Reducing Uncertainty in Production System Design through Discrete Event Simulation

A case study at Volvo Construction Equipment

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Abstract

In a market environment that is subject to continuous changes, companies need to adapt their production systems in order to maintain the competitive edge. Current literature shows that with a successful production system design, higher levels of output, efficiency and quality can be achieved.

However, designing a production system is done infrequently and therefore tends to lack experience. As a result, design decisions have to be made under uncertainty due to a lack of information, structure and knowledge. In fact, the success of a design process is directly linked to the level of uncertainty.

The purpose of this thesis is to reduce uncertainty in production system design through Discrete Event Simulation before an assembly system is implemented. Therefore, a theoretical study was carried out defining types and sources of uncertainty in production system design. Parallel to the theoretical study, a case study in Volvo Construction Equipment Operations Hallsberg was conducted. Discrete Event Simulation was tested as a tool to reduce uncertainty in production system design.

The analysis illustrates the observed sources of uncertainty in production system design cover a process, organizational, corporate, market and cultural context. The relevant uncertainty types identified in the case study in Volvo Construction Equipment Operations Hallsberg were environmental, system, technical, structural, temporal, lack of knowledge and lack of information. The information provided by the Discrete Event Simulation in order to reduce uncertainty are in form of KPIs, process structure and visualization. The provided information had a positive impact on the degree of technical uncertainties, the lack of knowledge and the lack of information. As a result, the level of uncertainty in the Volvo Construction Equipment Operations Hallsberg future line designing process was reduced.

Keywords: Production System Design, Uncertainty, Discrete Event Simulation
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Västerås, 27.05.2016
Confidentiality Clause

This thesis has been concealed by the authors at request of Volvo CE due to confidentiality reasons. Any inspection of this thesis by third parties will require the expressed permission of Volvo CE.

Västerås, 28.06.2016
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List of Abbreviations

Cab A . . . . Product A of Volvo CE
Cab B . . . . Product B of Volvo CE
Cab C . . . . Product C of Volvo CE
Cab D . . . . Product D of Volvo CE
CAST . . . . Common Architecture Shared Technologies
CES . . . . Continuous Event Simulation
DES . . . . Discrete Event Simulation
KPI . . . . Key Performance Index
MDH . . . . Mälardalen University
NP . . . . New Product introduced by Volvo CE in the Future State
TBF . . . . Time Between Failure
Volvo CE . . Volvo Construction Equipment
1 Introduction

1.1 Background

When two or more companies interfere with each other seeking the same objective, typically using some common resources, competition occurs (Pianka, 1981). Competitiveness therefore is a key factor that firms need to handle in order to gain (and retain) the upper hand in the market (Narver and Slater, 1990).

Because of the changing nature of the market needs, companies need to adapt continuously in the same way (Narver and Slater, 1990). Firms are directly linked to their environment when performing their operations, as they need to satisfy its demand (e.g. customer orders) by using resources from it (e.g. money, material and labour)(Ruffini, 1999). In line with the above, the chief executive of General Motors Dan Akerson said: "Every corporation has to change, or it dies. You lose your competitive edge." (Durbin and Krisher, 2011). Hence, firms not only need to grow and evolve in the same way as the markets do, but they also need to maintain a competitive edge (Bennett and Forrester, 1993). However, competition is no longer limited to local challenges, but spread to a global level, setting high product standards (Wu, 2001). Therefore, simultaneous local and global competitiveness can only be achieved by satisfying customer requirements, that imply reducing overall costs, improving product and service quality and reliability, effectively handling fluctuations of the demand and satisfying special customer requests and orders (Bennett and Forrester, 1993).

Those requirements have to be adopted by the current production system in order to retain competitiveness. Two approaches have been proposed to confront these challenges: either by controlling and improving the key parameters of the existing production, or by effectively designing a production system capable of handling changes (Bennett, 1986). In this manner, Bennett (1986) argued that too much effort is spent on controlling current parameters of a production, even if the former would bring greater success:

"As industrial competition increases, it becomes more apparent that improved levels of output, efficiency and quality can only be achieved by designing better production systems rather than by merely exercising greater control over the existing ones."(Bennett, 1986, p. 1)

Therefore, if companies want to design successful production systems, they need to pay extra attention in the early stages of the design process (Bellgran and Säfsten, 2010). During the period when an idea is first considered and a concept is judged ready for implementation, design decisions need to be taken, where several alternative system solutions may be elaborated (Kim and Wilemon, 2002). In order to find the most suitable one, these concepts have to be compared against each other considering core criteria (Bellgran and Säfsten, 2010). However, given that production system design itself is done infrequently, it tends to require increased time, structure and experience (Krajewski, Ritzman and Malhotra, 2013). A structured approach dealing with production system design is
recommended (Bellgran and Säfsten, 2010; Suh, 2005), but empirical findings indicate
that companies react in fire-fighting manner (Wu, 2003), showing a gap between theory
and practise in actual Production System Design application (Wu, 2003). Consequently,
early-stage design decisions need to be made under a given lack of information, structure
and experience.

1.2 Problem Formulation

When facing the production system design, real-world companies usually have one pre-
dominant possible solution in the decision making process, usually originated from cor-
porate strategies or even particular engineering guesses. In any case, as in any other
decision making process, there is always the doubt whether the possible solution is the
right one or not. The lack of knowledge about the consequences of the solution, coupled
with the lack of information, structure and experience of the design phases, makes the
design difficult and reduces the feasibility to design the best possible outcome (Bellgran
and Säfsten, 2010).

This knowledge gap between the information needed to formulate a well founded so-
lution and the information that the designers have is defined as *uncertainty* (Galbraith,
1973). After all, such uncertainty is mainly caused by either the lack of experience of
the company in the field of the solution evaluated or the lack of information of the so-
lution caused by the system complexity (Suh, 2005). Complexity can be originated by a
lack of understanding of the structure and behaviour of the future process (DeToni and
Tonchia, 1998; Efthymiou, Pagoropoulos, Papakostas, Mourtzis and Chryssolouris, 2012)
or an inability to predict all the variations of the future system (ElMaraghy, Kuzgunkaya
and Urbanic, 2005). In any case, uncertainty in production system design must be care-
fully handled, since studies show that the success of a project is linked to the uncertainty
level which can be decreased by increasing information (Daft and Lengel, 1986).

The problem arises when trying to reduce the uncertainty by gathering the information
required to select the best alternative. To physically build a model or alter the existing
system, in terms of information gathering, would probably be the optimum way (Kelton
and Law, 2000). However, these tests could be very costly and disruptive in terms of time
and money. Hence, other actions need to be carried out to gather information.

Simulation comes very handy for companies in that sense, as it allows the practitioners
to model and help understandings the structure and behaviour of the possible alterna-
tives (Shannon, 1998), before they are physically built. This way, tests can be carried
out without disrupting company activities and allocating fewer resources than physically
building the model (Banks et al., 2005).
1.3 Aim and Research Questions

Since simulation may have a positive effect on the production system, this research will show how simulation, in form of Discrete Event Simulation (DES) can contribute to the reduction of uncertainty in production system design. Thus, the aim of this thesis is the reduction of uncertainty in production system design through the use of Discrete Event Simulation.

In order to full-fill this aim, this thesis will answer the following questions:

1. What uncertainties need to be dealt with in production system design?
2. What causes uncertainty in production system design?
3. What information does Discrete Event Simulation provide to reduce uncertainty in production system design?
4. What types of uncertainties can be dealt with through Discrete Event Simulation?

1.4 Scope of the Research

The theoretical framework of this thesis was narrowed down to uncertainty in a specific phase of the Production System Development, the production system design. Hence, no further phase such as implementation was studied.

This study assumed that the use of Discrete Event Simulation as an information gathering tool would result in an uncertainty reduction in the designing process. This implied that in this thesis no study was carried out to verify this statement.

Due to time restrictions, this thesis was narrowed down to the analysis of the main production lines of the Volvo Construction Equipment plant, in Hallsberg. This implied that all the pre-assemblies that supply the main production lines were not analysed for the purposes of this thesis. In the same manner, the material handling was out of the scope.

All the data, including times, measurements and schedules was provided by the company, thus, no deeper evaluation on the validity of such was carried out in this thesis. Moreover, due to lack of data and in order to build a representative simulation model, some assumptions were made.

The software used for building the simulation model was ExtendSim. This program was provided by Mälardalen University, putting any kind of software alternatives study out of the scope of this project.

The purpose of the simulation study was to understand the current and future state processes, resulting into a specific comparison of the states in regard of the KPIs previously defined, which were Operator Quantity, Total Cab Assembly and Lead Times. In the same way as the theoretical framework, the simulation study finished with the design and analysis of the future state process, and thus, no implementation was carried out for the purpose of this thesis.
2 Research Method and Procedure

The scientific and systematic search for information in order to find solutions to a problem is defined as research. That includes formulating the problem and hypothesis, collecting data, analysing data and drawing conclusions in form of solutions towards the formulated problem (Kothari, 2004).

Therefore, the following chapter gives an overview of the research design by showing the applied methods of performing a case study and a DES. Moreover, the research process of the literature overview, the production design case and the DES are shown. Hereafter it is described how results were interpreted and the validity and reliability of the research study is discussed.

2.1 Research Design

Within the current literature DES is already known as a possible tool in production system design (Johansson, Skoogh, Mani and Leong, 2009). The aim of this research was to investigate how DES as a tool can reduce the level of uncertainty in production system design decisions before an assembly system is implemented. To make observations about the impact of DES, four research questions were formulated. By performing a DES conducted in a case study, observations were made and activities carried out. These activities and observations were qualitatively analysed by their effect on the observed uncertainties in production system design.

2.1.1 Case Study

By applying the case study method, questions concerning the 'how' and 'why' of a particular unit can be investigated intensively (Kothari, 2004; Yin, 2009). By conducting a case study, choices about the amount of case studies to be adduced, the selection of an appropriate case and also the sampling has to be made (Karlsson, 2010; McCutcheon and Meredith, 1993; Meyer, 2001). Since an in-depth investigation was intended, exclusively one case in Volvo CE located in Hallsberg was picked. All models and conclusions were based on this single case study. In order to make first-hand observations, a real-time case study was selected. The chosen sample within the study was expected to be highly relevant to the conceptual frame and research question, particularly showing the phenomena of uncertainty in production system design, that was to be studied.

All observations made were based on a set of contemporary events within Volvo CE Operations Hallsberg over which the investigators had little control (Yin, 2009). By using multiple sources of data, details from the viewpoint of the participants were examined (Schramm, 1971). Within the case study qualitative information in the form of documents provided by Volvo CE Operations Hallsberg, interviews and observations were collected.

The methodology for performing the case study followed the steps acquired by Yin (2009) that guides the investigator in the process from the problem formulation to the final conclusions by collecting, analysing and interpreting the observations made in the
Research Method and Procedure

2.1.2 Simulation

The simulation modelling and analysis of the simulation case performed were conducted for the purpose of gaining insight into the operation of a production system and testing new concepts and systems before it’s implementation (Chung, 2004). The simulation model was considered to be a partial model, therefore all aspects of the problem not related to it or not affecting the effectiveness of the problem solution were left out. Given the intention to build a model that would explain and capture parts of the decision making problems that are faced by decision makers in real life operational processes, this model was quantitative based (Karlsson, 2010). The quantitative model-based research implies a causal relationship of variables, meaning that a change of an input variable would lead to a change in the output variable. Changes of the independent variable lead to changes in a quantitative form of dependent variables. Due to the quantitative and causal character, the model could be used to predict the future state of the modelled process, but was not unambiguous and verifiable outside this model (Karlsson, 2010).

The quantitative model-based research can be further divided in two classes: the axiomatic and the empirical research (Karlsson, 2010). Since the goal of the simulation model was to fit observations and causalities of the reality and the model made of the reality, the authors chose an descriptive empirical approach.
2.2 Research Process

Figure 2.1 shows the research process from the problem formulation to the final results.

First, through the study of current research papers, a problem was framed addressing the gap of knowledge within this topic. In order to investigate the research aim, four research questions were formulated and a suitable case study located. Parallel to the literature review, data in the case study was collected. Based on the collected data a DES was carried out. Data of the simulation, observations and interviews were analysed and evaluated based on the problem formulation and compared to literature findings. In any case, although the process is illustrated in a sequential way, it has been iterative between literature review, data collection and analysis.

The following sub chapters show how the process of literature overview, the production design case and the simulation has been carried out.

2.2.1 Literature Overview

The literature study was divided into three main sections, covering the subjects of production system design, uncertainty and Discrete Even Simulation. First, driving factors of production development were described and then narrowed down in detail to production system design as part of the whole production system development. An overview of the different definitions and types of uncertainties are given. Challenges within production system design were analysed, connecting it to the topic of uncertainty as one significant challenge. Within this chapter different definitions and sources of uncertainty are presented. After giving a background, tools and strategies to manage uncertainty were presented.

Simulation was introduced as a tool to manage uncertainty. In this particular case, DES was introduced. Further advantaged of performing simulation studies and it’s applicability and types are described. Within this study a structured approach to perform a DES study was applied. Therefore the process is explained in detail later in the chapter.

The gathering of literature was performed though the web search engine for scholarly literature as Google Scholar and using databases as Discovery, DiVA and ResearchGate covering articles, books and research publications. Searched documents include literature over a span of time between the years 1985 and 2015. The emphasis was on the latest
publications, though the snowball system was used to detect commonly used concepts. Therefore production system design was mainly based on the concepts developed by Bellgran and Säfsten (2010) and manufacturing system design by Wu (1994). The simulation approach was based on commonly used simulation and modelling process developed by Banks and Gibson (1997).

Besides the general topic of production system design and uncertainty, literature within the interface of these two topics was gathered. Table 2.1 shows the key words being used and their number of hits, considering full text search in Google Scholar. Though a great number of literature was available dealing with uncertainty and production systems, a limited amount covers the topic of uncertainty reduction in the process of production system design.

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</tr>
<tr>
<td>“production system design” uncertainty manufacturing</td>
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</tr>
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<td>“production system design” + uncertainty</td>
<td>1,170</td>
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<tr>
<td>“production system design” + “uncertainty reduction”</td>
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<tr>
<td>“manufacturing system” design uncertainty</td>
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<td>“manufacturing system design” + uncertainty</td>
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<td>“manufacturing system” “design uncertainty”</td>
<td>49</td>
</tr>
<tr>
<td>“uncertainty in design” “production system”</td>
<td>56</td>
</tr>
<tr>
<td>“uncertainty in design” “manufacturing system”</td>
<td>33</td>
</tr>
<tr>
<td>“design uncertainty” “production system”</td>
<td>81</td>
</tr>
<tr>
<td>“design uncertainty” “manufacturing system”</td>
<td>49</td>
</tr>
<tr>
<td>“learning before doing” uncertainty manufacturing</td>
<td>406</td>
</tr>
</tbody>
</table>

### 2.2.2 Production System Design Case

To fulfill research aim of reducing uncertainty in production system design through the use of DES before an assembly system is implemented, a case study at Volvo CE Operations Hallsberg was performed. The information required in form of documents, interviews and observations served the purpose of performing a DES. Therefore, data was collected from the case study in order to build the simulation models and finding the types and sources of uncertainty the company is facing. First, a model representing the current state of the three analysed production lines was built referring to the year 2015 and served as a basis for further assumption when simulating the future state.

Data for the simulation study was collected from calendar week 6 to week 18 of 2016 at Volvo CE Operations Hallsberg on a regular basis of two times per week from 8:00 to 16:00. Here the simulation served as an indication what data was required. By direct observation of the three assembly lines, Value Stream Maps of the processes from Volvo CE Operations Hallsberg and interviews during every on site visit with the Line and Production Managers, a basic understanding of the assembly processes, material handling
and working content for each line was acquired. Further more detailed information was gathered, shown in Table 2.2. All information in Table 2.2 was collected for each of the three studied assembly lines, using quantitative data of the year 2015.

<table>
<thead>
<tr>
<th>Data</th>
<th>Time frame</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working content in each station</td>
<td>2015/2016</td>
<td>Operation description</td>
</tr>
<tr>
<td>Number of operators in each station</td>
<td>2015/2016</td>
<td>Operators active in station</td>
</tr>
<tr>
<td>Production Schedule</td>
<td>2015/2016</td>
<td>Weekly production time [min]</td>
</tr>
<tr>
<td>Cycle times in each station</td>
<td>2015/2016</td>
<td>Current times in [min]</td>
</tr>
<tr>
<td>Line Assembly Capacity</td>
<td>2015</td>
<td>Calculated capacities</td>
</tr>
<tr>
<td>Historical Total Assembly</td>
<td>2015</td>
<td>Number of assembled cabs</td>
</tr>
<tr>
<td>Disturbances for each station</td>
<td>2015</td>
<td>Length and frequency of disturbances causing a stop of the whole line</td>
</tr>
</tbody>
</table>

Besides the on-site collection of data, regular meetings and follow-ups took place to provide feedback on the simulation model progress. Once a week the simulation progress was presented to an internal group working on related projects at Volvo CE Operations Hallsberg and milestones were presented on-site to the responsible production engineers, manufacturing engineer and line managers.

The future state layout of the production lines was developed by Volvo CE Operations Hallsberg and the CAST Assembly Enablers project group, further describes in Section 5.2. Here, during the design process the authors were passive observers.

The CAST Assembly Enablers group was composed of three units. First the Volvo CE Operations Hallsberg interns as the CAST concept owner for cab assembly deployed in the Hallsberg plant, a production engineer likewise from the Hallsberg plant and a production engineer deployed in a Volvo CE plant located in Poland. Secondly, an external consultant and third, a group composed of MDH interns as the professor for Innovation and Product Realisation, doctoral students in the fields of design of assembly systems, product realization and virtual manufacturing.

Within the CAST Assembly Enablers project group a weekly online meeting was carried out, as well as two workshops where the future concept was discussed. These workshops, the online meetings together with the observations made on-site, served as a basis for the data collection regarding types and sources of uncertainties in production system design, but also the impact of DES.

### 2.2.3 Simulation

Within the case study a DES was carried out. The data outcome of the simulation study was used to answer the research questions. The following lines show the method, the data collection and how data was analysed.
The steps followed for the building of the simulation model can be seen in Figure 2.2, based in the 12-step process defined by Banks et al. (2005). Similar approaches were taken by other authors (Chung, 2004; Kelton and Law, 2000; Law and McComas, 1991; Shannon, 1998), but in all of them the core of the process remains intact.

**Step I. Problem Formulation**

In the first step, the problem was clearly defined and ensured that it was understood by all the parties involved in the study (Banks et al., 2005; Chung, 2004). It was very important to precisely state the problem and the questions that the simulation should answer (Shannon, 1998), since finding the right solution to the wrong problem a waste (Musselman, 1994). Meetings were carried out with the customers and the system experts, together with a presentation of the definitive problem formulation.

**Step II. Set Objectives and Project Plan**

After defining the problem it was decided if simulation was the right tool to solve the problem or not (Banks et al., 2005) (see 3.3.2.3). Due to the affirmative answer, the project was planned by defining some key parameters such as the people who would take part in the project, the time and the schedule of it and the overall technical goals of it (Chung, 2004; Kelton and Law, 2000; Law and McComas, 1987). Given that the current study was part of the thesis, the time and schedule of it were already defined. Regarding the goals on the other hand, they were described together with the problem formulation.

**Step III. Conceptual Model Formulation**

In the third step, the process was graphically modelled by defining the components, describing the variables and interactions of the system (Shannon, 1998). Robinson (2014) defined a conceptual model as:

"[…] a non-software specific description of the simulation that is to be developed, describing the objectives, inputs, outputs, content, assumptions and simplifications of the model" (Robinson, 2014, p. 65).

This means that the conceptual model was designed as a simplified version of the real life, and complexity was added later (Banks et al., 2005; Kelton and Law, 2000; Pidd, 1999). In this manner, the conceptual models created for the purpose of this project can be seen in the Appendices (see Chapter 9.2).

**Step IV. Data Collection**

In order to build the simulation model, data was first identified and gathered (Shannon, 1998) (see 2.2). The data collected consisted of a combination of historical data, anecdotal data and observational data (Chung, 2004) (see 2.3).
2 Research Method and Procedure

Figure 2.2: The simulation modelling process (Banks et al., 2005)

Reducing Uncertainty in Production System Design through DES
Table 2.3: Classification of the data gathered

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Data Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical Data</td>
<td>Assembly Line Total Output</td>
</tr>
<tr>
<td></td>
<td>Assembly Line Capacities</td>
</tr>
<tr>
<td></td>
<td>Line Disturbances</td>
</tr>
<tr>
<td>Anecdotal Data</td>
<td>Cycle Times of the Stations</td>
</tr>
<tr>
<td></td>
<td>Number of changes in the takt time per year</td>
</tr>
<tr>
<td>Observational Data</td>
<td>Number of Operators per Station / Assembly Line</td>
</tr>
<tr>
<td></td>
<td>Working Schedules</td>
</tr>
</tbody>
</table>

The data could be further classified in two different forms: *deterministic* and *probabilistic* (Chung, 2004). For example, in the case given the deterministic data would be the working schedule of the operators, since occurs in a predictable way. Probabilistic data would refer to the disturbances of each line, since they will not always occur with the same regularity.

In order to define the deterministic data (e.g. the distributions of the station disturbances), the following four steps were followed, based on Banks et al. (2005):

1. **Collect data from the real system of interest.** The historical data regarding the disturbances of the main production lines was gathered.

2. **Identify a probability distribution to represent the input process.** By using histograms, the probability distributions that fit best the disturbances were identified. The Negative Binomial for the disturbances below 30 minutes and Triangular for the ones above were used.

3. **Choose parameters that determine a specific instance of the distribution family.** In the case of the negative binomial distributions, the number of failures ($s$) and the probability ($p$) were defined, while for the triangular distributions, the minimum, maximum and the most likely values were defined.

4. **Evaluate the chosen distribution and the associated parameters for the goodness of it.** The disturbance distributions were validated by the production engineers in Volvo CE Operations Hallsberg.

Due to time and resource restrictions, some data was not possible to gather (Banks et al., 2005). Hence, some assumptions were made (see Table 4.1), with their respective validation process (Musselman, 1994).

All in all, this data collection step constituted an important and difficult phase in the simulation model building. Difficult because it was not always available or recorded in the form needed, and important because even if the model structure was the correct one, with inaccurate, inappropriately analysed or not environmentally representative data, the output of the simulation would not be the proper one (Banks et al., 2005).

Because of its importance, and since data collection takes a large portion of the total simulation building time, this step was carried out together with the previous step, the conceptual model building (see 2.2.3). As it can be seen in the Figure 2.2, this is a very common approach (Banks et al., 2005).
Step V. Model Translation

Once the conceptual models were built and the data was gathered, the simulation model was designed by using ExtendSim (Shannon, 1998). The model building should have the same approach as the conceptual model building (see Section 2.2.3); in the beginning the model should be simply built, and complexity would be incrementally added (Musselman, 1994).

Step VI. Model Verification

Before analysing any simulation output, it was verified that the model was operating properly (Balci, 1994; Banks et al., 2005; Shannon, 1998). The overall aim of this step simply stated was: "Building the model right" (Balci, 1994, p. 215). This meant that the model needed to include all the components previously specified and be able to run without any errors (Chung, 2004).

In this phase, verification of the model and white-box validation was carried out (Robinson, 1997). This two concepts might be theoretically different, but they can be performed at the same time (Robinson, 1997). After all, they both consist of micro checks. Examples of these micro checks performed for the project were timings (e.g. cycle times), control elements (e.g. station breakdowns) and control logic (e.g. scheduling of the production).

Step VII. Model Validation

Validation constituted the calibration of the model, ensuring that the output of the model was representative to the real-world system (Balci, 1994; Banks et al., 2005; Shannon, 1998). Simply stated, the aim of this step was: "Building the right model" (Balci, 1994, p. 215).

In addition to the previously described white-box validation two other validation techniques were used during the simulation building process: face validation and black-box testing. The first one consisted of subjective evaluation of the model based on experience, knowledge and intuition of the production engineers of Volvo CE Operations Hallsberg (Balci, 1994a). They reviewed the model assumptions and overall behaviour to check if the model was representative or not of the real-world system (Law and McComas, 1991). In the black-box testing on the other hand, the accuracy of the input-output transformation was checked (Balci, 1994a). Different input data was given to the model, as cycle times, takt times and breakdowns, and the output was evaluated, checking whether it was representative to the real-world system or not.

Step VIII. Experimental Design

Once the model was validated, the design of the experiments or scenarios that would yield the information needed were defined (Chung, 2004; Shannon, 1998). For each alternative decisions concerning the simulation length and the number of simulation runs needed to be taken were defined (Banks et al., 2005). Following Law and McComas advice, each alternative was run hundred times, using the average output of those runs as an overall output (Law and McComas, 1991). This overall estimate should be more precise than the result of just one run, since many times random variables are used in simulation models.
Step IX. Production Runs and Analysis

In the next step, the scenarios were carried out as previously designed, generating the expected data (Shannon, 1998). Analysis and interpretation of the information followed (Banks et al., 2005), where statistical techniques were needed (Kelton and Law, 2000). In the end, a comparison between the model’s output and the production engineer of Volvo CE Operations Hallsberg output estimation was done (Musselman, 1994).

Step X. More Runs?

An analysis whether it was necessary or not to perform more runs and scenarios was carried out (Banks et al., 2005).

Step XI. Documentation and Reporting

Following Musselmans (1994) guidelines, frequent reporting and documentation was used through the simulation model building process. All the input, output, assumptions and model itself was documented, in case the simulation model would be used in the future for other purposes (Kelton and Law, 2000). Regarding the assumptions, they were clearly described in order to enhance the credibility of the model (Law and McComas, 1991).

All in all, together with all the reporting and documentation, it should be possible for other analysts to conduct the same simulation study by using the same input values (Banks et al., 2005). This also makes easier for other parties to understand the model and its output.

Step XII. Implementation

The last step would be to put all the results gathered into use (Shannon, 1998). In any case, this final step was out of the scope for this project, and therefore the implementation was not reported and documented.

2.3 Analysis

The analysis was based on the data conducted within the case study and the executed simulation. Before the analysis was performed, information was gathered and filtered in order to elaborate a detailed case description. Accordingly, a data coding was performed in three steps as suggested by Miles and Huberman (1994). First, all the data that was collected through documents, observations, interviews and the outcome of the simulation study was filtered to the information that serve the purpose of answering the four research questions. Second, data was categorized into types of uncertainty, sources of uncertainty, information provided by the DES and their impact on the previous elaborated types of uncertainty. Third, the data was displayed by matching to the respective research questions.

After the data coding the analysis was performed as suggested by Eisenhardt (1989). The first step was the analysis within the case data. Here the data was processed and visualized by constructing arrays and displays. Within the arrays causality and explanations were elaborated.

Exclusively one case was investigated, literature in this research area was enfolded (Voss, Tsikriktsis and Frohlich, 2002). Since the literature gave a broad spectrum of different
types and sources of uncertainty, the first step was to compare the definitions in theory to the empirical findings. Also a comparison between DES literature and the executed simulation was done. The degree in which empirical and theoretical findings matched was evaluated.

After performing the DES study, the outcome of the simulation in form of predefined KPIs were compared to the real KPIs in current production. By performing different scenarios within the simulation, design alternatives were evaluated and presented to the CAST project group and Volvo CE Operations Hallsberg.

2.4 Validity and Reliability

Due to Yin (2009) four tests have been commonly used to establish the quality of an empirical social research: construct validity, internal validity, external validity and reliability. This tactics can also be applied to case study research as one form of empirical research (Yin, 2009; Karlsson, 2010).

Construct validity occurs during the data collection and composition strengthened by a clear chain of evidence and triangulation (Mathison, 1988; Karlsson, 2010). Here multiple sources of evidence were used, as own on-site observations, interviews with distinct employees and historically by Volvo CE Operations Hallsberg recorded data. Through weekly meetings and presentation on the progress in front of different audience, review of key data was gathered on a regular basis. Since the data gathering was also performed within the CAST Assembly Enablers projects, triangulation was feasible due to employees and project members of different backgrounds.

Internal validity during the phase of data analysis is described by a causal relationships between variables and results and can be strengthen by a clear research framework, pattern matching and theory triangulation (Mathison, 1988; Karlsson, 2010). To achieve a clear research framework, how and which information leads to a decrease in uncertainty was analysed. Later on, the empirically observed patterns were compared with previous study outcomes based on theory triangulation. Therefore, already the literature study provided a broad overview on the approached topics in order to be able to compare the empirical findings to a variety of theory concepts.

Eisenhardt (1989) argues that even if there is no ideal number of cases it should be not less than four in order to generate theory and provide a good basis for analytical generalization. Since the research was based on exclusively one case, construct validity and internal validity were emphasized and triangulation with current literature performed. Further the research reliability should enable other the same insight if they conduct the study along the same steps. Therefore transparency and replicability in form of careful documentation, especially following an established step approach by Banks et al. (2005) when performing the simulation, and clarification of research procedure were enhanced. The model verifications and validation was described in detail in Chapter 2.2.3.
3 Theoretic Framework

The purpose of this chapter is to describe the theoretical background that is relevant for this research study and give an overview of previous research. The chapter is divided into three parts: production system design, uncertainty and simulation. The first part gives an overview of production system design as part of Production System Development, the importance, but also challenges of production system design. The second part focuses on uncertainty as one of the challenges that has to be managed in the context of production system design. Definition, differentiation, types, sources and tools in order to handle uncertainty are described. The last part details DES as a tool in production system design. Advantages, disadvantages and the application of DES are further described.

3.1 Production System Design

3.1.1 Definition and Differentiation

Production systems, manufacturing systems and assembly systems are often used as synonyms, but it is important to make a distinction between these terms before enlarge upon production system design (Bellgran and Säfsten, 2010). In general, a system is defined as a set of connected parts that operate together to produce a desired output by using definite inputs (Cochran, 1999). A system consists of many sub-systems that interact and influence the system output as a whole. All the sub-systems must act as a whole to produce the desired output (Cochran, 1999).

In that manner, a production system consist of the arrangement and operation of machines, tools, material, people and information employing a series of value adding manufacturing processes to produce a physical, informational or service product (Wu, 1994; Cochran, 1999).

Production is defined as a process of creating goods and services though a combination of capital, material and work (Bellgran and Säfsten, 2010). Bellgran and Säfsten (2010) differentiate manufacturing from production systems by an hierarchical approach: manufacturing is superior to production. Therefore, manufacturing systems contain production systems that in turn contain sub-systems as the technical system, the material handling system, the human system and the control system (Bellgran and Säfsten, 2010; Groover, 2008). From a structural perspective, production systems cover a range of different elements that interrelate with each other, as shown in Figure 3.1.
When designing a system, sub-systems, elements, events and their relationships in this system have to be conceived and planned. The design of a production system can be described as

"[...] defining the problems, objectives and outlining the alternative course of action (problem-solving), and the evaluation, choices among alternatives and detailed design of proposed production systems (decision-making). The result of the design work is a description (specification) of the production system. Along with the definition of the product development process, the term production system development comprises both the design and the realisation of the production system" (Bellgran and Säfsten, 2004, p. 5).

Production system design is referred the production of goods within the industrial production henceforth, where the transformation of raw material into products is carried out.

### 3.1.2 Production System Design Process

The organizational transformation can be a complex, dynamic, unpredictable and a chaotic process, but at the same time the need for "[...] flexible processes that give customers what they want, when they want it, at the highest quality and affordable cost" (Liker, 2005, p. 8) confront many companies with the challenge of developing new production systems in an efficient and fast manner (Sullivan, 2004; Amagoh, 2008).

To achieve the flexibility and responsiveness demanded by the customer, a holistic approach to production system design is required (Gayed, Jarvis and Jarvis, 1998). However, unlike product development, studies have shown that production system design is carried out irregularly and suffers from a lack of interest. As a result structured and systematic ways are used rarely and a holistic approach is not feasible.

The implementation of a structured way of working would counteract the overall chaotic process as introduced above and further activities can be focused, instead of spending time to plan what has to be done and in what order (Bellgran and Säfsten, 2010).

A structure is also auxiliary in the process of decision making, as it can avail to make the decision process understandable, rational and communicable throughout the whole organization (Bellgran and Säfsten, 2010; Cochran, 1999). In order to help industry to tackle the issues, a high amount of research has been carried out and techniques, tools and structured approaches have been developed (Wu, 2001).
One approach developed by Bellgran and Säfsten (2010) shows a structured way of working with production system development that contains production system design, realization and ramp up of the production system. Below this concept is detailed, with the focus on production system design.

The production system design process is part of production system development that can be divided into five phases: management and control, preparatory design, design specification, realisation and planning and start-up. Within the production system development, production system design covers the first three phases of management and control, preparatory design and design specification. In Figure 3.2 the production system design process is summarized. The production system design process includes three main phases (see Figure 3.2): the initiation, preparatory design and the detailed design leading to the final solution. Each phase can be further divided into sub-phases and corresponding activities (Bellgran and Säfsten, 2010).

The initiation phase covers the preparation of the investment based on requirements and investment decision process. In this phase the project is planned, including project management, resources, a time plan, work team composition, routines for administration and information (Bellgran and Säfsten, 2010).

Accordingly, requirement specifications are set by performing a background and a pre-study. Here the current production system is analysed and evaluated. Production analysis and benchmarks can also be considered. Further the development and market potential, as well as requirements from interested parties, management objectives and strategies, information about system factors and processes are analysed. System functions and system tasks are defined and objectives set. The elaborated requirements serve as a basis for the design specification and guide future work (Bellgran and Säfsten, 2010).

The design of conceptual production systems deals with general questions of layout, process choice, material supply, work place design and work environment. Building a conceptual model the production designer will face and be in the need to manage complexity. In this phase a number of possible alternatives are elaborated. The alternatives are evaluated based on a determined method. Finally a detailed design of the chosen production system is elaborated and communication and support established (Bellgran and Säfsten, 2010).

![Figure 3.2: Typical activities carried out when designing the production system (Bruch, 2012)](image-url)
3.1.3 Challenges when designing the Production System

Research provides techniques, tools and structured approaches within production system design, but there is still a gap between industry and academic perspective (Bellgran and Säfsten, 2010). Since designing a production system is not a every day activity, estimation in form of a rule of thumb and a trial-error approach are used instead.

Chryssolouris (2013) describes this trial-error approach in two steps. First, a suitable production system is guessed. Then the performance of this system is evaluated. If the results are satisfying the process is completed, otherwise step one is repeated again. Wu (2001) researched causes for the lack of application of structured approaches in industry. He came to the conclusion that there are problems using design methodologies. Due to Wu (2001) companies lack awareness of actual application of methodologies in practise. There are also barriers within the planning and documentation of assumptions, design notes and justification. Also the manufacturing strategy formulation and analysis is considered to be difficult in practise.

When companies adapt a framework or a structure while designing the production system they are confronted with other challenges, as the structuring of their organisation to be able to apply these. Ruffini, Boer and van Riemsdijk (2000) discovered the phenomena related to decision making under uncertainty, when characterising the structuring of organisations. They found the importance of different roles of individuals and organised groups in the decision making process through power and politics, bounded rationality, personal preference, imperfect information, limited processing capacity of information, opportunism, satisfying behaviours and coalition forming.

Especially when studying the designing process as it is shown in Figure 3.2, it occurs that in every phase and step decisions have to be taken, starting with setting system requirements and objectives up to evaluating different system solutions. Choudhari, Adil and Ananthakumar (2010) summarized the decision areas within the production system design process into the following six:

1. Production planning and control
2. Organisation structure and control
3. Human Resources
4. Facilities
5. Sourcing
6. Process Technology

In every of this areas, decisions have to be taken by individuals or a group of people under uncertainty. Considering for example a predicted annual production volume as a basis for the production system, a change or divergence in practise in this predicted number would cause dramatic consequences in the prerequisites and accordingly in the production system itself (Bellgran and Säfsten, 2010).
3.2 Uncertainty

3.2.1 Definition

In organizational theory the uncertainty concept has been a central and historically significant aspect (Frishammar, Floren and Wincent, 2011). High dynamics and variability of current and future production paved its way into production system development, but considering the beginnings of the term uncertainty in manufacturing, sources go back to 1879 (Shenhav and Weitz, 2000). Journals and magazines like the American Machinist and the Engineering Magazine were the main trade journals, forums for discussions and sources of documentation of management practice and techniques.

As the science based industry in the middle of the 19th century emerged, companies started to pay more attention to increase their profits in higher rates than their competitors. To achieve these goals they had been seeking for complete control over the production processes, in mechanical and labour context. As a result, standardized parts and workers’ practice were introduced as a first attempt to reduce uncertainty in manufacturing (Shenhav and Weitz, 2000).

The approach of dealing with uncertainty was based on the success of mechanical engineers, working with technical uncertainty. Thereafter, it expanded to the organizational level. Uncertainty has been a dominant threat to all organizations on their way to achieve stability, order and efficiency (Shenhav and Weitz, 2000). A major example for uncertainty in the 19th century has been the labour unrest (Shenhav and Weitz, 2000).

Due to the change of market requirements these days uncertainty might not be in the form of labour unrest, but still it is present though all areas and so there are many interpretations and faces of uncertainty (Shenhav and Weitz, 2000).

The most common definition used in today’s literature and also applicable to historical development is the definition by Galbraith (1973): “the difference between the information one has and the information one needs to complete a task.” (Frishammar et al., 2011, p. 551). Further definitions followed, as the one based on early psychology work of Daft and Lengel (1986) defining uncertainty as the absence of information. The lack of information may regard goals, alternatives and consequences (Zhang and Doll, 2001). Uncertainty can also include, besides the things that are not known, the things that are just known imprecisely (McManus and Hastings, 2005). Stochastically speaking uncertainty is defined as the inability to assign probabilities to outcomes and risks (Zhang and Doll, 2001). The overall consensus of these definition is the absence of specific information to accomplish a task. This condition is served as a basis for this paper.

Even though there is a consensus, uncertainty derives from multiple dimensions that can be categorized (Galbraith, 1973). The awareness of different types of uncertainties is major in order to apply the suitable approach to the given dimensions (Olausson and Berggren, 2010). The categorization can be performed based on distinct point of views or sources. Therefore Table 3.1 shows an overview of common types of the uncertainty phenomenon sorted by authors and date of release.

Some of the types resemble, as for example the classifications by Milliken (1987), Rowe (1994) and Lane and Maxfield (2005) which focus on market changes, its’ effects, the interpretation and response to those. The definitions provided by Gerwin (1988) addresses the three areas (technical, financial and social) where uncertainties can appear. Current research conducted by McManus and Hastings (2005) and Clarkson and Eckert (2010) address the difference of uncertainties into those that are known and those that are unknown.
One of the most apparent and commonly used classification in current literature is developed by Ho (1989) who separates uncertainties into environmental and system. Some of the authors use the internal and external as a subdivision of the main classification. As an example external and internal uncertainties defined by Clarkson and Eckert (2010) can occur in product, process and organization itself (internal) and political events, in the context of product or process operates (external).
<table>
<thead>
<tr>
<th>Author (year)</th>
<th>Types</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milliken (1987)</td>
<td>State, Effect, Response</td>
<td>The <em>state uncertainty</em> of the environment addresses the non-understanding how components of the environment might be changing. <em>Effect uncertainty</em> is the inability to predict the character of the future impact on the organisation. <em>Response uncertainty</em> in form of response options that are available and what the value of each might be.</td>
</tr>
<tr>
<td>Gerwin (1988)</td>
<td>Technical, Financial, Social</td>
<td><em>Technical uncertainty</em> refers to the difficulty in determining the precision, reliability and capacity of new processes and further if new technologies may appear and make the current equipment obsolete. <em>Financial uncertainty</em> covers the uncertainty whether return on investment should be the major criterion and whether returns can be forecasted properly. <em>Social uncertainty</em> covers questions about the nature of required support systems and possible conflicts during the implementation.</td>
</tr>
<tr>
<td>Ho (1989)</td>
<td>Environmental, System</td>
<td><em>Environmental uncertainty</em> refers to the production process such as demand and supply uncertainty. <em>System uncertainty</em> appear within the production process for example in operation yield, production lead times, quality issues, failure in production and possible changes in production structure.</td>
</tr>
<tr>
<td>Rowe (1994)</td>
<td>Temporal, Structural, Metrical, Translational</td>
<td><em>Temporal uncertainty</em> addresses the future state and past tense uncertainties while <em>structural uncertainty</em> appears due to complexity issues, <em>metrical</em> within measurements and <em>translational</em> while explaining uncertain results.</td>
</tr>
<tr>
<td>McManus and Hastings (2005)</td>
<td>Lack of knowledge, Lack of definition</td>
<td><em>Lack of knowledge</em> addresses facts that are not known or known just imprecisely, but are needed. Things about the system that have not been decided or specified are defined as <em>lack of definition</em>. Further, each of the classes can come with the following characteristics: statistically characterized random variables, known unknowns and unknown unknowns.</td>
</tr>
<tr>
<td>Lane and Maxfield (2005)</td>
<td>Truth, Semantic, Ontological</td>
<td>When it is uncertain if a statement is true or not it is defined as <em>truth uncertainty</em> while the uncertainty about the meaning or interpretation of the proposition is called <em>semantic uncertainty</em>. <em>Ontological uncertainty</em> depends upon the concept of actors’ ontology, therefore the uncertainty conducted by the actors’ being, becoming, relations and reality.</td>
</tr>
<tr>
<td>Clarkson and Eckert (2010)</td>
<td>Known, Unknown</td>
<td><em>Known uncertainty</em> can be described as variability in past cases and can be characterized by probability distribution. The key problem here is the estimation of the known uncertainties in unique or new product and processes. <em>Unknown uncertainties</em> occur unexpected and can be internal or external. Both <em>known</em> and <em>unknown uncertainty</em> appear in two areas: <em>uncertainty of description</em> (selection, naming, ambiguity, in scope) and <em>uncertainty of data</em> (completeness, accuracy, consistence, measurement).</td>
</tr>
</tbody>
</table>
3.2.2 Sources of Uncertainty in the Production Design Process

Since the success of any process change depends on the level of uncertainty, particular attention needs to be paid to this issue (Rajabalinejad and Spitas, 2011). Sources of uncertainty are multitudinous and can be split into types as shown in the previous section (McManus and Hastings, 2005). Besides the categorization, sources of uncertainty have to be identified and approaches to reduce them have to be instituted (Yang, Burns and Backhouse, 2004). The importance of generating awareness of uncertainty sources is stated by Carrillo and Gaimon (2002) as following:

"From the empirical and case literature, we know that uncertainty plays a crucial role in process change strategy formulation and success. A variety of sources of uncertainty exists that impact the resources required for process change and the ultimate performance gains attained" (Carrillo and Gaimon, 2002, p. 420)

Even though the importance of uncertainty awareness is well stated in current literature, there is still little research within sources, levels and tools to handle uncertainty in production system design. On the other hand, the area of product design process has been in researched largely. Since the process of designing a product and a production system are comparable, in the following research papers have been conducted dealing with uncertainty in product design processes.

Looking at the system design process, uncertainty may arises from internal and also from external sources and feature an important part for future success (Rajabalinejad and Spitas, 2011).

As summarized in Section 3.2.1 uncertainty is defined as the lack of information. Within production system design that might lead to a significant problem when proceeding to the next steps of the design process, since decisions have to be made under lack of information (Rajabalinejad and Spitas, 2011). Especially if design decisions are based on market forecasts, for instance demands, uncertainty may arise from market changes (Verworn, 2006).

A more holistic overview illustrating sources of uncertainty within the product and system design process by De Weck Olivier et al. (2007) who based his model on the assumption that sources of uncertainty appear in a range of known and unknown, depending on the understanding of the issue. Figure 3.3 shows a variety of uncertainty sources and their context developed by De Weck Olivier et al. (2007).
The dashed box in Figure 3.3 encloses the system boundary, the endogenous (internal) uncertainty. The uncertainties within this box arise from within and can be influenced by the product or system designer while the uncertainties outside the system boundary are subject to restricted influence. Besides the differentiation of endogenous (internal) and exogenous (external), sources of uncertainty can be subdivided into contexts of product, corporate, use, market and political and cultural context (De Weck Olivier et al., 2007). Each development process carries an aggravated technological risk due to the novelty of a product or process. Usually, these technical uncertainties are estimated in the beginning and resolved over the design process. Interactions between part of the system as hardware, software and humans might lead to uncertainty, due to unmodelled interaction in case of changes within the process or even occurring failures. Reliability and durability of components over its' life cycles can also be causes of uncertainty. Within the corporate context uncertainties may arise from the business context as company strategies influence the design process (De Weck Olivier et al., 2007).

Many uncertainties are outside the companies’ direct control, arising form the market, the way the product is in operation and cultural and political influence. Especially the market environment causes a high level of uncertainty due to the degree and speed of change for example in demands and innovation (De Weck Olivier et al., 2007).

Another approach concerning sources of uncertainty in engineering system architecture is conducted by McManus and Hastings (2005). He defines empirical quantities as measurable properties of real world systems and categorizes seven sources of uncertainty in these empirical quantities:

1. **Statistical variation**: from random error in direct measurement of quantities due to imperfection of measuring instrument and techniques.

2. **Systematic error and subjective judgement**: due to biases in measurement apparatus and experimental procedure and key assumptions by the experimenter.
3. **Linguistic imprecision**: due to lack of proper definitions.

4. **Variability**: due to natural frequency distribution.

5. **Randomness**: quantities that arise randomly or have to be treated as random, because they can not be computed accurately enough.

6. **Disagreement**: due to different technical interpretations of data.

7. **Approximation**: numerical approximations to equations and model reduction by approximation.

Also the research performed by Wynn, Grebici and Clarkson (2011) deals with uncertainties in the design process, especially the ones the designer is facing. Even if his work had a product design background, aspects of uncertainty and levels of uncertainty can be correlated to the production system design. Wynn, Grebici and Clarkson (2011) come to the conclusion that there are five main aspects in the design process, causing uncertainty:

**Imprecision**: Early in the design process there are many ideas and possible solutions to a problem. Imprecision arises if design decisions remain open and the designers needs to consider a vast span in which the information could lie.

**Inconsistency**: Inconsistency may arise between different descriptions applied during the design process. This might be caused by assumptions made, simplifications in modelling and a limited overview.

**(Expected) Inaccuracy**: During the design process, tools and methods can be used to create information. As a result there is an expected difference between the predicted value and the actual value.

**Indecision**: Indecision may arise when the designer have several alternatives and has to select the most promising one he or she is about to continue working on. As a result the consideration of all options is likely to take longer time the greater the indecision is.

**Instability**: Instability in design descriptions may have an impact on the working approach of the designer. If input information are likely to change, the designer will spent little effort on the task in order to avoid extensive work he or she has to edit in case of probable changes. Vice versa if input information are not expected to change, it is probable that the designer will organize the process into smaller and more time consuming subtasks. Accordingly, the designer will detect fewer opportunities to recognize and react to problems or changes.

### 3.2.3 Reducing Uncertainty in Production System Design

As the outcome of innovation processes are supposed to be new, it can not be predicted during the design process. Therefore, dealing with uncertainty in practise is based on knowledge of previous processes that have been successful and individual problem solving abilities. Consequently, the designer finds himself in an unfamiliar situation and does not know how to proceed. The designer will solve the unfamiliar situation through trial and error using know or even new procedures (Daalhuizen, Badke-Schaub, Batill et al., 2009).
Besides the ability of the individual to solve problems, also the level of uncertainty affects the ability to make decisions. As shown in Section 3.1.3, the production system design process is characterized by decisions that have to be taken in every phase (Choudhari, Adil and Ananthakumar, 2010). Therefore, uncertainty is maximized in this time of the production system development. Rajabalinejad and Spitas (2011) produced the Figure 3.4 to show the relationship of time and uncertainty within the whole product development process.

![Figure 3.4: Uncertainty versus available information in the design process (Rajabalinejad and Spitas, 2011)](image)

As a result, the design process in the early beginnings is critical to the success and can be decreased by new and relevant information. Furthermore, experience, creativity, imagination and intuition are valuable decreasing uncertainty (Rajabalinejad and Spitas, 2011). Figure 3.5 represents a typical action with uncertainty in the design process and suggests searching for relevant information.
Moreover, if the level of uncertainty is very high, Rajabalinejad and Spitas (2011) recommends using a decision support tool. Figure 3.6 show appropriate tools during the product system design process. Figure 3.6 illustrates that different tools have to be used through out the development time.

Even though the tools shown in Figure 3.6 are easy to apply, Frishammar et al. (2011) argues the importance of tests in lab and technical tests. Particularly when dynamic and
complex development of systems requires great deal of information to be dealt with in an efficient, accurate and fast manner by a great number of people, more advanced tools are required. Since the 1990s computer based simulation is used in production design, but not integrated in general, nor widespread (Holst and Bolmsjö, 2001).

3.3 Simulation

Simulation was defined by Shannon as the process of designing a model of a real system and conducting experiments with it in order to understand the behaviour of the system and/or evaluate different scenarios (Shannon, 1998). Simulation can be very useful to represent, analyse and evaluate situations that would not be possible or cost-efficient in real life. This way, it allows the user to predict the performance of a forthcoming system, validate a design, test hypotheses or even visualize operations (Banks et al., 2005). Thus, in current competitive markets, simulation is a very useful tool available to decision-makers, designers and engineers (Shannon, 1998), making it one of the most used technique in operations research and management science (Kelton and Law, 2000).

3.3.1 Discrete-Event Simulation

As stated by Banks et al. (2005), systems can be classified as discrete or continuous. The Discrete Event Simulation (DES) refers to the modelling of a system in which the state variables will change at once in a countable number of points in time (Kelton and Law, 2000). In these points in time, an event will occur, which is defined as an incident or phenomena that will change the state of the system. From a theoretical point of view, this means that discrete event systems could be mathematically modelled, but the high amount of data needed to be manipulated and stored in real-world systems urges the use of computers (Kelton and Law, 2000).

3.3.1.1 The Stochastic nature of DES

When a simulation model contains no random variables, it can be classified as deterministic. Given that DES models are an input-output transformation, these models will result in unique outputs. On the other hand, there are also the models where some of the data input are random variables, which are classified as stochastic (Banks et al., 2005). The use of stochastic variables can be very useful for the cases when one wishes to study the behaviour of a system by running different scenarios and obtain estimates out of them (Banks et al., 2005). But of course, random input variables lead to random output variables, which means that before drawing any conclusions, a proper statistical analysis of the output data is necessary. The statistical analysis will ensure that the estimates are sufficiently precise to back-up the conclusions defined (Banks et al., 2005).

3.3.1.2 ExtendSim

Originally named as Extend™, ExtendSim is one of the first simulation software using many so-called modern features found in other software (Krahl, 2012). Examples of these characteristics are the interface, architecture and extensibility. Previously, simulation programs involved complex programming in a simulation language. But with the introduction of ExtendSim, an interactive drag-and-drop modelling was introduced, making the simulation program easy to use and to re-use for other projects (Krahl, 2012).
3.3.2 Simulation in Production System Design

Lately, the most representative application area of simulation modelling has been manufacturing (Holst and Bolmsjö, 2001). Within that field, the most common performance measures analysed were throughput, lead times, queue times, queue sizes, timeliness of deliveries and utilization.

The study of performance measures allow the analysts and managers to observe and understand the behaviour of a system without experimenting with the actual system (Wu, 1994; Shannon, 1998). For example, they may try out different production system scenarios, with new operational conditions, new equipment, new layouts or different cycle times in order to analyse the performance of the disturbances or to identify any possible bottlenecks.

In production system design application, simulation can be classified in to two different categories (Wu, 1994): in systems evaluation, the current system can be simulated to be adapted or changed according to certain operating conditions, while in systems design, a new system can be simulated to avoid expensive pitfalls or radically change some operating conditions. Nevertheless, in practice simulation models often consist on a combination of both categories, as they provide analysis, description and evaluation of the capabilities of the system (Holst and Bolmsjö, 2001). This way, simulation can improve knowledge, shorten the development lead time and support decision making.

After all, a rough simulation model developed with the purpose of system analysis and conceptual design, can be modified or adjusted and used for the re-design of a system (Kosturiak and Gregor, 1999). The same model can be further adjusted with control functions and interfaces with the environment to support dynamic scheduling, capacity plans or even labour allocation. This could be one of the reasons why simulation modelling is used at all levels of management in the 500 largest corporations of the United States (Babulak and Wang, 2010).

3.3.2.1 Advantages of using Simulation

<table>
<thead>
<tr>
<th>Model type</th>
<th>Descriptive</th>
<th>Physical</th>
<th>Analytical</th>
<th>Procedual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method of prediction</td>
<td>judgement</td>
<td>manipulation</td>
<td>mathematical</td>
<td>simulation</td>
</tr>
<tr>
<td>Method of optimization</td>
<td>?</td>
<td>experiment</td>
<td>mathematical</td>
<td>experiment</td>
</tr>
<tr>
<td>Cost</td>
<td>low</td>
<td>high</td>
<td>medium</td>
<td>high</td>
</tr>
<tr>
<td>Ease of communication</td>
<td>poor</td>
<td>good</td>
<td>poor</td>
<td>excellent</td>
</tr>
<tr>
<td>Limitation</td>
<td>not repeatable</td>
<td>cannot represent information process</td>
<td>only able to cope with simplified cases</td>
<td>optimal solution not guaranteed</td>
</tr>
</tbody>
</table>
Simulation offers many advantages when compared to other optimization and analytical models (see Table 3.2). As mentioned before, probably the most representative advantage is that simulation allows the user to model and represent different scenarios (e.g. new designs and layouts) before committing any resource to it (Shannon, 1998). This way, without disrupting any company activity, new future design alternatives or even machinery acquisitions can be represented and analysed (Banks et al., 2005).

Consequently, simulations allows the analyst to experiment with unfamiliar scenarios and to answer "what if" questions (Shannon, 1998). This can be a key element in any production system design process (Banks et al., 2005).

Simulation also enables the study of alternatives for a long time frame in a compressed time (Kelton and Law, 2000). This way, within seconds the analyst can slow-down or speed-up certain phenomena that may occur in each scenario (Shannon, 1998).

Together with that, simulation can ease the identification of bottlenecks in information, material and the production process (Banks et al., 2005), and thus, help the analysts to gain insight and understand the model itself (Shannon, 1998).

Moreover, simulation may help analysing complex real-world systems that mathematical models cannot solve (Kelton and Law, 2000). Simulation might also be a more suitable tool than analytical modelling when presenting the project to the management or the customers. Often it is easier to comprehend and justify (Shannon, 1998), making it also an effective communication tool for the management (Robinson, 2014) (see Table 3.2).

3.3.2.2 Disadvantages of using Simulation

Nevertheless, simulation also has some drawbacks. First of all, simulation requires special training and experience (Shannon, 1998) and therefore the utility of the simulation study is highly dependent on the quality of the model and the skill of the modeller. Such skills come in handy, because simulation results can be difficult to interpret (Banks et al., 2005). This is the case when the simulation is based on random inputs, where most simulation outputs will also be random variables, and it can be difficult to distinguish if an output is a result of a relationship or a randomness (see Section 3.3.1.1).

Given that the gathering of reliable input data can be very time consuming and expensive, simulation studies tend to have the same trend (Banks et al., 2005; Kelton and Law, 2000) (see Table 3.2). In any case, this is a must-do expense, since inadequate or poor data would have even worse consequences (Shannon, 1998).

Simulation models are just an input-output model, where for a given input they will yield the most probable out (Shannon, 1998). Therefore, simulation models do not give an optimal solution to the problem, they are simply a tool for analysing different behaviours or alternatives. The optimization and conclusions of such analysis rely on the analysts or modeller (Shannon, 1998).

That dependability on the modeller may also bring another drawback, the overconfidence on the model (Robinson, 2014). After all, when analysing the results of a simulation model the validity of it should be at least considered, giving special focus to the assumptions and simplifications of it.

3.3.2.3 Applicability of Simulation

Due to all the advantages that simulation offers in the early stages of a production system design, the popularity of simulation has increased considerably. In many cases, this may led to a successful project, but as a tool, it can also be sometimes misapplied (Banks
3 Theoretic Framework

and Gibson, 1997). For example, simulation should not be used in the cases where the problem could be solved either physically, analytically or by the use of "common sense" (Banks and Gibson, 1997). The high costs of the simulation can make the model not worth it. On the other hand, for complex systems where informational, organizational or environmental changes should be considered simulation can come very handy (Banks et al., 2005).

Another important aspect to take into consideration is that if the expected savings out of the simulation modelling are smaller than the actual costs of it, the modelling should not be carried out (Banks and Gibson, 1997). Data gathering, model development, model validation, experimentation and documentation can all increase in a great deal the overall cost of the project, and if they exceed the potential savings or the cost avoidances, the simulation would not be justified.

As stated before, simulation modelling requires, among other things, analysts expertise, data and time. Hence, if any of those resources would not be available for the project, simulation would no longer be the right tool (Banks and Gibson, 1997). Any unavailability of those would also cause difficulties when verifying and validating the model (Banks and Gibson, 1997), directly affecting the results and analysis out of it.
4 Discrete-Event Simulation Modelling

The aim of this chapter is to describe the steps followed to build the DES model. The chapter follows the structure of simulation model building defined by Banks et al. (2005) (see Figure 2.2). In contrast to Section 2.2.3 where a description on how the model was built was shown, this chapter describes in detail what was the outcome of those steps.

4.1 Step I. Problem Formulation

The first step of the simulation modelling was to formulate the problem. As the DES was part of the CAST Assembly Enablers project, the problem was stated as:

How to assemble different cabs on the same assembly line?

The conducted simulation study is based on the above formulated problem. As a final outcome the simulation should serve as a basis to compare the current state, composed of three lines with the future one line concept.

4.2 Step II. Setting Objectives

When setting the aim of the simulation model, the overall objective was stated as:

Compare current state cab assembly lines for Cab A and Cab D, Cab B, and Cab C to a future single assembly line where all cabs are to be assembled.

In this manner, the overall objective would be further decomposed into three sub-objectives that would help to evaluate and analyse the comparison between the current and the future assembly lines:

(i) Compare the total number of assemblers in the main assembly line for the current and future assembly lines.

(ii) Evaluate the effect of introducing one more product into the current and future assembly lines.

(iii) Determine the effects of assembly line disturbances in the current and the future assembly lines.

The evaluation of these sub-objectives were based on the analysis of KPIs defined together with the involved Volvo CE Operations Hallsberg production engineers. In order to analyse the sub-objective I the total Operator Quantity was used as a performance measurement. For the sub-objectives II and III, the Total Cabs Assembled and the Lead Time were used as KPIs.

Initially, efficiency as a KPI was defined for the analysis of the sub-objectives II and III. However, since efficiency was not tracked in the company, it was decided together with the involved production engineers to not consider it neither for the simulation model.
4.3 Step III. Conceptual Model Formulation

Once the objectives were formulated, and together with the data collection (which was carried out parallel to this step), the conceptual models for assembly lines of the current state were developed. The three conceptual models are shown in the Appendices (see Section 9.2).

Even if the pre-assembly stations were out of the scope of the simulation model, they were represented in the conceptual models to give a more holistic overview of the production system. Furthermore, the pre-assembly was essential to the correct performance of the main lines and had high importance when developing an integrated solution for the future state line.

The conceptual modelling did not only serve the purpose of visualizing the assembly lines in a simple and summarized way, but also helped understanding the system and building the model (see Section 4.5). After all, the simulation model could be seen as a dynamic version of the conceptual models.

4.4 Step IV. Data Collection

In order to build the simulation model, data from the Volvo CE Operations Hallsberg plant was gathered. All the data available describing the current assembly process included the following points:

- **Station work content description.** The activities carried out in each station were defined. Even if simulation wise this input would not have a transcendent influence, it would help arranging and defining the stations of the future assembly line.

- **Number of operators.** As one of the defined KPIs (see Section 4.2), it was crucial to clarify how many operators were used per station in the current assembly lines. In fact, the total amount of operators vary through the year, so together with the Volvo CE Operations Hallsberg engineers it was decided to build the simulation based on the "maximum capacity" features (see Section 5.1).

- **Cycle times of each station.** Related to the workstation description, the cycle times of each station were gathered. Since this times were mainly affected by two variables, first the amount of operators assigned to the station and second the type of option of the cab, standard times currently used by the Volvo CE Operations Hallsberg engineers were applied (see Table 9.1).

- **Line capacities.** At Volvo CE Operations Hallsberg, the assembly lines are based on the *takt time*. Takt times are not only applied to avoid waste, such as overproduction, but also to full-fill the objective of adjusting the production to the seasonality of the products. Hence, when building the simulation the takt time would allow the model to more accurately represent the real output of the plant through the year. Nevertheless, the historical data regarding the changing takt times were not tracked by the company. To overcome this, the weekly line capacities were used instead. The total weekly production time when divided by the weekly line capacity would result in a weekly takt time.

- **Production schedules.** The production schedules were based on both, the working calendar used in Volvo CE Operations Hallsberg and the daily working schedule.
They were gathered with two main purposes, on one hand, to know how the simulation model should run and, on the other hand to be able to calculate the weekly takt time.

- **Total output.** The total output, as another defined KPI (see Section 4.2), was gathered not only to be able to compare and analyse the current state and future state scenarios, but also as a performance measure when carrying out the verification and validation of the model.

- **Line disturbances.** In order to include process variability into the model, line disturbances were gathered. Since the high amount of disturbances are usually handled in practise within the takt time, only the disturbances that were above the takt time, and hence stopping the whole assembly line were considered for the current state (see Section 4.4.1).

### 4.4.1 Line disturbance data

Due to an estimation made by the production engineers the production lines were standing still approximately % of the total production time. In order to add this variability to the simulation, disturbances have been considered.

The company used a tracking system to record the occurring disturbances in every line and station. When disturbances occur, the operator triggered the system that in turn recorded the stops. The system tracked the station number where the disturbance occurred, the beginning time, the end time and the duration of the stop. Detailed information about the cause of disturbances could be reported by the operators.

For the simulation, disturbances causing a stop of the whole line, for every station, in the year 2015 were gathered from the system. In order to feed in the disturbances into the DES, the data needed to be prepared. First, planned stops were filtered out, since they were already considered within the capacity data. Moreover, stops within not-production times were cleared. For the sake of a overall view, a histogram for every station was produced, showing the length of stops and their frequencies (see Appendices, Section 9.3.2).

The histograms showed a clear similarity: a high frequency of stops under 5 minutes. With increasing stop duration, the frequency decreases to zero. In addition to that, some stations show a group of stops with a length over 30 minutes.

Due to the results of the histograms and in order to find a proper distribution, the disturbances were split into disturbances with a length under 30 minutes and disturbances with a length equal or longer than 30 minutes. Disturbance under 30 minutes were fitted into negative binomial distributions and disturbances over, or equal to 30 minutes into a triangular distribution, considering a most likely, minimum and maximum value. Time Between Failures (TBF) were calculated based on the total production time in 2015, assuming a constant behaviour.

As a result, every station in every assembly line was allocated an individual negative binomial distribution. In case more than 10 stops that were longer than 30 minutes occurred in one station, this station was assigned a triangular distribution as well (see Appendices, Section 9.3.1).
4.5 Step V. Model Translation

The next step was the building of the simulation model. The approach used, was to start building up the simulation simply and build complexity afterwards. Hence, based on the conceptual models the representation of each line was carried out. In order to make the representation as close to reality as possible, some assumptions were made due to lack of data (see Table 4.1).

The model was built in a way that it would take all required input data automatically from an excel file at the beginning of the simulation run, process the data, run the simulation and afterwards send the output back to the excel file. This way, every time a parameter was changed for representing different scenarios (e.g. cycle times and/or disturbances), the model was adjusted automatically.

<table>
<thead>
<tr>
<th>Assumptions Made</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takt time Changes</td>
<td>Given that in the real system the takt times for the production lines do not change monthly, an assumption was made. This assumption was defined together with the production engineers at Volvo CE Operations Hallsberg.</td>
</tr>
<tr>
<td>Production Schedule</td>
<td>In the real system, each assembly line has a different production schedule. In any case, as a simplification, and given that the differences were rather minor, it was decided to use the same production schedule for all of them.</td>
</tr>
</tbody>
</table>

4.6 Steps VI and VII. Model Verification and Validation

Once the simulation model of the current system was built, verification and validation processes followed. For that, a series of various steps divided into three phases were defined:

As seen in Figure 4.1, Phase 1 consisted of building the simulation model using a fixed takt time and without any line disturbance. Three different runs were tracked and compared to the historical data regarding the total assembly line output: one month, six months and one year.

After confirming that the results of the simulation were adequate, Phase 2 was developed. At this stage, the model used changing takt times to represent the seasonality of the products, but line disturbances were not represented yet. In this case, two different runs were tracked: six months and one year.

The last step, Phase 3, involved the use of changing takt times and line disturbances. This final model that could accurately represent the reality was also run in two different forms: six months and one year.
The outcome of the KPIs of the 1 year run of the Phase 3 was approved in a face validation model by the engineers of Volvo CE Operations Hallsberg. This supposed the end of the validation process and the start of the experimental runs of the future state.

### 4.6.1 Results of Current State Simulation

The results of every step of the validation process can be seen in the Table 4.2. The reason for validating just the total amount of assembled cabs was the lack of data. Lead times were not tracked by the company, and hence could not be compared against each other.
Table 4.2: Results of the Validation of the Current State.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Step</th>
<th>Cab A / Cab B</th>
<th>Cab C</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 month</td>
<td>9%</td>
<td>18%</td>
<td>25%</td>
</tr>
<tr>
<td>Phase 1</td>
<td>6 months</td>
<td>21%</td>
<td>27%</td>
<td>32%</td>
</tr>
<tr>
<td></td>
<td>1 year</td>
<td>21%</td>
<td>27%</td>
<td>32%</td>
</tr>
<tr>
<td>Phase 2</td>
<td>6 months</td>
<td>1%</td>
<td>3%</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>1 year</td>
<td>1%</td>
<td>3%</td>
<td>4%</td>
</tr>
<tr>
<td>Phase 3</td>
<td>6 months</td>
<td>9%</td>
<td>6%</td>
<td>9%</td>
</tr>
<tr>
<td></td>
<td>1 year</td>
<td>8%</td>
<td>6%</td>
<td>7%</td>
</tr>
</tbody>
</table>

As predicted, Phase 1 had the results with the highest variance, due to the fixed takt time. The one month period, since usually in the real system there is no changing takt time, has much more accurate result that the longer periods, where seasonality directly affects the total output.

On the other hand, Phase 2 showed very accurate results when comparing them to the real system, ranging differences between 0 and 3%. The reasoning behind the unexpected accuracy in this phase, when compared to Phase 3 is discussed later (see Section 5.4.4).

The output of the one year runs of Phase 3 showed a difference of 7%, which was good enough to satisfy the production engineers at Volvo CE Operations Hallsberg. In any case, a study of the total output was carried out to insure whether the output followed a normal distribution or not:

Figure 4.2: Distribution total cabs assembled yearly

Figure 4.2 shows the frequency of the total assembled cabs of the three assembly lines in 100 simulation runs. The mean value out of those runs was 100 cabs, while the standard deviation of the sample was 20 cabs.

Following the properties of the normal curve, 68.27% of the scores should lie within one standard deviation of the mean, while 95.45% of the scores should lie within two standard deviations, and 99.73% within three standard deviations (Banks et al., 2005). Taking the results from the 100 simulation runs, out of the sample, 71 runs score within one standard deviation of the mean, 95 score within two standard deviations, and 100 score within 3 standard deviations (see Figure 4.3). Summarized, it can be said that the total cabs assembled follow a normal distribution. As a result the total assembled cabs average has a representative value, since the simulation model will very rarely make a run where the total assembled cabs will be very large or very low.
4 Discrete-Event Simulation Modelling

Regarding the lead time of the assembly lines, the one year runs of Phase 3 showed an average value of [redacted] minutes in the Cab A / Cab D assembly line, [redacted] minutes in the Cab B line, and [redacted] minutes in the Cab C line.

4.7 Step VIII. Experimental Design

Once the current state simulation model was validated, the experimental design process was carried out. Therefore, a two-phase future state process was defined for the Volvo CE Operations Hallsberg plant. In the first phase, the one-line-concept was analysed, by comparing the three assembly lines of the current state with the only assembly line of the future state. In the second phase, the four different scenarios defined by Volvo CE Operations Hallsberg were simulated. An overview of the phases and scenarios can be gathered in Figure 4.5:

![Figure 4.5: Simulation of Future State: Phase and Scenario Description](image-url)
4.7.1 Future State Phase 1: One line concept

The first phase of the future state, as described above, was to compare the current three line concept against the future one line. Therefore, the aim of this phase was to check if the one line concept would be able to meet the demand requirements of the three current assembly lines.

In order to be able to do a proper comparison between the two concepts, both simulation models should have some common variables. They both used the same calendar, production schedules and one production shift.

Moreover, the takt time needed to meet the yearly demand was defined as 9 minutes. The reason for defining 9 minutes as the takt time was that with a takt time of 10 minutes, the system would not be able to meet the yearly assembled cab demand. With a takt time of 8 minutes the demand would be met, but the number of stations needed would be the same as with 3 assembly lines, and therefore the improvement from three lines to a single one would be minimal.

Given that the cab with the highest workload was the Cab B with minutes, by dividing it with the required takt time, it shows that the number of stations needed was 33. Based on the current state data of 2015, variability in form of disturbances was also considered in this model. Since this first phase of the future line contains 33 stations, including all products, an estimated allocation of stations was used and disturbance distribution were recalculated (see Tables 9.8, 9.9 and 9.10).

4.7.2 Future State Phase 2: Volvo CE Operations Hallsberg scenario modelling

The second phase of the future state consisted of modelling the scenarios described by Volvo CE Operations Hallsberg. In this manner, four cumulative scenarios were defined. This means that the second scenario used the requirements of the first one, the third scenario of the second, and so on.

Every future scenario includes variability in form of seasonality and disturbances. Based on the current state the disturbances have been allocated into 20 station, shown in the Appendices, Table 9.11. In Phase 2, Scenario 3 a new product was introduced within the production line, assuming 115% of the work content of a Cab A. In this case the disturbance distribution of the Cab A was assigned to this new product, by assuming the new product causes 15% more stops than the Cab A line (see Appendices, Section 9.14).

- **Scenario 1: Future State.** The first scenario consisted of building the model based on the Future State Phase 1 (see Section 4.7.1), but with three main modifications: working on 2 shifts, with twenty stations and a 15 minute takt time.

- **Scenario 2: Future State using the un-utilized (Obelagd) Station.** The second scenario was an adaptation of the first one. Four stations were added into the assembly line, with no workload assigned to them. The objective of them was to give flexibility to the line so that it can handle the disturbances or any other problems more easily. Hence, the location of these un-utilized stations were right after the stations with most disturbsances (see Table 9.11).

- **Scenario 3: Future State with the introduction of a new product.** In the third scenario, a new product was added to the assembly mix. This product was suppose to have 115% of the work content of the Cab A, with a yearly demand of
1,200 cabs. The disturbances were also based on the Cab A, calculating the demand proportional to the occurring disturbances. The allocation and the recalculated TBF can be seen in the appendices (see Tables 9.14, 9.15 and 9.16).

- **Scenario 4: Future State with a change in the demand.** In the fourth scenario a new production mix was represented. Therefore, the demand of the Cab A (high volume) was switched with the Cab B (low volume). This change was the most conflictive production mix change, since the Cab B has the highest work content, and when its demand increases, the disturbances were expected to have a higher impact on the whole assembly line.
4.7.3 Assumptions made for the Future State

In order to build the future state model, some assumptions had to be made. The first assumption entailed that the new product workload equals \(115\%\) workload of a Cab A. In other words, if the total amount of workload of the Cab A was \(\text{minutes}\), the workload of the new product would be \(\text{minutes}\). Additionally, it was also assumed that the total yearly demand of this new product would be \(\text{cabs per year}\). In the same way, the total disturbances of the line also increased, since the inclusion of new products in the assembly lines generally cause an increase in the line stops (see Tables 9.14, 9.15 and 9.16).

In the time this thesis had been carried out, the future state design did not come to the detailing of work content per each station. As a result, it was assumed that all the stations in the line would have the same workload (and in the same way, cycle time) for each product. In other words, for a given Cab A, in the future line all stations had a cycle time of \(\text{minutes}\), \(\text{minutes}\) for an Cab B, \(\text{minutes}\) for the Cab C. Table 4.3 shows the cycle times for all five products:

<table>
<thead>
<tr>
<th>Cycle Times for the Future State Phase 2 Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cab A</td>
</tr>
<tr>
<td>Cycle Time [min]</td>
</tr>
</tbody>
</table>

Another assumption used for the modelling of the future state was the seasonality. In the current process the total amount of assembled cabs varied every month. This variety was transferred to the future line simulation.

4.8 Steps IX and X. Simulation Runs and Analysis

The last step was running every phase and scenario and collecting the output KPIs for further analysis. As mentioned in Section 2.2.3, every phase and scenario were run hundred times in order to get more representative values. The final and entire results will be shown and discussed in Section 6.3.1.
5 Empirical Findings

The following chapter gives an overview over the company, the CAST Assembly Enablers project, the products and the current state of the assembly.

Therefore, first the company and the CAST Assembly Enablers project is described briefly, followed by a description of the current state production system. Here observations, documents, interviews and recordings from meetings were used to give an overview about the current state assembly system and how production system design was handled within the company. Further the work, including challenges working with the DES is detailed. Thereafter, the results of the performed DES study is shown and discussed.

5.1 Company Introduction

Volvo Construction Equipment (Volvo CE) is a business unit within the Volvo Group and has focused on the manufacture of machinery for the construction industry and other related industries around the world since 1950. The company had at the end of 2011, approximately 15,000 employees worldwide and delivered in 2010 about 66,000 construction machinery. Volvo CE in Sweden had at the end of 2011 4,110 employees distributed Arvika Operations (about 1,000 employees), Operations Hallsberg (about 500 employees), Braas Operations (800 employees) and Volvo CE Operations Eskilstuna (approximately 1,800 employees).

Established in 1868, Volvo CE Operations Hallsberg is the main production site for cabins (hereafter referred as cabs) within Volvo CE, located in a two-and-a-half hour journey from Stockholm, Sweden. Here, the cabs are welded, painted and assembled.

5.2 The CAST Assembly Enablers Project

As a way of increasing efficiency within Volvo CE, the implementation of a Common Architecture Shared Technologies (CAST) was identified as a key factor. Based on the CAST philosophy, the ambition of Volvo CE was to use the same assembly system for different products. But operations wise, mixed model/product assembly lines supposed an increase in variation and uncertainty combined with a higher level of complexity that needed to be handled in order to keep the same efficiency levels as in separate assembly lines. In order to face these challenges, an increase in flexibility in the assemble line was needed, which can be achieved by the use of CAST Assembly Enablers. In this manner, the overall objective of the CAST Assembly Enablers project was to develop, demonstrate and document an optimized toolbox of technical enablers to manage the variation, uncertainty and complexity mentioned above.

Considered as a whole, the CAST Assembly Enablers project was part of the CAST Vehicle Module Development, scheduled within three years, as shown in 5.1, spending one year in development and two more years on the piloting.
Within the CAST Assembly Enablers project, Volvo CE Operations Hallsberg was just one part in order to verify findings in real case. Therefore the CAST Assembly Enablers approach was applied for the assembly of cabs to test the enablers and in order to do some physical tests.

The structure of the CAST Assembly Enablers project for the first scheduled year can be seen in Figure 5.2. A cross-functional team (see Section 2.2.2) was set up to work on every of the parts showed in Figure 5.2.

The CAST Assembly Enablers project was divided into four major parts: the concept development, where enablers related to variation, uncertainty and complexity were defined, the benchmark, where enablers used in other factories are analysed, the real case verification, where the enablers defined were taken into practice, and the investigation and demonstration of the challenges and enablers. The study that was carried out at Volvo CE Operations Hallsberg served as a real case verification.
5 Empirical Findings

Since Volvo CE Operations Hallsberg was planning a change in the current production system coming from a three lines production to a one line concept, the company was facing many challenges. In order to meet the challenges of managing variation, uncertainty and complexity, the CAST Assembly Enablers project was combined with the current design project at Volvo CE Operations Hallsberg.

The following sub chapter gives a description of the future concept developed by Volvo CE Operations Hallsberg.

5.2.1 Future Production System

The future assembly line was based on the concept of producing every product and model in one line, regardless different total production times of each product and customer options. The main goal was to run the production in the whole factory, including welding, painting and assembly in two shifts with a takt time of 15 minutes. All pre-assembly supply was supposed to be handled around this one line. Disturbances and options in this concept, would be handled within an unoccupied station. The number of unoccupied stations was not determined, but it was limited to four stations in total due to the lack of space in the factory floor. By using technical enablers variation, uncertainty and complexity in the one line assembly should be solved. These solutions were elaborated by the CAST Assembly Enablers project in form of a tool box.

The key motivating factor for the one line concept was prescribed by the corporate strategy. Within the strategy it was planned to save a certainty percentage of costs within a given time frame. The company needed to fulfill the given requirements and at the same time prepare for future challenges. Already at that moment the company was facing market uncertainties in change of demand, model-product mix and the prospect of a new product introduction in the future. Since there was no space in the factory to build a fourth line for a new product, the one line concept was seen as the solution to save costs by reducing operators and as an enabler for a new product.

Despite the corporate strategy and the new product introduction, the company expected an increase in efficiency by establishing the one line concept. Since the takt time was calculated by demand, often exceeded by far the cycle time and operators were unoccupied due to waiting for the takt time.

5.3 Product Description

As previously stated, the main production of the Volvo CE Operations Hallsberg plant are the cabs. Nevertheless, other products such as hydraulic cylinders or fuel and oil tanks are also produced. In any case, the assembly lines for these products will remain out of scope for the purposes of this thesis.

A cab or an operator working environment is a closed space in a truck or construction machine where the driver is seated (see Figure 5.3). Since the cabs produced in Volvo CE Operations Hallsberg serve construction purposes, the cabs are reinforced for ensuring the drivers safety.
5 Empirical Findings

Figure 5.3: Cab produced at Volvo CE Operations Hallsberg

The high amount of models, coupled with the large additive option possibilities (e.g. air conditioning, heater, sound system etc.) means that almost all the cabs produced in the plant are different in some degree. In any case, the cab production can be classified into four different groups, depending on to which construction machine the cab will belong to: Cab A, Cab B, Cab C and Cab D.

5.4 Current State Description

5.4.1 Production Process Description

The Volvo CE factory located in Hallsberg (Sweden), is currently producing cabins for Cab A, Cab B, Cab C and Cab D. The final assembly of the cabin to the vehicle is not performed in Volvo CE Operations Hallsberg, but in other in Sweden located plants. Volvo CE Operations Hallsberg cover the welding, painting and assembly of the cabins. Since the research study deals exclusively with the assembly process, the current assembly lines are described in detail. The conceptual model for every assembly line is attached in Section 9.2 in the Appendices.

Currently, the four products, Cab B, Cab C, Cab A and Cab D are assembled in three separated lines. Due to the similarities within the assembly process and comparable cycle times, the Cab A and Cab D are assembled on the same line, and both Cab C and Cab B are separated. Every line follows their own takt times, calculated based on the customer demand.

The mixed product line, containing the Cab A and the Cab D consists of 14 stations and 16 operators responsible within the assembly line. The welded and painted products are transported by an elevator from the automated warehouse to the assembly line. Every station has a defined work content. The assembly line of the Cab A and the Cab D is a steady moving conveyor line, so that the product is moving from one station to the next within the given takt time.
The Cab C line has 10 stations and 10 operators in full capacity production, whereas the number of stations is reduced to 7 during seasonality lows. Unlike the Cab A and Cab D assembly line, the cabs in Cab C line are pushed manually forward to the next station, when its takt time is met.

The same manual-push process applies to the Cab B assembly line that contains 11 stations and 15 operators.

Table 5.1 shows an overview of the amount of stations, operators and total production times for every assembly line. The table illustrates the differences within the stations regarding station numbers and total work content that is of importance when thinking of a one line concept including all three lines (see also the cycle times in the Appendices, Table 9.1).

Table 5.1: Number of stations, operators and total work content of the three assembly lines

<table>
<thead>
<tr>
<th>Assembly Lines</th>
<th>Cab A/Cab D</th>
<th>Cab B</th>
<th>Cab C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Stations</td>
<td>15</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Number of Operators</td>
<td>16</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Total Work Content [min]</td>
<td>▪▪▪</td>
<td>▪▪▪</td>
<td>▪▪▪</td>
</tr>
</tbody>
</table>

Besides the operators that are assigned to one particular station, every assembly line has further personal that can be called by the station operators by demand, if extra help is needed. That can occur due to high variety of model mix within the line or special options that appear rarely. This extra personal, called Andon has the function to ensure that help is provided to the station operators and the product can move to the next station within the takt time.

In order to smooth the flow within the assembly lines, some work is done at the pre-assembly stations. The pre-assembly stations are directly next to the line and in a zoned area apart from the assembly lines, supplying the three main assembly lines.

### 5.4.2 Characteristics of the Current State Assembly System

One of the main aspects that characterizes the assembly process is the high amount of theoretical un-utilized time per takt time in the Cab B and Cab C assembly lines. Or in other words, the big difference between the takt time used in those lines with their respective cycle times. This time is only theoretically un-utilized since in the real everyday life, it is used as a way to increase the flexibility of the line and handling the minor disturbances. Another driving factor for the definition of this high takt time is the very broad model mix, which coupled with the high amount of different options makes the assembly process very complex. Operators need to use complex and different assembly instructions, and the complexity can be translated in a loss of time, requiring a higher takt time.

Regarding the lay-out of the assembly lines, the Cab A has a singular set up. The line is built in a height above the ground floor. This allows the material flow to feed the line from the below level, saving space. In the same way, a challenge is created when designing the one-line concept.
Moreover, the material handling has a complex configuration. Some pre-assembly lines are located next to the line, while others are located in another section of the plant. Not only that, but due to the high amount of different models, there is also a vast number of similar materials and parts used. This highlights another problem, the material presenting. Volvo CE Operations Hallsberg currently uses mobile "material façades" to feed the lines, but this might get very complex with the mix-model line (see Section 5.2.1).

Disturbances also played an important role in the assembly line performance. The line engineer estimated that around $\%$ of the total time was wasted with line disturbances. Since the high majority of the problems are originated by material problems or due to complex cab models, Andon personnel aids the lines (see Section 5.4.1). But even with the extra help, disturbances suppose a real problem.

Furthermore, disturbance records are not 100% accurate. When reporting the disturbances, operators find it difficult to precisely describe the disturbance cause. This makes the analysis and problem solving of disturbances difficult. Other KPIs are also either poorly tracked (e.g. lead time) or not being carried out (e.g. utilization and/or efficiency).

Additionally, key documentation is low. Due to the high amount of different models, the cycle times of each station are based on expert prediction (see Table 9.1). In the same manner, there is no historical data of the takt times documented.

Another important aspect, and probably visible beyond Volvo CE Operations Hallsberg, is the difficulties for the operators and other employees to be pro-active to change. It seems that people do not want to go out of the comfort zone and experiment new changes in the working environment. This is probably one of the main causes why the current production system has the same configuration as when it was initially designed.

The change of mindset of the operators and other employees when facing new projects can be very difficult. Nonetheless, the use of simulation can help in this manner, as it can serve as an effective communication tool being able to predict the outcome of a change before any implementation is carried out.

5.4.3 Working with Production System Design

The above described assembly lines are in operation and have not been subject to major changes since they initially were set up. Production system design therefore, is not an activity that is performed regularly or has been performed in this scope for many years. Consequently, there is a lack of knowledge and experience among the involved employees regarding production system design procedures and methods. Besides the lack of experience, there is no standardized way of working within production system design. Since the company is currently facing a change in production system and perceives it as a challenge, a project is ongoing, aiming for a standardized design procedure document elaborated by the CAST Assembly Enablers project.

In general no standardized process is observable. Since the simulation study was performed at a point in time where the project was already initialised, no clear statement about the initialising can be made. The project of designing a one line concept has been launched and dropped several times in the past years. Also now there is no fixed date for the start of production for the one line assembly.

Further no visible evaluation of the existing production system, neither an analysis was performed. Currently the Cab A and the Cab D are sharing the same assembly line and could give information about experiences and challenges with mixing two products in one
line.

On the other hand, a benchmark was carried out (see Figure 5.2) within the CAST Assembly Enablers project and here also requirements were elaborated and objectives set.

After a general design of the new production system, a detailed design should be elaborated. Here the company gave elementary information about the new production system requirements, but it was problematic to set system parameters and properties since that would have required a decision at a early point of the design process.

The CAST Assembly Enablers project initialised the simulation study and worked on how to handle complexity in a one line concept. The simulation study should generate solutions and give a basis in order to evaluate ideas for implementing a mixed product-mixed model line. The company stressed especially that the DES should serve the purpose of testing before doing and as a basis for confirming a 'gut feeling'.

So far no DES was previously carried out within the company, resulting in a lack of knowledge of common DES procedures. Therefore, the first step here was to impart what results a DES can give and how to proceed when performing a DES, giving a clear structure.

Within the company and especially the CAST Assembly Enablers team many challenges were named connected to design of a new production system. Due to the variations of assembly times and work content, depending on the product and model the balancing of the line is seen a difficult task. Also it is open how many operators are needed and how to balance the operators within the line.

An other factor is the material handling and presentation. Matching three lines into one lead to the problem that the operator need to know what is the right part to pick and to assemble to the product. In the current production the variety of models and options already caused problems for the operators. Taking into account that the operator has to deal with at least four different product increases the apprehension that this issue will become more important.

Not only parts needs to be presented, but also the presentation of layout and equipment. The workforce is expected to be a major challenges as well including people management in a multi product assembly line, the huge work content the operator need to adapt and the new work environment (as working in teams).

Implementing one line also means to change the information flow. Information need to be handled in a standardized way, including documentation.

Aside from the technical challenges, the responsible production engineers involves in the design process see the decision making process arduous. Getting acceptance for changes from operators and other employees not involved in the design process is seen as very difficult, especially giving a well elaborated basis for the management to take decisions.

Last, the apprehension of factors that have an impact, but were not considered so far (things that are unknown), raise the desire for testing before implementing.

### 5.4.4 Justification of the difference in the real and simulated output

In order to detect the reasoning behind the difference between the real output of the assembly lines in 2015 and the current state Phase 3 simulation output in the same time frame, a brainstorming was carried out. Out of this process, six possible causes were spotted: use of unreliable data, seasonality, different working schedule, different calendar,
over-time work, and unreliable line capacity calculus. Therefore an evaluation and impacts assessment of every possible cause was carried out.

Table 5.2: Evaluation of the possible explanations of the Output Difference

<table>
<thead>
<tr>
<th>Possible Explanation</th>
<th>Was that really the reason?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use of Unreliable Data</td>
<td>No</td>
</tr>
<tr>
<td>Seasonality</td>
<td>No</td>
</tr>
<tr>
<td>Working Schedule</td>
<td>No</td>
</tr>
<tr>
<td>Calendar</td>
<td>No</td>
</tr>
<tr>
<td>Overtime Work</td>
<td>Yes</td>
</tr>
<tr>
<td>Unreliable Line Capacity</td>
<td>Yes</td>
</tr>
</tbody>
</table>

- The use of unreliable data was discarded based on the validity and reliability of the data used for the model building (see Section 2.4).
- The seasonality was also discarded, since it was already represented in the model due to the changing takt time.
- The difference in the working schedule was discarded after the confirmation from the production engineers and production line managers that the one used in the model was the same as the one in reality.
- The difference in the calendar was discarded with the same reasoning as the previous point.
- The use of overtime work, which was not considered in the current situation modelling, was confirmed by the company. Even if the values of it were rather low (20 hours in the case of the Cab A/Cab D line and ▭ to ▭ hours in the case of the Cab B line), they supposed a minor difference between the simulation model and the real system.
- All the previous reasoning led to unreliable line capacity calculus as being theoretically the main cause behind the spotted difference. Based on the observation during the validation of the current state showing that before implementing the disturbances the difference between the simulation model and the real output was rather low. That led to the presumption that the line managers calculated the weekly assembly line capacity, already considering the disturbances that would occur. Since the calculus of the takt time was based on the weekly line capacity (see Section 4.4), this would mean that the disturbances would be considered twice in the model. After discussing this possibility with the responsible production engineers this presumption was confirmed, suggesting that when calculating the capacity, a rule of thumb was used estimating disturbances ranging from ▭ to ▭ %.

After confirming the causes of the difference between the simulation model and the real system, another simulation run was carried taking into account both causes: the overtime work and the capacities used for the takt time calculus were increased by a 10 % (and therefore, the takt time reduced).
Table 5.3: Difference in the Output between the real system and the simulation with and without the rule of thumb.

<table>
<thead>
<tr>
<th>Using Rule of Thumb vs. Not using it</th>
<th>Output difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cab A / Cab D</td>
</tr>
<tr>
<td>Without Rule of Thumb</td>
<td>8 %</td>
</tr>
<tr>
<td>With Rule of Thumb</td>
<td>0 %</td>
</tr>
</tbody>
</table>

As shown in Table 5.3, the difference between the real system output and the simulation output dramatically decreases when applying the rule of thumb in the capacity and the takt time calculus.
6 Analysis

In this chapter the future state simulation scenarios and empirical findings are analysed, based on the research questions. Therefore, first the observed types of uncertainties are described and compared to the types elaborated in the literature study. Second, the sources of uncertainty in production system design are summarized. Third the results of the future state simulation are shown and information provided by the DES study discussed. Finally, the types of uncertainties found and the information provided by the DES are collated in order to see what types of uncertainties can be reduced by performing a DES.

6.1 Research Question 1: Types of Uncertainties

When comparing the empirical findings and the types of uncertainties in current literature, as shown in Table 3.1, similarities, but also deviations can be found. Since the Table 3.1 is a summary of common definitions of uncertainty, the quoted authors have different backgrounds of research. When applying it to production system design, some aspects are more present and observable than others. Therefore, Table 6.1 summarizes the results of the comparison between empirical findings and the given definitions of types of uncertainties. The table shows the authors, the defined type of uncertainty, the fitting to the empirical findings and argumentation of applicability. The consensus of observations and theory is rated as following:

+ + + High degree of consensus of theory and empirical findings.
++ Some consensus.
+ Little consensus.
− No observed consensus.
Table 6.1: Types of Uncertainty that were observed during production system design

<table>
<thead>
<tr>
<th>Author</th>
<th>Definition</th>
<th>Fitting</th>
<th>Argumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milliken (1987)</td>
<td>State</td>
<td>+++</td>
<td>The non-understanding of how components of the environment change or in what degree they will change (such as future demand, the scope of a new production introduction, competitors).</td>
</tr>
<tr>
<td></td>
<td>Effect</td>
<td>+</td>
<td>The character of the future impact on the organization is not known, but the flexible production line is supposed to be a solution to it.</td>
</tr>
<tr>
<td></td>
<td>Response</td>
<td>+</td>
<td>The response to the environmental changes should be provided by the flexible production line.</td>
</tr>
<tr>
<td></td>
<td>Technical</td>
<td>+++</td>
<td>Designing a new production system that does not exist in any form so far, implies difficulties in determining the precision, reliability and capacity of this new process. The formulated problem within the DES process asking how to assemble different cabs on the same line, deals with the uncertainty arises from a technical point of view.</td>
</tr>
<tr>
<td>Gerwin (1988)</td>
<td>Financial</td>
<td>++</td>
<td>The motivation of changing the production system, besides flexibility aspects, is being more efficient and saving costs. Therefore, the return of investment is an important aspect and the main driver of this change.</td>
</tr>
<tr>
<td></td>
<td>Social</td>
<td>++</td>
<td>Due to complex assembly, variation of product and mix the operator might be over-challenged and new supporting systems might be necessary. As described in the previous chapter, the high amount of different parts and options is already challenging in the current production system, where the operator need to handle one product. The company expects an increase in complexity when it comes to four different product in the same station that the operator has to manage.</td>
</tr>
<tr>
<td>Ho (1989)</td>
<td>Environmental</td>
<td>+++</td>
<td>The production needs to adapt the current and future market demand. That includes handling seasonality, model- and product-mix, change of the product design, introduction of a new product.</td>
</tr>
<tr>
<td>System</td>
<td>+++</td>
<td></td>
<td>Many uncertainties arises from a process context. This uncertainty is highly related to the formulated problem how to assemble different cabs on the same line? which include the allocation of operators and work content per station, balancing the lines and managing disturbances.</td>
</tr>
</tbody>
</table>

Continued on next page
Table 6.1 – *Continued from previous page*

<table>
<thead>
<tr>
<th>Author</th>
<th>Definition</th>
<th>Fitting</th>
<th>Argumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temporal</td>
<td>+++</td>
<td>Many uncertainties due to future, but also past changes regarding for example lack of documentation. Since the purpose of production system design is the development of a new, not existing system, future uncertainties are apparent to arise. The assembly of the product is highly complex, due to the variety of customer options and amount of parts. An increase in complexity is expected when the operator has to handle three different products instead of just one.</td>
</tr>
<tr>
<td></td>
<td>Structural</td>
<td>+++</td>
<td>Uncertainty while explaining results may arise when performing tests or simulation studies.</td>
</tr>
<tr>
<td>Rowe (1994)</td>
<td>Metrical</td>
<td>+</td>
<td>Uncertainty regarding measurements in form of collected data, as disturbances, cycle times. During the process of designing a new production system, assumptions have to be made, they are based on experience and available data. If this data is not correct or have been measured incorrect, it can have a big impact on the future state. As for example disturbances are a current problem of the lines, the scope of this disturbances seemed to be not evaluated and not considered in the future development.</td>
</tr>
<tr>
<td></td>
<td>Translational</td>
<td>+</td>
<td>Uncertainty while explaining results may arise when performing tests or simulation studies.</td>
</tr>
<tr>
<td>McManus and Hastings (2005)</td>
<td>Lack of knowledge</td>
<td>+++</td>
<td>Can be observed in many areas, as how to perform production system design, but also knowledge about the current state.</td>
</tr>
<tr>
<td></td>
<td>Lack of definition</td>
<td>+++</td>
<td>Objectives, common visions, but also requirements are not clearly defined. There is also no clear start of production of the new production line which makes it difficult to push forward a process and to work as a team for the same goal.</td>
</tr>
<tr>
<td>Lane and Maxfield (2005)</td>
<td>Truth</td>
<td>-</td>
<td>No observed uncertainties about doubting statements.</td>
</tr>
<tr>
<td></td>
<td>Semantic</td>
<td>-</td>
<td>Not observed.</td>
</tr>
<tr>
<td></td>
<td>Ontological</td>
<td>-</td>
<td>Not observed.</td>
</tr>
<tr>
<td>Clarkson and Eckert (2010)</td>
<td>Known</td>
<td>+</td>
<td>Known uncertainties were mapped by probability distributions as in the case of disturbances.</td>
</tr>
<tr>
<td></td>
<td>Unknown</td>
<td>-</td>
<td>Not accounted for.</td>
</tr>
</tbody>
</table>
Evident from Table 6.1, it can be seen that state, technical, environmental, system, temporal, structural, lack of knowledge and lack of definition match to the case study conducted in this thesis. Furthermore, in general uncertainties can be split into system and environmental, as defined by Ho (1989). Since the state uncertainty, defined by Milliken (1987) deals with the uncertainty of how and what degree market components change, it can be assigned into the environmental (external) uncertainties. A lack of knowledge and lack of definition as proposed by McManus and Hastings (2005) was observed within the system itself. Technical (Gerwin, 1988) and structural (Rowe, 1994) uncertainties are also part of the system (internal) uncertainties, while temporal uncertainties (Rowe, 1994), dealing with future and past uncertainties may appear in both environmental (external) as well as system (internal) scope.

Since Rowe (1994) defined temporal uncertainties in the dimension of future and past uncertainties, we suggest here an additional dimension, taking into account past, current and future.

Figure 6.1 shows the results of the fitting in Table 6.1 and the allocation of the matching uncertainty types into environmental and system uncertainties. Therefore Figure 6.1 summarizes the observed uncertainties in production system design.

6.2 Research Question 2: Sources of Uncertainty

After defining what types of uncertainties were observed, it is necessary to investigate what causes uncertainty in production system design.

De Weck Olivier et al. (2007) developed a model (see Figure 3.3), mapping the sources of uncertainty. De Weck Olivier et al. (2007) developed this model based to uncertainties observed in product design, splitting the sources first into endogenous and exogenous. He further differentiates the sources into product, corporate market and political and cultural context. Engineering design covers product, process and system design and therefore having comparable design processes (Kusiak, 1999). Thereby, the research results conducted by De Weck Olivier et al. (2007) can give direction to sources of uncertainty in production system design process.

Adapting the model by De Weck Olivier et al. (2007) to the sources of uncertainty observed in the design of a production system, the product context he defined play a minor role. Instead the production process itself has a significant function. Furthermore, many sources of uncertainty arise from an organizational context. Similar to the sources
of uncertainty in product design, the market, the corporate and political and cultural context impact the design process.

Based on this five elaborated contexts, all observed sources of uncertainty are allocated. Figure 6.2 shows the sources of uncertainty within their context.

Some sources are initialised by the market and have direct impact on the corporate context and the production process context. In fact, market changes are the origin of major uncertainty not just for current production in form of seasonality, but also when designing a new production system. Changes in the demand in form of volume, model and customized solutions are difficult to estimate and to consider during the design phase. The introduction of a new product, aimed within the corporate context and/or market demands, cause uncertainty of how to integrate the new product in the current production under given circumstances (as the lack of space and knowhow). At the same time, the existing process can be origin of uncertainty too. The designer might be restricted to a certain physical area on the shop floor and high complexity of the product, making the assembly planning hard to map and plan. The complexity of the process combined with the experience and skills of operators at the line leads to an other challenge.

Empirical quantities, defined by McManus and Hastings (2005) as measurable properties of real world systems (like lead time, cycle times, efficiency, disturbances in the case study) causing uncertainty, can also be found in the design process. In Figure 6.2 the empirical quantities are summarized in the process context and its' content illustrated in the blue box.

Empirical quantities related uncertainty appear both in the current and future state. Since every production system design alternative is based on assumptions, it is necessary that the given data is accurate. Due to statistical variation and subjective judgement within measurements this is not always the case. An example for this is the scope of disturbances when estimating the impact on the assembly lines. Furthermore, linguistic imprecision has been observed when talking about the future state ideas and that led to misunderstandings and equivocality, such as the purpose of an unoccupied stations. It is also hard to consider variability and randomness that have a high impact on daily processes, as disturbances or availability of operators, due to the lack of appropriate data. Besides that, disagreement on technical data interpretations and numerical approximation when modelling a not existing process in order to simplify and understand it, cause consequences.

Many sources of uncertainty arise form an organizational context. Current procedures in information sharing, the use of a 'rule of thumb' (when calculating capacities and considering disturbances in daily business) and documentation impact the design process. Especially decision making and production system design methodology is a source of uncertainty. This area can be split into five more precise problems, defined by Wynn, Grebici and Clarkson (2011). In Figure 6.2 the five aspects of uncertainty are assigned to the production system design methodology and illustrated in the blue box.

Since the simulation study was conducted in an early stage of the design process, many not clearly defined ideas (inconsistency) of the one line concept were open for discussion. This decision remained open and cause imprecision, since all ideas needed to be considered. The higher the imprecision in the decisions, the longer it takes designer to select one alternative to start working with. During the production system design process simulation was used as a tool to create information. The result of the simulation compared to the real system, can not be completely accurate (expected inaccuracy due to missing efficiency and lead time data), and causes in turn uncertainty. Besides the imprecision, a great impact on
the production system design was the instability that has consequences on the working approach. Since it is very likely that input information would change or added (since no detailed decisions were made or shared) little effort was spend to develop ideas. The only assumptions made in the study case regarding the future design were that is should be one line, 15 minutes takt time, 20 stations and a yearly output of 10,500 pieces per year. The splitting of the work content per station had not been done, but was an important factor to be able to meet the takt times and the number of required stations. As a result, little effort was spent with the design, since this information was essential and needed before moving on in the design process.

In the corporate context uncertainties are caused by the prospect of a new product introduction within the existing shop floor. Moreover a corporate strategy initiates a financial uncertainty to reduce costs and result in a return of investment as a main driving factor.

Outside the system boundary uncertainties might arise from the people attitude towards changes and 'unknown' changes within political and cultural context. Since for example the production lines had not been subject to greater changes since their implementation, operators are not used to changes and taking them slowly. That in turn forces the production engineer to implement improvements by testing them in a smaller scope to make the operators comfortable with changes. The introduction of a new production line therefore can cause rejection.

Considering both, the observed types of uncertainty (research question 1) and the sources of uncertainty (research question 2), the types of uncertainties matches the sources of uncertainty. Many sources of uncertainty, as awareness of the current production, balancing lines and production system methodology are due to a lack of knowledge and definition. Structural and technical uncertainties are in the form of high complexity of the product and the impact of market changes as new products, changes in volume and product mix. The temporal aspect is shown in the current line, the non awareness of past actions and future changes.
Figure 6.2: Observed sources of Uncertainty
6.3 Research Question 3: Information provided by Discrete Event Simulation

After defining the types of uncertainty and the sources of it in production system design, the next step would be to clarify what information DES can provide to reduce it. In the following lines the output of the different phases of the future state will be described. Afterwards, supported by the findings from the future state, a clarification on what information DES can provide to reduce uncertainty in production system design will be carried out.

6.3.1 Simulation modelling outcome

As described previously, the models built for analysing the future state can be classified into two phases (see Figure 4.5). In Phase 1, using the same input data a single assembly line was modelled, with 33 stations and a 9 minute takt time. Phase 2 on the other hand, was split into four different scenarios, with cumulative effect. In the first scenario, a single line with 20 stations and 15 minute takt time was modelled. In the second one, based on the first, four un-utilized stations were introduced after the most disturbed stations. In the third scenario, a new product was introduced into the assembly line. In the fourth scenario, the production mix was altered. All in all, the resulting KPIs were the following ones:

**Future State: Phase 1**

The results of the future state phase one of the first compared KPI, the total amount of operators needed in both systems can be seen in Table 6.2:

<table>
<thead>
<tr>
<th>Cab A/Cab D</th>
<th>Cab B</th>
<th>Cab C</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current State</td>
<td>10</td>
<td>16</td>
<td>15</td>
</tr>
<tr>
<td>Future State</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difference</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As shown in Table 6.2, the total amount of operators required would be reduced by 8, compared to the current state. This result was already predicted, given that the total amount of stations used was also reduced from 37 in the current state to 33 in the future state.

Regarding the total amount of cabs assembled yearly, the difference between the current and the future states is shown in Table 6.3. It can be noted that the results are analogous.
Table 6.3: Comparison of the total cabs assembled (Current State versus Future State Phase 1)

<table>
<thead>
<tr>
<th>Cab A / Cab D</th>
<th>Cab B</th>
<th>Cab C</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current State</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Future State</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difference</td>
<td>+ 3 %</td>
<td>+ 2 %</td>
<td>+ 1 %</td>
</tr>
</tbody>
</table>

Whereas the impact on the number of operators and total output are not significant, the improvement in lead time is apparent (see Table 6.4). Cab A and Cab D lead time would have increase by 1 % (minutes), whereas Cab B and Cab C lead time would decrease by 54 % and 45 % respectively.

The main reasoning behind the improvements in lead time was the fact that in the current state the Cab B and Cab C assembly lines had too big difference between the takt time and the cycle time. This led to high un-utilized time per station, which in turn dramatically increased the lead time.

Table 6.4: Comparison of the Lead Time (Current State versus Future State Phase 1)

<table>
<thead>
<tr>
<th>Lead Time of the Current State and Future State Phase 1 [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cab A/Cab D</td>
</tr>
<tr>
<td>-------------</td>
</tr>
<tr>
<td>Current State</td>
</tr>
<tr>
<td>Future State</td>
</tr>
<tr>
<td>Difference</td>
</tr>
</tbody>
</table>

Future State: Phase 2

Regarding the outcome of the scenarios of the Future State in Phase 2, the total assembled cabs are shown in Table 6.5 and the total lead time in Table 6.6:

Table 6.5: Comparison of the total cabs assembled of Future State Phase 2 Scenarios

<table>
<thead>
<tr>
<th>Total Output of the Future State Phase 2 Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cab A</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Scenario 1</td>
</tr>
<tr>
<td>Scenario 2</td>
</tr>
<tr>
<td>Scenario 3</td>
</tr>
<tr>
<td>Scenario 4</td>
</tr>
</tbody>
</table>
As can be seen in Table 6.5, the total amount of cabs assembled is far below from the objective (see Table 6.7). The reasoning behind this difference is explained later in the chapter.

Table 6.6: Average Lead Time comparison of the Future State Phase 2 Scenarios

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead Time [min]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The first conclusion that can be taken from the scenario analysis is that the use of un-utilized stations in Scenario 2 enables the company to assemble % more cabs in a yearly basis (see Table 6.5). This is mainly caused by the fact that when using the un-utilized stations, the main line will not stop so often due to disturbances, and the flow will be more continuous. But it will suppose an average increase of minutes in the lead time of the cabs (see Table 6.6).

Secondly, the introduction of a new product will suppose a decrease in the total output (see Table 6.5). After all, this will be directly linked to the increase of the disturbances (see Section 4.7.3). The lead time values will also be higher, as on average it will increase in minutes (see Table 6.6).

On the other hand, the change in the product mix in the Scenario 4 will not have dramatic impact. After all, the change in the total output would only be cabs per year (see Table 6.5) and the average lead time would just increase by seconds (see Table 6.6).

Justification of the Output Difference

When analysing the total number of cabs assembled in a year in the future state simulation, the difference between the original objective of Hallsberg Operations, which was cabs per year, and the simulation output, which was cabs per year is noticeable. That difference of cabs is mainly caused by two reasons: seasonality and disturbances (see Table 6.7).

Table 6.7: Justification of the total Cabs assembled in Future State Phase 2

<table>
<thead>
<tr>
<th>Total Cabs assembled justification of the Future State Phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective</td>
</tr>
<tr>
<td>Total Cabs Assembled</td>
</tr>
</tbody>
</table>

As previously described, an assumption was made that the future state simulation model would follow the same seasonality pattern (in a proportional way) as the real
system did in 2015 (see Section 4.7.3). Therefore, in some months when the simulation reaches a given value, it will stop assembling cabs, emulating the reality.

This assumption has direct consequences: as long as the seasonality is comparable to the historical data used, the objective yearly assembled cabs would be impossible to achieve. Instead, the maximum output with a theoretical 0% disturbance ratio would result in[c] cabs per year.

But of course, that theoretical ratio is far from real. This brings the next cause, the disturbances. When applying the disturbances to the maximum possible output of the simulation, in this case, the total amount of cabs assembled yearly would be[c] cabs. In other words, with the inclusion of disturbances, the total yearly assembled cabs would be reduced by[c] %.

6.3.2 Information provided by Discrete Event Simulation

As discussed above, one of the main advantages of DES is the ability to model and represent different scenarios before committing any resource to it (Shannon, 1998). This is demonstrated in this thesis, as different future state scenarios were modelled and analysed. Moreover, questions like: "Would the un-utilized station have any effect in the assembly line?" could be easily answered.

This way, uncertainty regarding the future state was reduced. After all, with the use of DES it was shown that the future state scenarios modelled were doable in practice. Even more, the importance of some factors were also highlighted. Factors like balancing of the workloads, seasonality or disturbances need to be seriously taken into account if the total cab assembly objective wants to be met (see Section 6.3.1). And these factors were not even considered in the early stages of the project.

Furthermore, Banks et al. (2005) stated that simulation allowed to measure and visualize the performance of the systems modelled. As shown Section 6.3.1, various KPIs were tracked for every scenario. Even if all the performance measures represented the data of a whole year, simulation allowed us to track them in a short time frame (Kelton and Law, 2000). Hence, we could know the total cabs assembled and their respective lead times in any future state scenario.

Due to the stochastic nature of DES, these resulting KPIs are not absolute values and need to be safely taken (Banks et al., 2005). Some random input variables and assumptions were used in the models, which makes the output of the models highly dependant on them. In any case, the models allow the study of the system behaviour and the gathering of estimations.

Regardless of the output taken from the models, the simulation modelling process brought a decrease in the uncertainty level. As a matter of fact, with steps like the problem formulation, where cross-functional backgrounds of Volvo CE Operations Hallsberg were gathered, the uncertainty regarding the project was defined. Data collection also helped in that manner, as relevant information for the stated problem was collected and processed. Also, the whole process was clearly defined in steps and documented, it would be easy to repeat the process for future projects. The steps performed to build the simulation model overlap with the steps that were suggested by Bruch (2012) in Figure 3.2. Here steps like the elaborating the list of requirements, setting objectives, evaluating the current production system, choosing system parameters and the system simulation were part of the simulation methodology developed by Banks et al. (2005).

All in all, the information that can be provided by a DES study are shown in Figure 6.3.
These information can be summarized into three types: KPIs, structure and visualization. The KPIs provide information about system behaviour and level of impact of certain factors. Regarding the KPIs used in the simulation, it occurred that tracking lead times and efficiency is relevant for future evaluation of the system performance.

The structure given by the DES steps contribute to the structure of the production system development.

An other significant result is that DES is capable of visualize information and make it understandable and accessible to people outside the project.

![Discrete Event Simulation Study Diagram]

Figure 6.3: Information provided by DES to reduce uncertainty in production system design
6.4 Research Question 4: Types of Uncertainties that can be dealt with through Discrete Event Simulation

Once defined what information DES can provide, the types of uncertainties that can be dealt with will be described. For that end, in Table 6.4, the uncertainty types described in Table 3.1 will be analysed and defined whether they were reduced or not by the use of DES.

Hence, as in Table 6.4 can be seen, effect, technical, system, temporal, structural, translational, lack of knowledge, lack of definition, known and unknown uncertainties were reduced in the project by using DES. For the other types defined, no impact was seen. Nevertheless, in case of the financial uncertainty described by Ho (1989), DES might also be useful. Since it was not analysed in the case study, Table 6.4 addresses it as "No impact".
Table 6.8: Types of Uncertainty that can be reduced with DES

<table>
<thead>
<tr>
<th>Author</th>
<th>Definition</th>
<th>Reduced?</th>
<th>Argumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Effect</td>
<td>✓</td>
<td>By modelling different scenarios that would represent future internal or external (corporate context) changes, and analysing the output, the uncertainty on the impact on the organization was reduced. In the case study, this was represented with the introduction of the new product, were the effect it would have in the total assembled cabs was reproduced (see 6.5).</td>
</tr>
<tr>
<td></td>
<td>Response</td>
<td>×</td>
<td>No impact.</td>
</tr>
<tr>
<td>Gerwin (1988)</td>
<td>Technical</td>
<td>✓</td>
<td>With the use of DES, precision, reliability and capacity of the modelled scenarios can be estimated. In the case study conducted in this thesis, it can be seen how the maximum number of cabs assembled yearly was calculated for the Future State Phase 2 (see Section 6.3.1).</td>
</tr>
<tr>
<td></td>
<td>Financial</td>
<td>×</td>
<td>No impact.</td>
</tr>
<tr>
<td></td>
<td>Social</td>
<td>×</td>
<td>No impact.</td>
</tr>
<tr>
<td>Ho (1989)</td>
<td>Environmental</td>
<td>×</td>
<td>System uncertainty was reduced with DES by tracking total assembled cabs, lead times and disturbances of different modelled scenarios (see Section 6.3.1).</td>
</tr>
<tr>
<td></td>
<td>System</td>
<td>✓</td>
<td>The purpose of the simulation was to analyse the system behaviour of the future line. Therefore future uncertainties like the change in demand and mix and the introduction of a new product were studies. Further, the applied DES methodology gives structure for future design processes.</td>
</tr>
<tr>
<td>Rowe (1994)</td>
<td>Temporal</td>
<td>✓</td>
<td>When modelling a system a simplification is made and subsystems can be split. This way complexity can be reduced and processes and systems can be broken down to understandable and assessable levels.</td>
</tr>
<tr>
<td></td>
<td>Structural</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

Continued on next page
Table 6.8 – Continued from previous page

<table>
<thead>
<tr>
<th>Author</th>
<th>Definition</th>
<th>Reduced?</th>
<th>Argumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rowe (1994)</strong></td>
<td>Metrical</td>
<td>×</td>
<td>No impact.</td>
</tr>
<tr>
<td></td>
<td>Translational</td>
<td>✓</td>
<td>The visual aspect of DES eases the communication of the outcome of the models. It makes it easier to understand and explain the process modelled to people out of the project.</td>
</tr>
<tr>
<td><strong>McManus and Hastings (2005)</strong></td>
<td>Lack of knowledge</td>
<td>✓</td>
<td>By tracking the lead time, knowledge about the current system was increased, as this was an unknown fact before the use of DES (see Figure 4.4). Moreover, uncertainty regarding the lack of knowledge of the future state was also decreased, as the importance of two aspects not considered before was highlighted (see Section 6.3.1). The simulation process conducted to build the models helps reducing uncertainty due to lack of definition. The first steps of DES, where a cross-functional team was put together, was to formulate a problem statement to be solved by the simulation. That facilitated all parties involved in the project to have a common vision and goals.</td>
</tr>
<tr>
<td><strong>Lane and Maxfield (2005)</strong></td>
<td>Truth</td>
<td>×</td>
<td>No impact.</td>
</tr>
<tr>
<td></td>
<td>Semantic</td>
<td>×</td>
<td>No impact.</td>
</tr>
<tr>
<td></td>
<td>Ontological</td>
<td>×</td>
<td>No impact.</td>
</tr>
<tr>
<td><strong>Clarkson and Eckert (2010)</strong></td>
<td>Known</td>
<td>✓</td>
<td>In the case study, known uncertainty was reduced by mapping and representing the disturbances with probability distributions (see Section 9.3).</td>
</tr>
<tr>
<td></td>
<td>Unknown</td>
<td>×</td>
<td>Not accounted for.</td>
</tr>
</tbody>
</table>
After mapping all relevant types of uncertainties in production system design (shown in Figure 6.1) and performing the DES study, the impact of DES on the types of uncertainty were analysed. Figure 6.4 shows the level of impact on the observed types of uncertainty in production system design. By DES technical uncertainties can be reduced in a high degree. Also the impact on the lack of knowledge and definition, as well as the environmental impacts can be reduced. Structural uncertainties are affected by the modelling process itself. Since it is impossible to influence the environmental changes (state uncertainty), DES can help to understand the effects that those changes might have on the system behaviour.

Figure 6.4: Degree of impact on the types of uncertainty by using DES
7 Conclusions and Recommendations

This study was set out to analyse the reduction of uncertainty in production system design through the use of Discrete Event Simulation. Since production system design is done infrequently, companies lack structure, information and experience during the design process (Krajewski et al., 2013). Current literature deal with tools to reduce uncertainty in the design process of product design, but less research has been carried out in the matter of production system design, even though studies show that the success of a project is linked to the level of uncertainty (Daft and Lengel, 1986).

In order to reduce the uncertainty in production system design using Discrete Event Simulation (DES) as a tool, the study sought to answer these four research questions:

1. What uncertainties need to be dealt with in production system design?
2. What causes uncertainty in production system design?
3. What information does Discrete Event Simulation provide to reduce uncertainty in production system design?
4. What types of uncertainties can be dealt with through Discrete Event Simulation?

These questions were able to be answered by performing a case study research in Volvo CE Operations Hallsberg, which was planning a change in the current production system. At that moment the assembly system consisted of three different lines where four different products were assembled. In order to safe costs and increase the flexibility of the assembly, a one-line concept was developed. The goal was to be able to assemble all products in one line, posing challenges due to product complexity and uncertainty towards the future line. In order to reduce the level of uncertainty, DES was performed.

Empirical findings were described in Chapter 5 to answer the research questions one and two. Here interviews, observations and documents were summarized to show how the company works with production system design and the challenges they see when developing the new production system.

To answer research question three, a DES study was carried out, simulating first the current assembly lines and then simulating different future scenarios. Therefore Chapter 4 and Section 5.4.4 contribute to the outcome of research question three.

Research questions four is a merge of the findings made in the first two research questions and research question three, reflecting observed uncertainties and information provided by the DES in order to reduce these.

The analysis of the types of uncertainty showed a high correlation between findings in literature and observations made in the case study. Uncertainty types like environmental and system (Ho, 1989), state (Milliken, 1987), temporal (Rowe, 1994), strutural (Rowe, 1994) and technical uncertainty (Gerwin, 1988) were observed. Further the lack
7 Conclusions and Recommendations

of knowledge and the lack of definition, as defined by McManus and Hastings (2005) play an essential role within the process of production system design.

Based on the findings in product design by De Weck Olivier et al. (2007), the sources of uncertainty in the production system design process were compiled. The findings show that especially intern sources cause a high degree of uncertainty covering the process, organizational and corporate context. Also the market initialises changes, which in turn cause intern uncertainties. Empirical quantities as measurable properties of the real world (McManus and Hastings, 2005) are a steady source of uncertainties and uncertainty aspects as imprecision, inconsistency, inaccuracy, indecision and instability impact the design process (Wynn, Grebici and Clarkson, 2011).

The performed DES provided useful information when designing a production system, not just in form of the tracked and compared KPIs in order to understand the system behaviour of the current and future scenarios, but also in form of structured processes and visualization aspects. With the information provided by the DES the technical uncertainty can be reduced in a high degree, as well as the lack of knowledge and lack of definition can be positively influenced. Small reduction of structural uncertainty can be achieved by DES.

However, the environmental uncertainties can not be reduced by performing of a DES, but it’s impact on the system can be studied and the production system prepared for possible market developments and variability.

It is believed that the DES in this study was performed in a too early stage, since not many design decision were made yet. In order to build the simulation model, many important assumptions and simplifications were taken, which directly affected the overall results of the project. In any case, it can be argued that simulation turned to be very beneficial. Even if the results due to the assumptions made might not be completely accurate, they were representative enough to identify the strengths and weaknesses of the systems implemented. Moreover, the simulation modelling process also reduced uncertainty.

As a consequence, we recommend to use DES in a later stage of this project, when more design decision would have been made. This way, the results can be more accurate and representative.

In addition to that, we recommend Volvo CE Operations Hallsberg to track efficiency (or utilization) and lead time performance measures. This would not only allow more specific description of the current processes, but also it would be a more accurate basis for comparison of the future state scenarios.

Besides the improvements that can be made in order to gather more reliable data provided by the DES, a production system design process should be introduced and followed. Even without performing the DES, many uncertainties that arise in the early stages of the design process due to lack of structure and definition would be reduced. Furthermore, it would be interesting to analyse in future research the combined use of DES and production system design process, in order to find out when is the right point in time to perform DES.

In general there is still a big gap of research regarding uncertainty in production system design, tools that can be applied to reduce uncertainty and the direct use of DES as a tool. Since this thesis just examined one case study, results can not be generalized, but can suggest what direction to take when conducting further research.
8 Bibliography


Banks, J. and Gibson, R. (1997), ‘Don’t simulate when... 10 rules for determining when simulation is not appropriate-while simulation tools are appropriate for solving many types of problems, in some situations there are quicker’, IIE solutions 29(9), 30–33.


Bellgran, M. and Säfsten, K. (2004), Production system design and evaluation for increased system robustness, in ‘Second World Conference on POM and 15th Annual POM Conference, Cancun, Mexico’.


Bruch, J. (2012), ‘Management of design information in the production system design process’.


URL: [http://www.thefiscaltimes.com/Articles/2011/12/18/GMs-Akerson-Companies-Need-to-Change-or-Die](http://www.thefiscaltimes.com/Articles/2011/12/18/GMs-Akerson-Companies-Need-to-Change-or-Die)


Liker, J. K. (2005), The toyota way, Esensi.


Miles, M. B. and Huberman, A. M. (1994), Qualitative data analysis: An expanded sourcebook, Sage.


9 Appendices

9.1 Cycle times

Table 9.1: Current State cycle times
9.2 Conceptual Models

Figure 9.1: Conceptual Model of the current Cab A/Cab D Assembly Line
Figure 9.2: Conceptual Model of the current Cab B Assembly Line
Figure 9.3: Conceptual Model of the current Cab C Assembly Line
9.3 Disturbances

9.3.1 Current State disturbance tables

Table 9.2: Negative Binomial Disturbance Distribution for the current state of the Cab A/Cab D assembly line

Table 9.3: Triangular Disturbance Distribution for the current state of the Cab A/Cab D assembly line

Table 9.4: Negative Binomial Disturbance Distribution for the current state of the Cab B assembly line

Table 9.5: Triangular Disturbance Distribution for the current state of the Cab B assembly line

Table 9.6: Negative Disturbance Binomial Distribution for the current state of the Cab C assembly line

Table 9.7: Triangular Disturbance Distribution for the current state of the Cab C assembly line

9.3.2 Current State histograms

Figure 9.4: Histogram of total disturbances of the current Cab A/Cab D assembly line

Figure 9.5: Histogram of total disturbances of the current Cab B assembly line
9.3.3 Future State disturbance tables

9.3.3.1 Phase 1

Table 9.8: Allocation of Disturbances into 33 stations

Table 9.9: Negative Binomial Disturbance Distribution for the Future State Phase 1

Table 9.10: Triangular Disturbance Distribution for the Future State Phase 1

9.3.3.2 Phase 2

Table 9.11: Allocation of Disturbances into 20 stations

Table 9.12: Negative Binomial Disturbance Distribution for the Future State Phase 2 Scenario 1

Table 9.13: Triangular Disturbance Distribution for the Future State Phase 2 Scenario 1

Table 9.14: Allocation of Disturbances into 20 stations with New Product

Table 9.15: Negative Binomial Disturbance Distribution for the Future State Phase 2 Scenario 3
9.4 Total Assembly Distributions

Figure 9.7: Histogram of the total cabs assembled in the current Cab A/Cab D assembly line

Figure 9.8: Histogram of the total cabs assembled in the current Cab B assembly line

Figure 9.9: Histogram of the total cabs assembled in the current Cab C assembly line