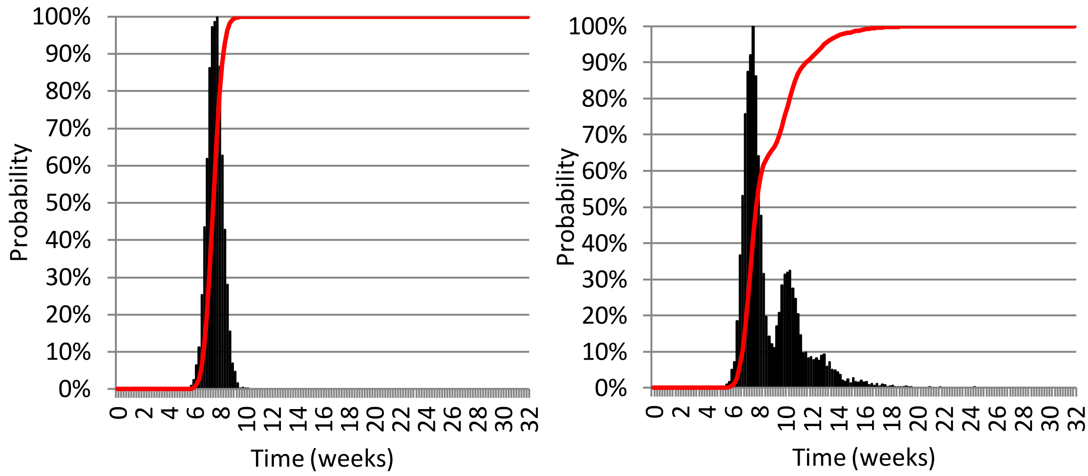


Figure 17. New method without disturbances, left chart, and with two disturbances, right chart

It has been selected to compare lead times at 30% and 85% probability of completing the process, and thus easier see how disturbances affect the process in terms of lead time, but also how the process with the new mesh method better can cope with disturbances. The lead times for the different probabilities and processes are compiled in Table 5.

Table 5. Comparison between new and old method

	Probability of completed process, without disturbances		Probability of completed process, with one added disturbance		Probability of completed process, with two added disturbances	
	30%	85%	30%	85%	30%	85%
Old method	11.5 weeks	12.8 weeks	11.5 weeks	15.2 weeks	11.7 weeks	16.9 weeks
New method	7.4 weeks	8.4 weeks	7.5 weeks	10.3 weeks	7.5 weeks	11 weeks

Both the old and the new process show no major change in lead time when disturbances occur when it comes to the low probability, but the lead time at the probability 85% differs much more between the two methods. The difference between same probability values of the new process is lower than for the old process, and the lead time for the new process with two disturbances included with 85% probability is lower than the old process's lead time with 30% probability and no added disturbances. This shows how valuable the new mesh method is when it comes to process duration and handling disturbances.

6.3 Resource allocation

Many times when delays and rework are a fact the first thought is to put in as much resources as possible to get the job done quickly and not increase the cost and lead time too much. To investigate if simulation can give a better insight on how to solve resource issues and guide how to allocate resources, the simulation model has been assigned a different number of available resources. It is also investigated whether it is more profitable to have all the resources linked to only one project or have a resource pool where two projects share resources. The simulated process looks like the one in Figure 14 and when two projects are simulated an exact copy of the process has been added in parallel, see Figure 18. A single project has been simulated using one and up to three resources because of the maximum three parallel flows. Resource sharing between two projects has been simulated with one and up to six shared resources because of the maximum six parallel flows.

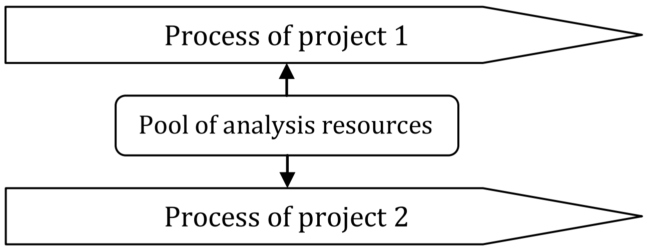


Figure 18. A view of the shared resource pool between two projects

In Figure 19 is the result from the resource simulations presented. The number next to each point represents the number of resources that cost and duration is expressed for. The duration used is when there is 75% probability of finishing the process. The cost is calculated from number of people, project duration and the hourly rate which is estimated to 1000 SEK/hour. In the case of shared resources the cost is divided in two to express the cost for one project.

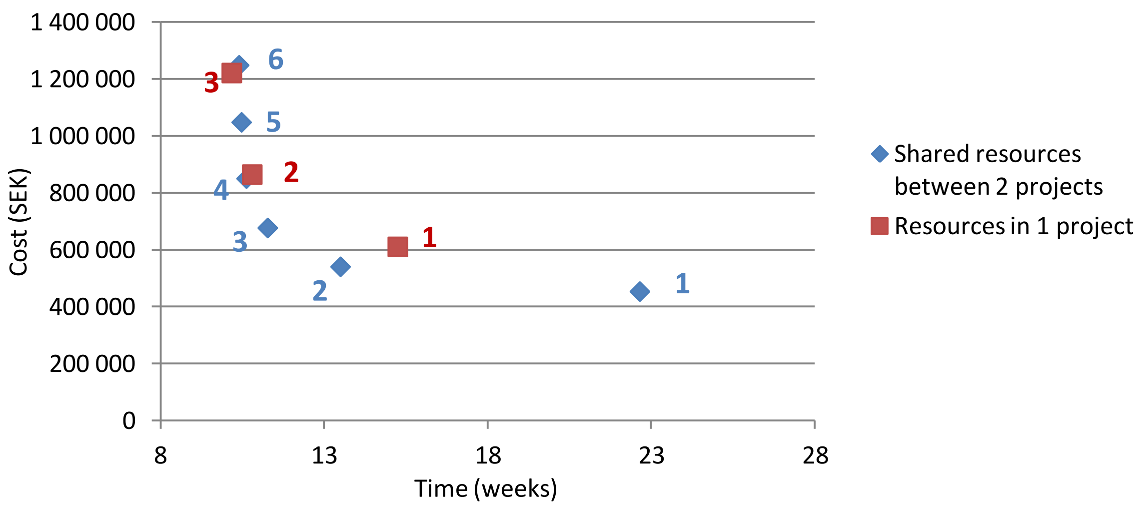


Figure 19. Lead time and cost for different number of available resources

Figure 19 indicates that it is not always best to put in as much resources as possible. When only one resource is available the lead time is high but the total cost is rather low. Using more resources reduces lead time but not in correlation to how the cost increases. This is due to that resources are calculated to cost for the whole project even though they are not covered to 100%.

The most efficient resource allocation is influenced by what the simulated process looks like and whether cost or lead time is most important. According to this process it is more efficient to share up to four resources when it comes to both cost and lead time instead of link one or two persons to one project. One reason for this could be that by sharing resources some parts of the waiting time is decreased by that resources can be used in the other project and thus get an higher utilization of resources.

If only evaluating the blue points in Figure 19, which represents resource sharing between two projects, it is not beneficial to have more than four resources. The difference between having four, five or six resources is very little in terms of lead time while the cost increases significantly. This is also shown in Figure 20 and Figure 21.

The probability curves for when the project is completed with different number of resources, when resources are shared with a similar project, are displayed in Figure 20. The black vertical line in the figure shows the probability for the process to be completed at 10 weeks depending on how many resources that is included.

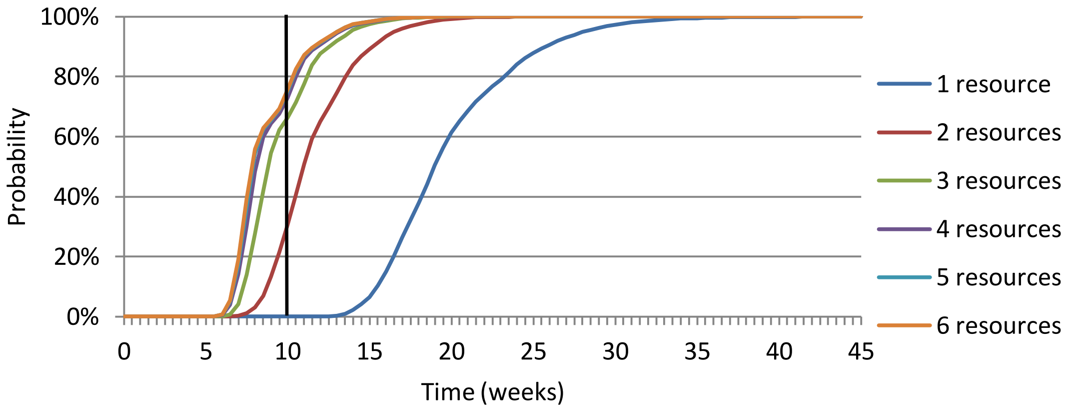


Figure 20. Probability curves for different number of resources

The probability for the process to be completed at 10 weeks for different number of resources is more clearly shown in Figure 21. With one or two resources the probability is very low, but having four to six resources the probability is almost the same at above 70%.

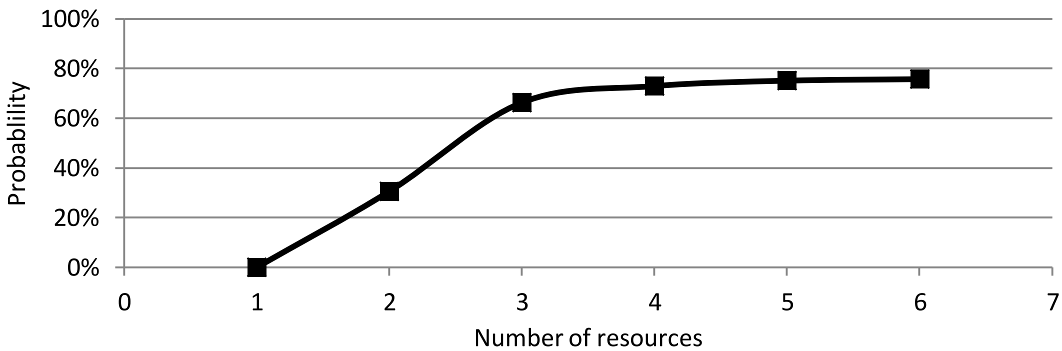


Figure 21. The probability that the process is completed at 10 weeks

6.4 DISCUSSION

By dividing RQ 4 into three sub questions a deeper insight of what knowledge can be gained and which problems can be solved by using simulation as a tool in development projects could be achieved.

The first two simulation tests were made to study how disturbances affect the development process and how an improved process handles disturbances compared to the old process. The advantage with simulation of improvements, before implementing them into the real process, is the chance to test whether the improvement is good enough in comparison with the money and time to be invested, but also to see the impact it has on the process. The outcome of the simulation indicates a more robust process when the new mesh method is implemented. Compared to the old process the new process has a shorter lead time and could also handle disturbances faster. This can lead to a faster process or have time to improve the design further and make an additional analysis. Even if the outcome of a simulation looks good it is easy to be fooled when this kind of result is interpreted. It must be remembered what has been simulated and the conditions inserted in the simulation.

The last simulation test was made to evaluate how the number of available resources affects lead time and cost, but also if there is some advantage of shared resources between two projects. The results indicate a small advantage of shared resources but only as long as the number of resources are fewer than the number of parallel flows. By simulating with various numbers of available resources, awareness can be obtained about how resource allocation decisions can affect a project's lead time.

When analyzing how resources should be placed and how many, it is important to have a clear picture of what the simulation aims at fulfilling. For example, if it strives to finish the activities as soon as possible or to as low cost as possible or both. It is also important to have good knowledge about how the process is built up, especially when the process is complex with much dependence between the activities.

The simulation tests made show examples on how simulation can help to understand the development process and to support planning.

6.4.1 EVALUATION OF SIMUL8

Simul8 is a user-friendly program where previous knowledge about simulation programs is not necessary. The logic of the program is easy to understand and it is almost immediately possible to set up a process. A major advantage of the program is the possibility to import and export data from Excel, which for example can simplify changes of activities' duration.

During the simulation of resource allocation, a limitation of the program was discovered. It was only possible to connect one resource to each activity. The limitation did not contribute to any major problem in the simulations made but when simulating a larger process or investigating another issue this may be a desirable option.

In the introduction of Simul8 it was mentioned that it is possible to use the programming language VBA to add conditions for the simulation. It is an effective way to set up the conditions for the simulation and sometimes necessary, but depending on previous knowledge of programming, it may require different effort to understand and be able to use this alternative.

Overall, Simul8 is a useful program for similar simulation as the ones above. However, a larger and more complex development process may be difficult to simulate.

7. Discussion and conclusions

As mentioned in the introduction, suppliers of aircraft engine components are all the time pressed to make improvements to stay competitive. Not only do they need to develop and manufacture better components faster they must also do this in a more cost efficient way. To develop components in a cost efficient way it is important that the project plan as accurately as possible can describe the outcome of a project. Having more resources than actually needed makes a project inefficient. However, having too few resources in the early phases of a development project can also make a project inefficient if, in order to meet a set deadline, a lot of extra resources must be put in late in the project.

It was also said that, to improve the ability to anticipate the outcome of projects an increased understanding of the development process is needed regarding amount of work, resources and how disturbances affect amount of work and resources.

The two studied methods in this report, distribution of man-hours in projects and process simulation, have both showed potential for increasing understanding of the development process and to support planning of projects.

Studying how man-hours are distributed over projects' phases has shown to give understanding about the amount of work carried out in different phases of projects and how the amount of work differs between phases. By dividing the amount of work in a phase with the phase duration the labor intensity was obtained. This gives more of an understanding how many resources are assigned in different phases and how the labor intensity differs between phases. Knowledge about the patterns of outcome of work-load and labor intensity can guide planning of new projects in the way of knowing how the work-load and labor intensity should differ between phases. Comparisons of patterns of outcome and plan of work-load and labor intensity give understanding about the need of planning differently. The heights of the patterns are interesting but also whether reported and planned peak are in same phase. Comparisons of outcome and plan in projects' phases give understanding about which phases that often are estimated too low or too high.

The actual data of man-hours in projects' phases should also be possible to use as basis for estimates of man-hours in new projects' phases, using so called analogous estimation. However, as seen in the case of projects at Volvo Aero when the conditions for the projects differ much and the variation is large, only using the mean of previous projects developing same component type as an estimate is not sufficiently accurate. The probability for the outcome to be close to the estimate would be small. More completed projects would probably have decreased the variation somewhat, but the need of considering more than what component to develop was obvious. For example, the knowledge that can be reused plays a big role when executing new projects. In this report the use of the complexity index model developed by Volvo Aero aimed at reducing the variation between projects by taking away the systematic differences between projects due to different preconditions. However, the underlying model of the complexity index was found not good enough as the projects were brought only somewhat closer and not sufficient to make good estimates.

In the study of Volvo Aero's projects it was decided to use the project phases in the GDP, which all new Volvo Aero projects follow, to be able to compare projects with different duration and to divide project duration by the type of development work being done. When resources in a new project is to be planned it also makes more sense to consider what type of development work that is to be done, than a measure how far into the project one is. Project resources have been analyzed as a whole, but to get understanding and make estimates on different resource types the different resource types must be analyzed separately.

Simulation of product development processes has shown potential to be a good support in order to get a deeper understanding of process behavior and to make better plans, especially at a more detailed level where dependencies between activities are easier to detect. Limitations for using simulation are though the complexity of the process and the knowledge about the process.

In the first simulation tests made the focus was to investigate how the lead time changes when disturbances occur, and how an improved process handles disturbances compared to the old. This gives an understanding of how disturbances and changes affect the process. Although the knowledge about disturbances may not influence a project's initial plans, due to that it may not be worth planning for disturbances, it makes the project team aware of how a disturbance affect and how to act when one occurs. This is valuable as the situation in development projects often is extremely stressful. The knowledge about how an improved process handles disturbances compared to the old can be valuable when thinking of implementing an improvement and if it then is possible to further optimize the design.

As demonstrated by the comparison of planned man-hours in projects and the actual outcome, resource utilization is an important issue when planning projects, both regarding cost and lead time. The last simulation test made shows the potential of using simulation in order to find the most efficient way of allocating resources as different alternatives easily can be evaluated. By simulating a process with different amount of available resources an understanding of how resources affect the process can be obtained which can be used when planning projects.

There are most certainly other issues and situations than those that have been evaluated in this study where simulation can be of help, for example to identify bottlenecks in a process. From simulation of different scenarios and see the effects a deeper knowledge about the process's behavior can be obtained. It also reduces the risk of miscalculations because of the possibility of testing. Process simulation can thus be of help when planning projects.

To conclude this report, the method of studying how man-hours are distributed over projects' phases gives a valuable understanding of the development process and can guide planning on an overall project level. Although only total resources have been studied in this report it is possible to study different types of resources. However, to be able to make good predictions of future projects enough project data with a small variation must exist. This can be achieved by having completed many similar projects and by using a model that can normalize projects regarding different preconditions in a good way, which the model used in this report could not.

The method of simulating development processes can give valuable understanding of how the process behaves, how the number of available resources affects and how disturbances affect. This understanding and the evaluation of different scenarios can guide planning on a detailed project level. The answers searched for using simulation decides the needed size and the level of detail of the process model. However, to make a reliable simulation good knowledge about what the development process looks like is needed. Simulating whole product development projects in detail therefore seems impractical but also unnecessary as it can be difficult to see the effects.

8. RECOMMENDATIONS

Studying the amount of work and labor intensity in projects' phases has shown potential to give a good understanding of the process and can support project planning. Volvo Aero and other companies in the same situation can benefit from continuing this work. However, for this to be practical companies must in a systematic and perhaps automated way collect the needed project data. If not many projects with similar preconditions have been completed an effort should be made on developing a model that can normalize projects regarding different preconditions to be able to make good estimates of new projects. Different types of resources should be studied to get more useful information about how many resources to assign projects.

Simulating a development process or a part of it has shown potential to give an increased insight of the process and its behavior which can be useful when planning projects or when disturbances occur. Many things and many scenarios can be studied with simulation, but in order to make a reliable simulation good knowledge about the process is needed. Volvo Aero and similar companies can definitely benefit from conducting process simulations to for example find most efficient resource allocation and understand how disturbances affect lead time. However, they must strive to make the development process more clear, especially between different resource disciplines, and be able to set truthful durations on activities.

Volvo Aero and other aircraft engine component suppliers will most likely have use of studying man-hours in projects and simulating their process, but it will take some time before good routines for data collection and good assumptions for the process model can give reliable and useful results. Next step for Volvo Aero should now be to simulate more parts of the development process, with reliable input data, to understand them better and to find improvements. For these simulations they should use the process simulation software Simul8 which they already use in the company and is relatively easy to use.

REFERENCES

Business Dictionary. (2011). *Original equipment manufacturer (OEM) definition*. (BusinessDictionary) Retrieved February 9, 2011, from BusinessDictionary: http://www.businessdictionary.com/definition/original-equipment-manufacturer-OEM.html

Chalupnik, M. J., Wynn, D. C., & Clarkson, P. J. (2009). Approaches to Mitigate the Impact of Uncertainty in Development Processes. *International Conference on Engineering Design.* Stanford University, CA, USA.

Cho, S.-H., & Eppinger, S. D. (2005). A Simulation-Based Process Model for Managing Complex Design Projects. *IEEE Transactions on Engineering Management , 52* (3), 316-328.

Eppinger, S. D., & Smith, R. P. (1997). Identifying controlling features of engineering design iteration. *Management Science , 43* (3), 276-293.

Eppinger, S. D., Whitney, D. E., & Gebala, D. A. (1992). Organizing the Tasks in Complex Design Projects: Development of Tools to Represent Design Procedures. *NSF Design and Manufacturing Systems Conference*, (pp. 301-309). Atlanta, Georgia.

Flanagan, T. L., Eckert, C. M., Keller, R., & Clarkson, P. J. (2005). Robust planning of design tasks using simulation. *International conference on engineering design*, (pp. 1-12). Melbourne.

Harrison, M. J. (2003). *U.S. versus EU Competition Policy: The Boeing-McDonnell Douglas Merger.* American Consortium on European Union Studies (ACES).

Högberg, J. (2011). *Measuring product development performance at Volvo Aero - Evaluating efficiency by normalizing complexity.* Göteborg: Chalmers University of Technology.

Joglekar, N. R., & Ford, D. N. (2005). Product development resource allocation with foresight. *European Journal of Operational Research , 160* (1), 72-87.

Karniel, A., & Reich, Y. (2009). From DSM-Based Planning to Design Process Simulation: A Review of Process Scheme Logic Verification Issues. *IEEE Transactions on Engineering Management , 56* (4), 636-649.

Krishnan, V., Eppinger, S. D., & Whitney, D. E. (1997). A model-based Framework to overlap product development activities. *Management Science , 43* (4), 437-451.

Kumanan, S., & Krishnaiah Chetty, O. V. (2006). Estimating product development cycle time using Petri Net. *The International Journal of Advanced Manufacturing Technology , 28*, 215-220.

Licht, T., Schmidt, L., Schlich, C. M., Dohmen, L., & Holger, L. (2007). Person-centred simulation of product development processes. *International Journal Simulation and Process Modelling , 3* (4), 204-218.

Liker, J. K., & Morgan, J. M. (2006, May). The Toyota Way in Services: The Case of Lean Product Development. *Academy of Management Perspectives* , pp. 5-20.

Löfstrand, M., & Isaksson, O. (2010). A process modelling and simulation approach for business decision support in pre-conceptual product design. *International Journal of Product Development , 12* (2), 158-175.

Mankins, J. C. (1995). *Technology Readiness Level.* NASA, Office of Space Access and Technology.

McQuarrie, E. F. (2006). *The Market Research Toolbox: A Concise Guide for Beginners* (2nd ed.). Thousand Oaks, California: Sage Publications, Inc.

Montgomery, D. C., & Runger, G. C. (2006). *Applied Statistics and Probabilty for Engineers* (4th ed.). USA: John Wiley & Sons, Inc.

NetMBA. (2010). *PERT chart*. Retrieved March 28, 2011, from NetMBA Business Knowledge Center: http://www.netmba.com/operations/project/pert/

Pardessus, T. (2004). Concurrent Engineering Development and Practices for Aircraft Design at Airbus. *24th International Congress of the Aeronautical Sciences*, (pp. 1-9).

Pinto, J. K. (2010). *Project Management - Achieving Competitive Advantage - International Edition* (Second Edition ed.). New Jersey, USA: Pearson Education, Inc.

Project Management Institute. (2008). *A Guide to the Project Management Body of Knowledge (PMBOK® Guide) - Fourth Edition.* Newtown Square, Pennsylvania, USA: Project Management Institute.

Scott, D., Hedenryd, E., & Buxton, D. (2006). *Current Aero-Industry Business Models.* VIVACE Consortium.

Simul8 Corporation. (2011). *What is simulation - Simulation software explained*. Retrieved May 10, 2011, from Simulation software by Simul8: http://www.simul8.com/products/what_is_simulation.htm

Smith, R. P., & Morrow, J. A. (1999). Product development process modeling. *Design Studies , 20* (3), 237-261.

Sommer, B., & Sommer, R. (1997). *A Practical Guide to Behavioral Research* (4th ed.). New York: Oxford University Press, Inc.

Sørensen, H. T., Sabroe, S., & Olsen, J. (1996). A Framework for Evaluation of Secondary Data Sources for Epidemiological Research. *International Journal of Epidemiology , 25* (2), 435-442.

Stackpole, B. (2011, April 15). *Applying Lean to Product Development*. Retrieved May 31, 2011, from Design News: http://www.designnews.com/article/talkback/517860-Applying_Lean_to_Product_Development.php#176180

UCLA Academic Technology Services, Statistical Consulting Group. (2008, July 10). *FAQ: What is the coefficient of variation?* Retrieved November 30, 2011, from UCLA Academic Technology Services: http://www.ats.ucla.edu/stat/mult_pkg/faq/general/coefficient_of_variation.htm

Unger, D. W., & Eppinger, S. D. (2009). Comparing product development processes and managing risks. *International Journal of Product Development , 8* (4), 382-402.

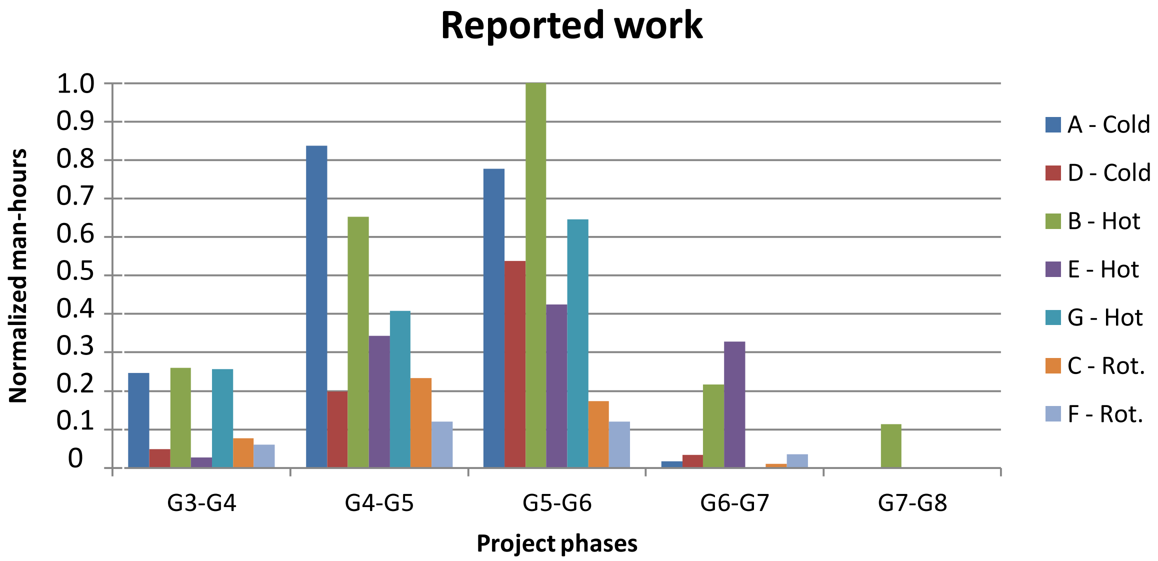
Volvo Aero Corporation. (2007). *Our company: Volvo Aero*. Retrieved March 30, 2011, from Volvo Aero: http://www.volvoaero.com/volvoaero/global/en-gb/aboutus/Pages/our_company.aspx

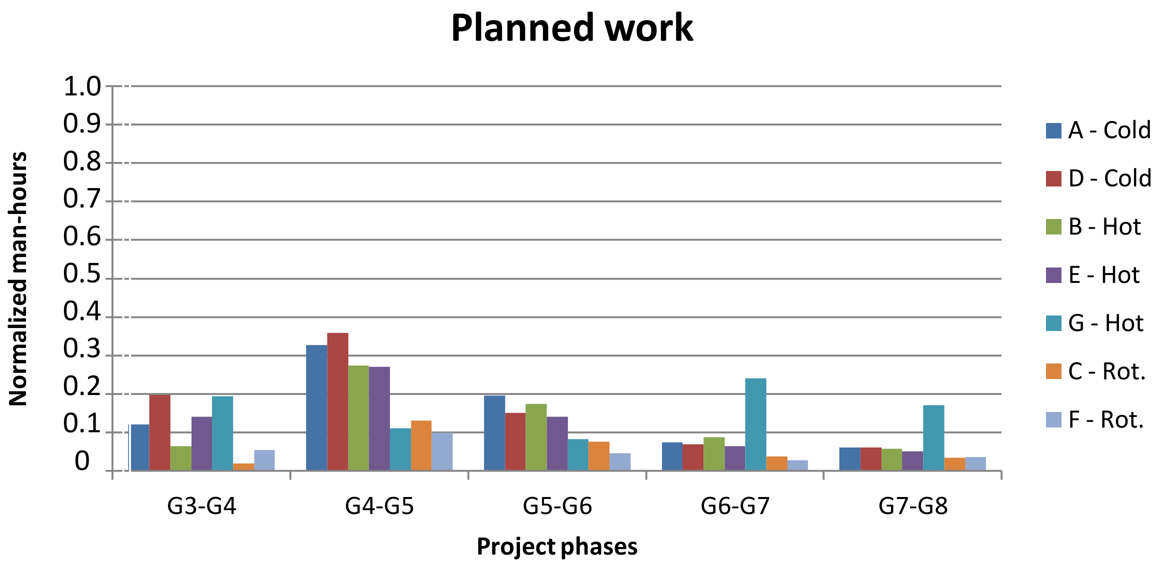
Wynn, D. C. (2007). *Model-Based Approaches to Support Process Improvement in Complex Product Development.* Cambridge: University of Cambridge.

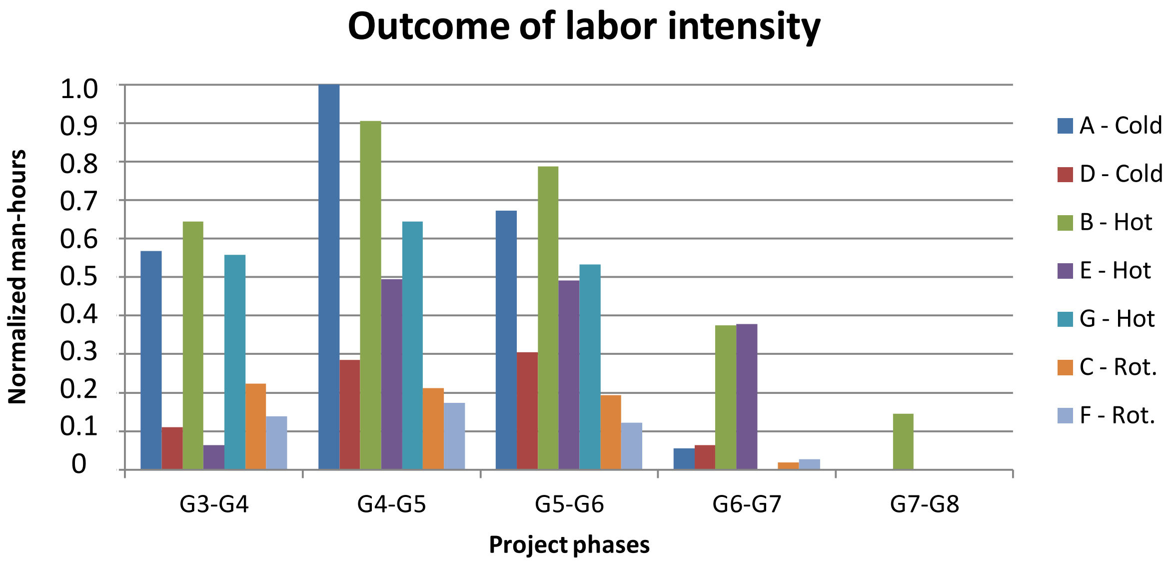
Wynn, D. C., Eckert, C. M., & Clarkson, P. J. (2006). Applied Signposting: A Modeling Framework to Support Design Process Improvement. *ASME 2006 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, (pp. 1-10). Philadelphia, Pennsylvania, USA.

Yan, H.-S., Wang, Z., & Jiao, X.-C. (2003). Modeling, scheduling and simulation of product development process by extended stochastic high-level evaluation Petri nets. *Robotics and Computer Integrated Manufacturing , 19* (4), 329-342.

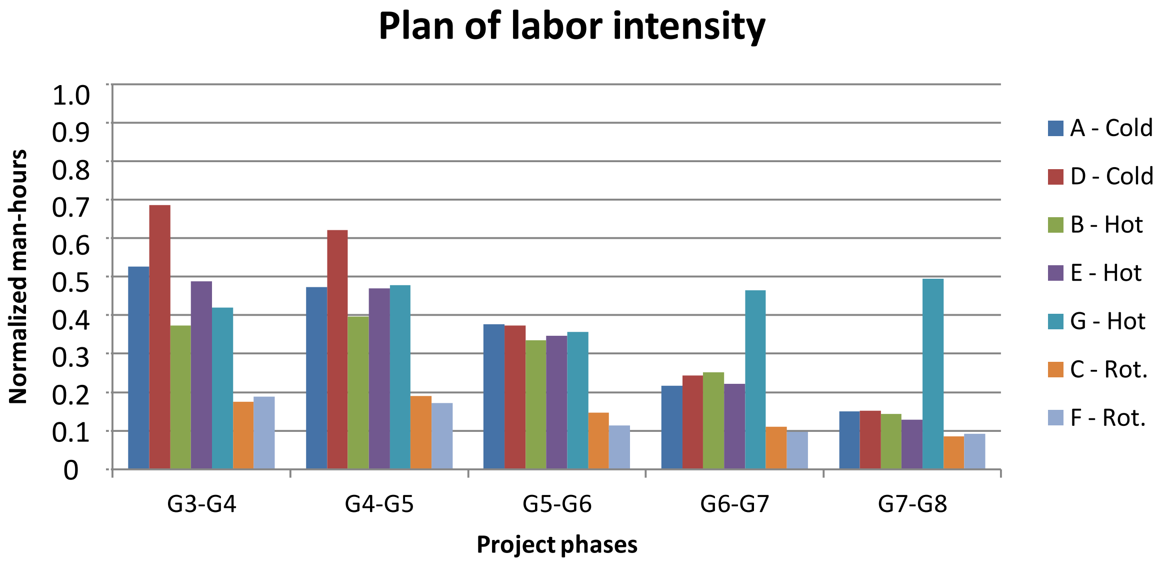
APPENDIX A - CHARTS ILLUSTRATING WORK AND LABOR INTENSITY







Outcome of labor intensity
Normalized man-hours
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
G3-G4
G4-G5
G5-G6
G6-G7
G7-G8
Project phases
A - Cold
D - Cold
B - Hot
E - Hot
G - Hot
C - Rot.
F - Rot.



Plan of labor intensity
Normalized man-hours
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
G3-G4
G4-G5
G5-G6
G6-G7
G7-G8
Project phases
A - Cold
D - Cold
B - Hot
E - Hot
G - Hot
C - Rot.
F - Rot.

APPENDIX B - SIMULATION IMAGE FROM SIMUL8