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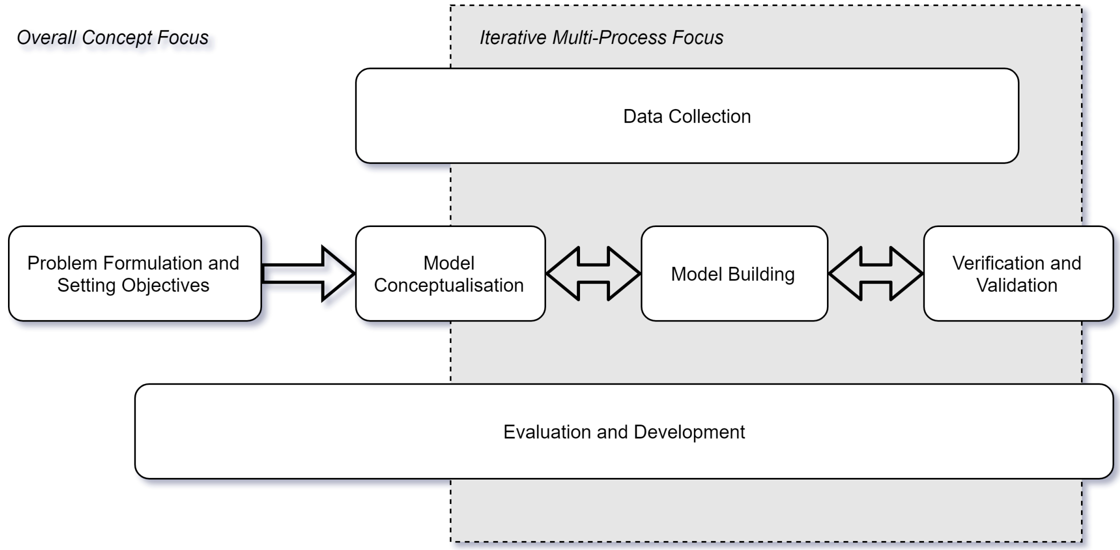

Utilising Discrete Event Simulation to Support Conceptual Development of Production Systems

A Methodology to Handle Contextual Challenges

Master's thesis in Production Engineering

HANNES ANDREASSON
JOHN WEMAN

Department of Industrial & Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2019

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JOHN WEMAN

Supervisor: Daniel Nåfors, Industrial & Materials Science
Examiner: Björn Johansson, Industrial & Materials Science

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Department of Industrial & Materials Science
Division of Production Systems
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden

Cover: The front cover illustrates the proposed DES project methodology which has been developed and evaluated in this thesis.

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Abstract

The use of Discrete Event Simulation (DES) to support the analysis of production systems is well-established. However, the development of new production systems creates conditions which can cause difficulties in successfully applying this type of simulation. This thesis investigates if and how DES should be applied during the development of a new production system concept. A number of significant challenges with this application and context have been identified, which are caused by uncertainties in project prerequisites, frequent changes of the system and concept, and limited availability and quality of input data. Accordingly, this thesis proposes an adapted DES project methodology which sets out to overcome the identified challenges. The adaptations include parallel and iterative methodology steps, and a critical importance of closely involving the simulation team in the development of the new production system concept. The proposed DES project methodology was applied and evaluated during the development of a new production system concept in an industrial case study. The findings from the evaluation show that the proposed simulation project methodology can reduce the impact of the identified challenges with an application of DES in this context. However, these challenges still exist and have to be considered. Additionally, the proposed simulation project methodology enables valuable feedback-loops which contribute to the development of both the simulation model and new production system concept.

Keywords: discrete event simulation, production systems, simulation methodology, project development.

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Hannes Andreasson & John Weman
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Contents

Glossary

This glossary presents and defines the key terminology which is used throughout the thesis.

Computer Aided Design (CAD)
Software for constructing computerised models or drawings in 2D or 3D.

Concept
A prototype or model of an idea.

Conceptual Model
A representation of a system that shows the logical relations between model entities to facilitate the development of a simulation model.

Data
A body of facts about events or subjects.

Discrete Event Simulation (DES)
A type of simulation that is based on a series of events that occur over time.

Fuel Cell
A device that transforms oxygen and hydrogen into electric current.

Fuel Cell System
A system which incorporates a fuel cell and the functions required for it to operate.

Input Data Management
The process of identifying, collecting and preparing quality data for simulation models.

Methodology
A particular or set of several scientific procedures employed within a discipline.

Production system
A subsystem of manufacturing which includes the functions a company uses to produce a product.

Simulation Modelling
The creation and analysis of a digital prototype which represents a physical model, to predict its performance in the real world.

Verification
The process of evaluating if a simulation model has been built and implemented as intended.

Validation
The process of evaluating if a simulation model has good enough correspondence with reality.

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1
Introduction

This chapter introduces the context and purpose of the conducted master's thesis. In the following sections, the background, aim and delimitations of the thesis are presented.

1.1 Background

Increased globalisation and competition puts high demands on the manufacturing industry related to the speed of innovation, cost of products and quality (Freiberg & Scholz, 2015). These aspects have to be considered to become a first-class manufacturer and the use of modern technologies is of additional importance. However, in spite of the trend that these technologies are becoming more affordable, Freiberg and Scholz (2015) states that many still are being rejected based on the difficulties in knowing what an investment in them would lead to. One way to analyse the effects of investments in technologies connected to production systems is to use Discrete Event Simulation (DES).

DES has the potential to deal with the difficulties related to increased competition within the manufacturing industry and can be a key tool when production systems are being analysed (Skoogh et al., 2012). This comes from the possibilities in analysing new production equipment and identifying potential areas of improvement in existing production systems (Skoogh & Johansson, 2008). The possibility to evaluate a new production system concept before its implementation is described by Kühn (2006) as an enabler to determine if the specified demands for the production can be fulfilled by the concept, while investment costs are kept at a minimum level. This view is strengthened by Banks (1999) who states that the cost related to performing a simulation study normally is significantly less than the cost of making changes after a system already has been implemented.

A company that aims to use DES to develop and evaluate a new production system concept before it is implemented is the company PowerCell Sweden AB. They manufacture fuel cell stacks and systems with a focus towards the automotive supplier industry, where the competition is significant. This competition originates partly from the expected great potential in fuel cells as a future environment-friendly propulsion technology within the automotive sector. Two manufacturers where this is exemplified are the automotive company Toyota which transitions towards mass production of fuel cell stacks with support from two new factories, and Hyundai Motor Group who will ramp up their annual fuel-cell system production excessively by the year 2030 (Toyota Motor Corporation, 2018; Hyundai Motor Group, 2018). The German project Autostack Industrie is another example of the trend within fuel cell manufacturing, where PowerCell Sweden AB is a key player in the development of an automated assembly line for mass production of fuel cell stacks (PowerCell, 2018). As part of this project, a collaboration has been established with the consulting firm Semcon AB to develop a new production system concept of the automated assembly line, and this development will be supported by DES.

The development of a new production system concept, as intended by PowerCell Sweden AB and Semcon AB, differs from the development of existing production systems with regard to the level of change that is conducted. Development projects of new production systems could require fundamental changes and entirely new production principles (Bellgran & Säfsten, 2010). With an existing production system, the degree of change conducted in the development project is often limited to alteration or improvement of the current system. The significance of the changes during the development of a new production system indicates a more challenging context for an application of DES.

1.2 Aim and Purpose

This thesis aims to investigate the potential challenges with applying DES within the development of new production system concepts and propose and evaluate an adapted simulation project methodology which is suitable for this context. Initially, the potential challenges are to be identified, from which a new simulation project methodology is to be developed. This methodology will then be applied and evaluated in practice within a development project of a new production system concept in an industrial case.

The purpose of the development and evaluation of a new simulation project methodology is to find a more suitable approach to using DES as a support in the development of new production systems. This is aimed at mitigating the impact from potential challenges which could occur if general simulation project methodologies are practised. Further, a new project methodology could enable a more sustainable approach to production.

Based on the presented background and thesis aims, the two research questions are:

I. What challenges signifies the use of DES within the development of new production system concepts?
II. How should DES methodology be adapted to deal with challenges presented during the development of new production system concepts?

1.3 Delimitations

The thesis is aimed at establishing a DES project methodology which supports the development of a new production system concept and will not concern any other operations or existing production systems. Further, the thesis is conducted within the boundaries of available software and in-house processes and is not aimed at finding the optimal combination of software and other project resources. Lastly, the thesis is taking place during the design phase of the development of a production system concept and the implementation phase is excluded from the scope of the thesis.

2

Theoretical Framework

This chapter describes the established theoretical framework. An introduction is made to key topics within the context of applying DES within production system development and the methodology used during the thesis.

2.1 Overview

This chapter introduces the theoretical framework upon which the conducted study is built, and it is divided into three subsections which are visualised in Figure 2.1. Initially, the context of the project is introduced, dealing with some key aspects of discrete event simulation, development of production systems, and fuel cell technology. Secondly, a selection of aspects within common DES project methodologies is presented. In addition to general characteristics these include problem formulation and setting objectives, model conceptualisation, input data management, and verification and validation of simulation models. Lastly, theory related to research methodology in the sub-areas of literature reviews and analysis, case study methodology and interviews is presented.

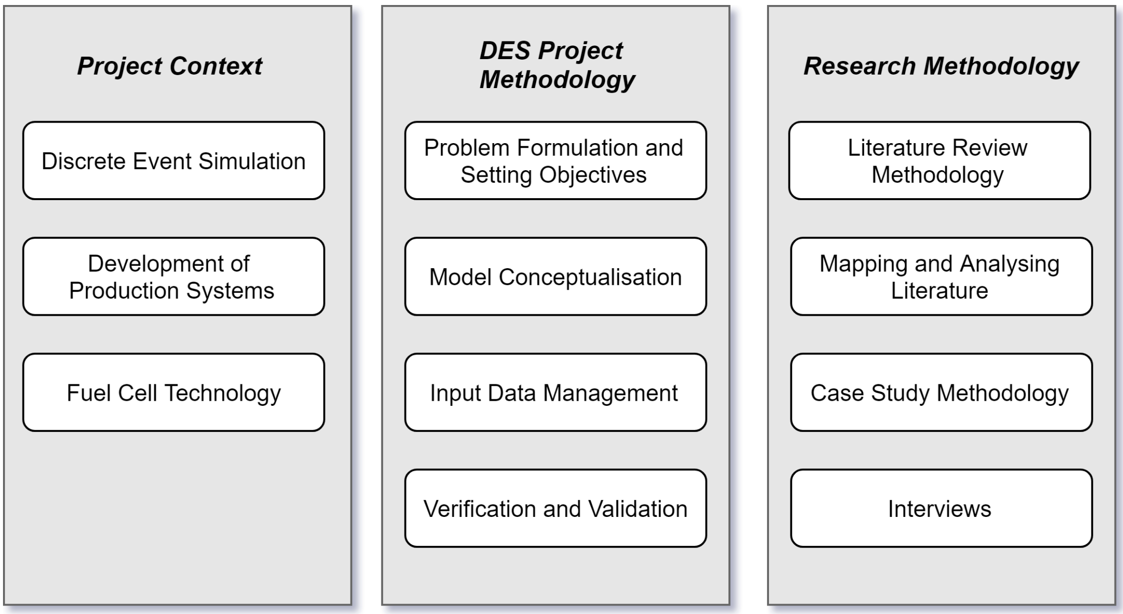

Figure 2.1: Overview of the theoretical framework.

2.2 Project context

The context and background which the thesis has been conducted within are of importance for the understanding of the thesis aim. In this section, the context is introduced with key characteristics within the fields of DES and production systems. Lastly, theory on fuel cell technology is presented to create a better understanding of the context where an industrial case study has been performed.

2.2.1 Discrete event simulation

DES is a frequently used technique for the purpose of analysing and evaluating production systems (Negahban & Smith, 2014). A simulation that is built on discrete events changes states and values discrete in time instead of linearly with time (Fishman, 2001). This means that the simulation is changing based on different events that occur, rather than how much time that has elapsed. Further, DES enables the possibility to perform analysis and evaluations without disturbing the real production system (Banks, 1999). Within these evaluations, fast and accurate analyses can be a useful aid to base decisions on in relation to different investments (Freiberg & Scholz, 2015).

The cost and time required to perform changes in a system which already has been built and implemented can be significant, and DES is described by Banks et al. (2005) to be a well-suited tool for minimising these risks during the development of production systems. To evaluate changes in a simulation model of the system rather than the real world is described to be a faster and cheaper approach, which enables the optimisation of a system before it is implemented. Further, the cost of performing a simulation study is significantly less than the implementation of a system. In combination, this makes DES a cost-effective tool for these applications (Banks, 1999). Carson (2005) describes a selection of the cases where an application of DES is most useful, and some examples are presented as follows:

- The real system has components which have defined interactions and characterisations. The system is not disorganised.
- The real system is difficult to grasp as a result of its complexity or interaction between its components. Thus making a prediction of the impact of proposed changes difficult or impossible.
- A new system is being designed which includes a completely new scope, or major changes in layout or operating rules of an existing system.
- A large investment is planned in a new system for which the knowledge is limited, leading to considerable risk.
- The involved stakeholders must agree upon, and see the results and effects of a set of assumptions. A common understanding is required.

Carson (2005) further states that a good DES model should give support to understanding the system performance in addition to numerical measures. This understanding can be achieved through suitable use of visual aids, such as DES model animations, and a well performed experimental design and statistical analysis. The term simulation will be used synonymously with DES after this point in the thesis.

2.2.2 Development of production systems

A production system is a subsystem within manufacturing and can be defined as an independent allocation of potential and resource factors for production purposes (Rogalski, 2011). Bellgran and Säfsten (2010) describe a selection of the common functions included in the production system to be premises, humans, machines, and equipment, and an example of their relations is illustrated in Figure 2.2. Throughout the thesis, a production system refers to these functions and their interrelations within the context of production.

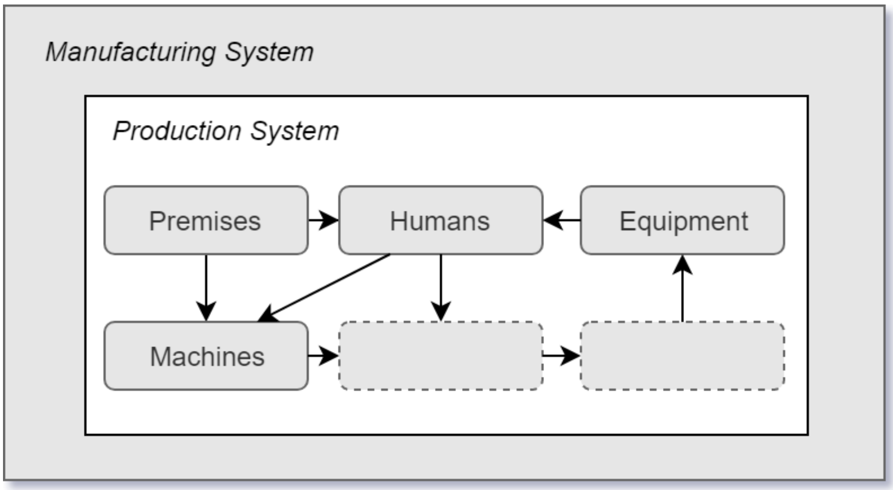

Figure 2.2: Example illustration of a production system.

One of the most common reasons behind a change or development of a production system is stated by Bellgran and Säfsten (2010) to be the introduction of a new product or product families. Additionally, the development could be initiated from the need to automate or increase the capacity of the production. In addition to the reason behind the change, an important aspect in production system development is described to be the degree of change. The development of a new production system could in many cases require fundamental changes and entirely new production principles, in contrast to when an existing system is altered and improved (Bellgran & Säfsten, 2010). The transition from a manual to automatic production is stated to be one example of these major changes.

As production systems are developed, two important and influencing factors are the uncertainties and frequent changes in project prerequisites (Bellgran & Säfsten, 2010). These lead to difficulties in determining the relevant objectives and prerequisites of the system, and uncertainty when choosing between different concept solutions. This view is supported by Flores-Garcia et al. (2018) who also describe a set of challenges that exist when production system development is supported by simulation at an early stage. Three key challenges are stated to be model verification and validation, input data collection and its analysis, and the availability and quality of input data. These challenges mainly arise due to the lack of a real system to draw data from, presence of high uncertainties and modelling with incomplete production system knowledge (Flores-Garcia et al., 2018).

2.2.3 Fuel cell technology

The functionality of a fuel cell involves the conversion of chemical energy from a fuel and an oxidant into electrical energy (Scherer et al., 2008). The most common combination of fuel and oxidant for this process is hydrogen used as fuel and ambient air used as an oxidant (Behling, 2013).

A fuel cell is composed of four basic components; *anode, cathode, electrolyte* and *electric circuit*, which is illustrated in Figure 2.3. These four components together enable the conversion to electrical energy. The hydrogen is supplied to an anode while the oxygen is supplied to a cathode. Between the anode and the cathode, an electric circuit is connected and in between them, there is an electrolyte. At the anode, ions and electrons are separated so the electrons go through the electric circuit while the ions go through the electrolyte (Behling, 2013). Through this process, the electrons create a direct current before they are reunited with the ions at the cathode. The reactions from electrons, ions, and oxidant at the cathode create water as by-product (Winter & Brodd, 2004).

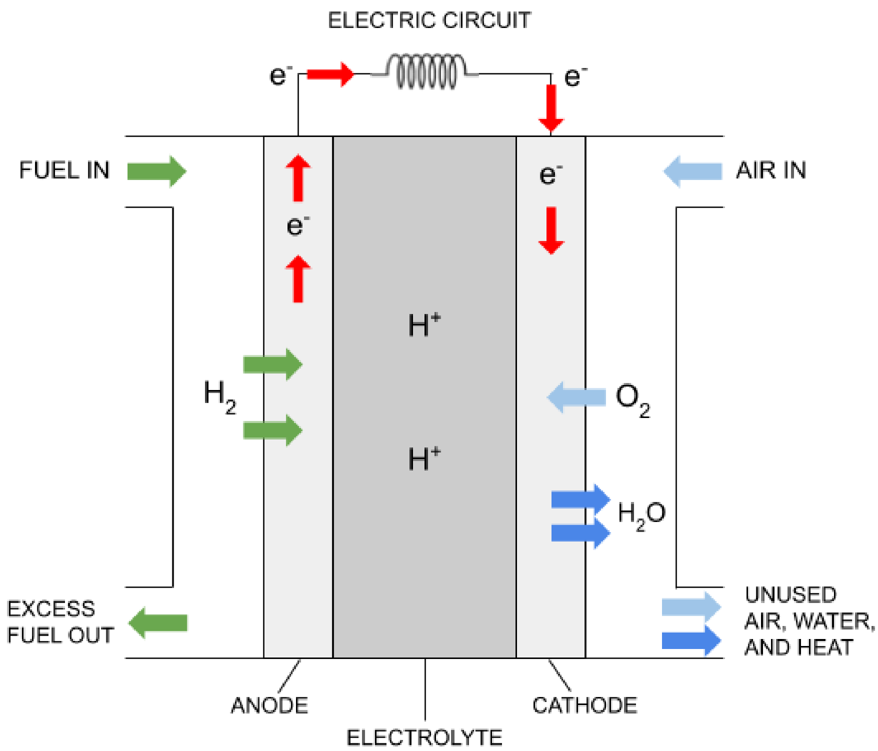

Figure 2.3: The technology behind a fuel cell.

A single fuel cell produces a relatively low voltage, so to achieve higher voltages fuel cells can be stacked into a bipolar arrangement (Scherer et al., 2008). For this, planar bipolar stacking is common where a bipolar plate with one cathode surface and one anode surface is connected to the respective opposite surface on another plate. These plates have channels for the hydrogen and the oxygen to be evenly distributed over each surface (Behling, 2013). The incorporation of a fuel cell and the supporting functions that make it possible for it to operate into one system is called a fuel cell system.

Fuel cells are seen as the energy conversion technology of the future (Scherer et al., 2008). This is due to the efficient conversion of energy and the more environmentally friendly technology compared to thermal combustion processes. Still, the high cost of materials and manufacturing of fuel cells is a big challenge for an implementation of the technology (Winter & Brodd, 2004).

2.3 DES project methodology

Multiple authors have described the field of simulation and the vast selection of project methodologies which can be used to carry out simulation studies, where some are more commonly used and highly regarded (Banks et al., 2005; Law & Kelton, 2000; Carson, 2005). Musselman (1994) describes a selection of the methodology steps which are common and most frequently used as follows:

1. Problem formulation
2. Model conceptualisation
3. Data collection
4. Model building
5. Verification
6. Validation
7. Analysis
8. Documentation
9. Implementation

The sequence in which the different steps are carried out is not fixed and Banks et al. (2005) describe the possibilities of overlap and iterations between steps, which deviates from the specified sequence. Further, Banks et al. (2005) present an example of the relationships between the different steps of a simulation project methodology, and these are illustrated in Figure 2.4.

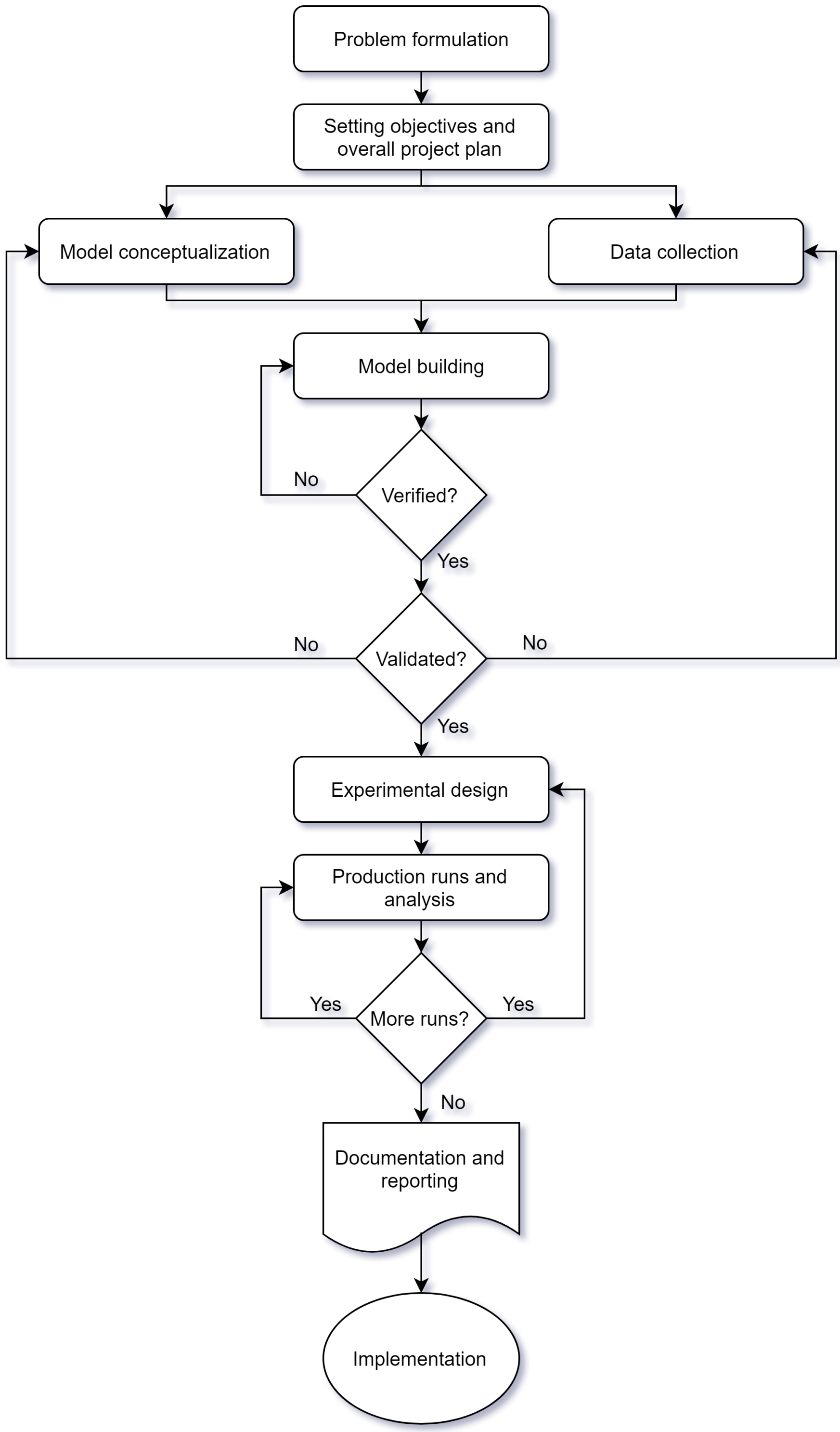

Figure 2.4: Methodology steps in a simulation study as described by Banks et al. (2005).

Another considerable aspect within simulation projects is the choice of simulation software. Banks et al. (2005) describe the importance of basing the software selection on the problems which the simulation should aid in solving and matching these against the specifications of the different simulation software packages.

2.3.1 Problem formulation and setting objectives

The common view within simulation project methodologies is that a problem formulation and setting of objectives should be the initial step of a simulation study (Musselman, 1994; Carson, 2005; Robinson & Bhatia, 1995; Banks et al., 2005). Robinson and Bhatia (1995) describe the importance of reaching a mutual understanding among stakeholders regarding the problem to solve at this stage, as this sets the direction of the simulation project. This can be established through discussions with customers and the objectives should be flexible enough to be adjusted as the project progresses. An additional part of these discussions and a continuing process is suggested by Musselman (1994) to be a setting and management of customer expectations. It is important that these expectations match the set objectives and problem to be solved.

The importance of including flexibility in the set objectives and problem is further supported by Carson (2005), who presents a suitable approach to deal with a limited understanding of the project to be a restated problem formulation as the nature of the problem becomes clearer. Carson (2005) further states the importance of defining a suitable scope and level of detail of the project and simulation model. This can be viewed as a specification of what to include in the model and how in-depth each component should be modelled.

2.3.2 Model conceptualisation

The model conceptualisation is described by Banks (1999) as an abstraction of the investigated real-world system by a series of mathematical and logical relationships to create an overview of the system's structure and components. Robinson et al. (2011) define a conceptual model as: "*a non-software-specific description of the computer simulation model (that will be, is or has been developed), describing the objectives, inputs, outputs, content, assumptions, and simplifications of the model.*" Some of these relationships and the structure of a conceptual model are visualised in Figure 2.5.

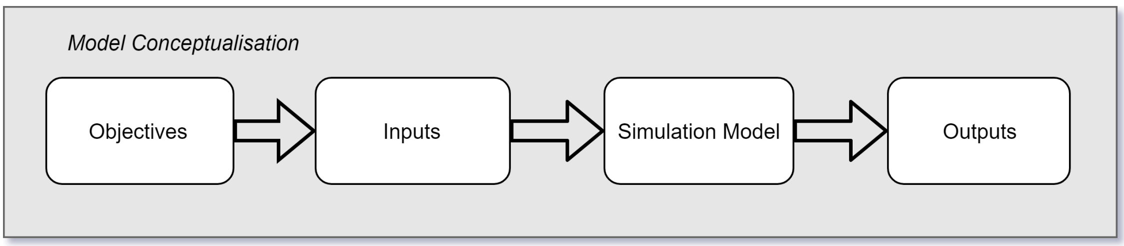

Figure 2.5: Structure of a conceptual model, adapted from Robinson et al. (2011).

The inputs of the conceptual model are based upon the set objectives and are the factors in the simulation model which can be adjusted to create a better understanding or improve the problem situation (Robinson et al., 2011). Further, the outputs can be described as the results that are generated from running the simulation model and are used to evaluate if and why the modelling objectives have or have not been achieved.

The inputs and outputs are two key elements which influence and define the content of the conceptual model. The inputs must be accepted and interpreted by the conceptual model while providing the required outputs with satisfactory accuracy based on the scope and detail level of the project (Robinson et al., 2011). Musselman (1994) describes two examples of possible approaches to collecting data for the conceptual model to be initial factory visits or discussions with process experts.

2.3.3 Input data management

The frequent use of input and output data throughout the different steps of simulation project methodologies makes the management of data a difficult challenge in these projects (Skoogh et al., 2012). Additionally, Trybula (1994) states that the time required to manage input data often is significant, which causes these activities to constitute a large part of the total time required to perform a simulation project. While an increased amount of input data often creates better possibilities for high-quality inputs to the simulation model, Skoogh and Johansson (2008) also state that the input data management process can benefit from an improved efficiency if accuracy requirements are specified on each data parameter. To support the specifications it is suggested that system experts are included to work collaboratively during these processes (Skoogh et al., 2012).

A common challenge with input data management during the design of a new system is the difficulty in collecting enough data with an accuracy suitable to model the manufacturing processes with a high confidence (Flores-Garcia et al., 2018). Further, Hatami (1990) describes the importance of high-quality input data in order to produce a high-quality simulation result. Consequently, a structured approach towards working with input data management is of importance.

2.3.3.1 Challenges with data acquisition

An important aspect within the field of input data management is the variety of issues and challenges that are presented during data collection. The challenges with data acquisition are well covered in literature, where some examples of authors are Skoogh et al. (2012), Robertson and Perera (2002) and Fowler and Rose (2004). Two important aspects behind the challenges are described as the availability and quality of the required input data. Based on the findings, Bärring et al. (2018) present a summary of eight different challenges with data acquisition for simulation models of production systems, which are shown in Table 2.1.

Table 2.1: Challenges with data acquisition summarised from Bärring et al. (2018).

Challenges	Description
Accuracy	Data contains mistakes or errors and has to be investigated.
Correctness	No standards, communication or correct labelling of data.
Duplication	There are two or more data sources for the same event.
Consistency	Different values from different data sources.
Timeliness	Validity of data expires after certain time period.
Validity	Data is not representing the real-world system.
Reliability	Stakeholders do not consider data trustworthy.
Completeness	Incomplete data leading to assumptions and more acquisition.

Bärring et al. (2018) further describe the need for a standardised method for data collection for simulation models, which relates to the importance of good input data to provide trustworthy results, the influence that the data has on the timeliness of the simulation model, and a variety and difference in data collection methods for simulation models of production systems.

2.3.3.2 Classification and collection of simulation data

One approach to support the process of input data management is to perform a classification of input data. Robinson and Bhatia (1995) present a way to perform this classification based on the availability and collectability of input data and divide it into three different categories. These three categories of classification are presented in Table 2.2.

Table 2.2: Categories for input data classification according to Robinson and Bhatia (1995).

Category	Availability	Collectability
A	Available	-
B	Not available	Collectable
C	Not available	Not collectable

An approach where the three categories are used to identify and classify relevant input data parameters is proposed by Skoogh and Johansson (2008). Depending on the different input data categories, various methods for data collection are suggested. The proposed classification functions as a support in input data management activities such as decisions and procedures for obtaining data. Short descriptions of the characteristics of each category are presented as follows:

Category A
The availability of category A data means that it can be obtained from existing sources or systems, such as data from previous projects or existing planning systems. Consequently, no additional data collection is required.

Category B
The data in category B is not available but can be obtained through one or more data collection activities, such as time studies or video analysis. As a result of this manual work, the collection of category B data normally takes a significantly longer time. When there is no existing system on which data collection can be performed or a new system is being developed, an approach to generate input data of good quality is suggested by Skoogh and Johansson (2008) to be the use of emulation tools or process-oriented simulation.

Category C
The input data classified in category C is neither available nor collectable and has to be estimated to be used. A common approach for these estimations is discussions with process experts or people with extensive knowledge of the context where the estimated data is to be used (Skoogh & Johansson, 2008). Further, these estimations of data are generally less time-consuming than the manual data collection activities of category B data. However, to avoid a lower simulation model quality as a result of data uncertainty it is described as important that the data estimation is carried out using a well designed strategy.

2.3.4 Verification and validation

Verification and validation are described by Sargent (2013) as the processes of ensuring that the simulation model has been developed with an output and behaviour which matches its intended use and objectives. The two processes are presented as follows:

Model verification
Aimed at comparing the simulation model with the conceptual model to evaluate if it has been built and implemented as intended.

Model validation
Aimed at comparing the simulation model against the objectives it was intended for, to ensure that the model has a good enough correspondence with the real system.

Banks et al. (2005) support this definition further and describe model validation as a way to determine if the accuracy of the simulation is at a suitable level to represent and substitute the real system within its area of application. To summarise, Balci (1997) describes model verification as the process enabling to build the model right, and model validation to build the right model.

In relation to model verification, it is highly advised by Banks et al. (2005) and Barker and Zupick (2017) that verification is performed at frequent intervals on smaller sections of the simulation model. This should be done in order to enable frequent testing and model adjustments, reducing the required debugging efforts at later stages of the project.

2.3.4.1 Techniques for verification and validation

The purpose and set objectives of a simulation model are described by Sargent (2013) as the key basis upon which model validation should be performed. These objectives determine the requirements on the simulation model behaviour, which are to be reached for an achieved validation. Thus, depending on the purpose of the simulation model and context in which it is being used, an assessment of validation for the same model could give different results if there are different objectives.

When an existing production system is available, a preferred method for model validation is described by Banks et al. (2005) as a comparison between simulation model output and historical data from the real system. However, to assess model validity becomes more challenging during the development of a new system or when no historical data of existing systems are available. With no possible application of objective validation techniques, such as statistical methods, the only possibility could be to use subjective (informal) techniques which are more dependant on system experts' reasoning, insights and intuition (Wang, 2013). When this is the case and simulation is used in the design of a new system, there is an increased importance in involving experts and people with extensive knowledge of the new processes during the model validation (Barker & Zupick, 2017). Additionally, data from similar systems or processes are suggested to be a suitable aid to create confidence in the model.

There are several additional techniques for verification and validation available, where a selection are presented by Balci (1997) and Sargent (2013). Three examples of informal validation techniques are described further as follows:

Animation
Validation through animation means that the performance and behaviour of the simulation model are visualised graphically and studied over a (normally short) period of time (Sargent, 2013). E.g. the movements of equipment and parts during production.

Face validation
Face validation includes reviews of the simulation model and its behaviour in close collaboration with process experts and people with extensive knowledge of the system, with the aim to determine if it is reasonable (Sargent, 2013; Balci, 1997). To facilitate good conditions to achieve face validity and a credible model it is suggested that users and other stakeholders are involved during the simulation model development, especially when the model development team is small (Sargent, 2013; Skoogh & Johansson, 2008).

Structured walkthroughs
The assessment of validity using walkthroughs is performed in order to determine the correctness of a single entity from the simulation model, which is done by a peer group to which it is formally presented (Sargent, 2013).

2.3.4.2 Uncertainty quantification

Roy and Oberkampf (2011) describe an increased importance of uncertainty quantification within the field of simulation and states that it often is included as a part of the processes of verification and validation. Model uncertainty is described by Walker et al. (2003) to be comprised by the nature, the level and the location of the uncertainty. The first two aspects describe the type and degree of uncertainty, and the location of uncertainty is classified in the following five areas, as described by Scheidegger et al. (2018):

Context uncertainty
The uncertainty related to the boundaries of the system and stakeholders' values and interests.

Model uncertainty
The uncertainty due to a lack of system understanding (e.g. input- and input-output relationships, assumptions and model formulations) or uncertainty from software errors, hardware errors and coding errors.

Input uncertainty
The uncertainty related to the input system data of the model and other external driving forces.

Parameter uncertainty
The uncertainty related to simulation model constants.

Model outcome uncertainty
The consolidated uncertainty in the resulting model outcome as a combination of the other four types of uncertainties.

An input uncertainty related to a finite amount of data from real systems, and simulation-estimation errors as a result of limited simulation efforts are described by Xie et al. (2014) as two sources of uncertainty which always are presented in a simulation of stochastic systems. Additionally, Roy and Oberkampf (2011) state that an aspect should be considered uncertain unless it is evident that its impact on the results of the simulation model is minimal.

2.4 Research methodology

This section presents the theory upon which the methodology for the thesis has been based. An introduction is given to the field of literature reviews, followed by how the different elements of the reviewed literature can be analysed and connected through literature mapping. Key aspects of performing a case study are then presented before concluding with theory within the field of research interviews.

2.4.1 Literature review methodology

A literature review is defined by Bryman and Bell (2011) as a: "*Critical examination of existing research relating to the phenomena of interest and relevant theoretical ideas*". The literature review creates the foundation to justify the research question and to build the research design. This is done by identifying what is already known about the research area, including what concepts and theories that are relevant within this.

Hart (2018) describes the basis of producing a literature review to be divided into two phases with four different stages, which is illustrated in Figure 2.6. The first stage is dedicated to a search for sources that are relevant for the specific research question and can contribute to the body of literature. In the second stage, these sources are read with the purpose to extract material based on categorised themes. In the following stage, material is extracted and noted based on themes that are relevant for the development of the specific theoretical framework. Some examples of these are data, theories and methods. The last stage includes writing sections on the themes with extracts from the different literature sources.

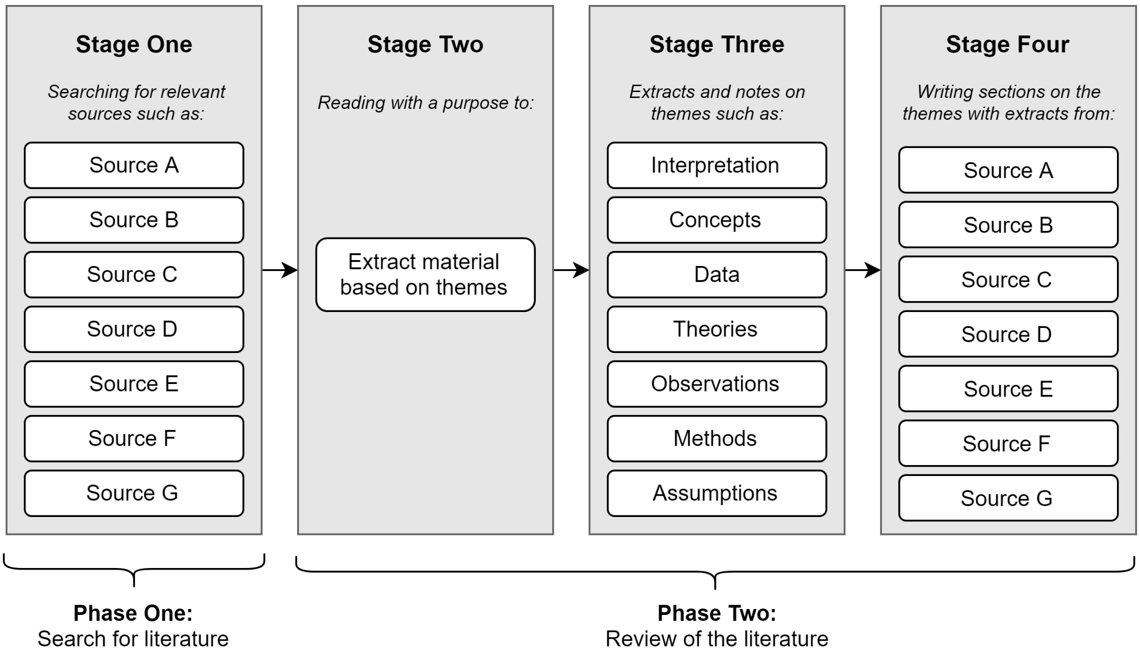

Figure 2.6: The process of a literature review as described by Hart (2018).

A good search strategy within literature reviews facilitates the process of finding relevant content to the body of literature (Rowley & Slack, 2004). Further, Rowley and Slack (2004) describes four examples of useful search strategies which are presented in Table 2.3. Additionally, Jesson et al. (2011) add a supplement to these strategies with a recommendation to use the reference list in the literature to discover more literature.

Table 2.3: Four examples of search strategies within literature reviews as presented by Rowley and Slack (2004).

Strategy	**Description**
Citation pearl growing	Start from one or a few literature sources and use suitable terms found here to gather more.
Brief search	Gather a few literature sources crudely and quickly.
Building blocks	Use keywords and extend them by using synonyms and related terms.
Successive fractions	Use the gathered literature sources and search within them.

One suitable method for categorising all the material in the literature review is described by Timmins and Mccabe (2005) to be *The grid method*. This method summarises information from the studied literature into a table. Depending on the specific purpose of the literature review, the headings used in the grid can differ and some examples of headings that could be used are: *Author and year, Journal, Type of study, Data collection* and *Key findings*.

2.4.2 Mapping and analysing literature

To map ideas, arguments and concepts from a body of literature is stated by Hart (2018) to be an important aspect of conducting a literature review. Further, through the use of mapping, it is possible to categorise and analyse key concepts and arguments while establishing possible relationships between the various literature sources that have been studied. An important aspect of performing a mapping of literature is described by Hart (2018) to be an organisation and classification of the content within the literature in sections, from which connections between the different concepts can be made. This enables an effective way of getting an overview of the topics and creates the foundation for future evaluation and assessment of the included concepts.

The methods used for mapping could be different depending on the intended analysis, but one common approach described by Hart (2018) is to create a relationship map. This type of map is suitable to isolate and target certain aspects of the literature, such as the specific arguments that the various authors present on the topic. The two key steps within the methodology of creating a relationship map are described by Hart (2018) as follows:

I. Create a summarising scheme of the arguments which are proposed by a specific study.

II. Use the identified arguments to locate similarities and differences with the arguments presented by other studies within the body of literature.

2.4.3 Case study methodology

Miles and Huberman (2018) define a case as: "*a phenomenon of some sort occurring in a bounded context*", and a case study is described by Hartley (1994) to be a well-suited research methodology to use for the purpose of analysing processes or behaviour. Further, it can be used to find the answers to the *how* and *why* questions related to different sets of events (Leonard-Barton, 1990). Gummesson (1988) describes the advantage of using a case study as a research methodology to be that: "*The detailed observations entailed in the case study method enable us to study many different aspects, examine them in relation to each other, view the process within its total environment and also use the researchers capacity for understanding.*"

Yin (2003) presents four different bullet points that can be used to determine if a case study is a suitable methodology to consider for a specific research study:

- The focus of the study is to answer *how* and *why* questions.
- You cannot manipulate the behaviour of those involved in the study.
- You want to cover contextual conditions because you believe they are relevant to the phenomenon under study.
- The boundaries are not clear between the phenomenon and context.

If it is deemed suitable to conduct a case study, the case needs to be determined and should be scoped and connected to the defined research questions (Baxter & Jack, 2008). If boundaries are placed on the case it is possible to avoid common pitfalls with case studies, such as having more to explore than feasible for one study. Some examples of how the case can be bounded are described as time, activity, definition and context (Baxter & Jack, 2008).

There are several types of case studies and a decision on which type of case study to perform needs to be made. Yin (2003) defines four different types of case studies (single- and multiple case) and for which purpose they can be used. The definitions are presented in Table 2.4.

Table 2.4: Different types of case studies and their associated definitions as described by Yin (2003).

Type of case study	Description
Explanatory	"This type of case study would be used if you were seeking to answer a question that sought to explain the presumed causal links in real-life interventions that are too complex for the survey or experimental strategies. In evaluation language, the explanations would link program implementation with program effects." (Yin, 2003).
Exploratory	"This type of case study is used to explore those situations in which the intervention being evaluated has no clear, single set of outcomes" (Yin, 2003).
Descriptive	"This type of case study is used to describe an intervention or phenomenon and the real-life context in which it occurred" (Yin, 2003).
Multiple-case studies	"A multiple-case study enables the researcher to explore differences within and between cases. The goal is to replicate findings across cases. Because comparisons will be drawn, it is imperative that the cases are chosen carefully so that the researcher can predict similar results across cases, or predict contrasting results based on a theory" (Yin, 2003).

2.4.4 Interviews

Different approaches towards research interviewing exist and these can be divided into two main categories; *Quantitative interviewing* and *Qualitative interviewing* (Bryman & Bell, 2011). Between these two categories, the quantitative interview is one of the most commonly applied types of interviews in research and is mainly aimed at standardising how questions are asked and responses are recorded. The two main approaches to how a quantitative interview is conducted are structured interviews and self-completion questionnaires (Bryman & Bell, 2011).

Bryman and Bell (2011) describe a key difference in qualitative interviewing compared to quantitative interviewing to be that the interviewer searches for elaborate answers with greater detail. It is an interviewing approach which is less structured and allows for flexibility in the conversation, with a focus on the interviewees' own perspective. Further, it is encouraged that the interviewee goes off at tangents as this could provide insights to the areas which are considered relevant and important by that person (Bryman & Bell, 2011). Kvale and Brinkmann (2015) describe an approach towards qualitative interviewing and a methodology which can be divided into the following seven stages: *thematising, designing, interviewing, transcribing, analysing, verifying* and *reporting.*

2.4.4.1 Structured interview

The structured interview is one of the key approaches within quantitative interviewing and is most commonly used in survey research (Bryman & Bell, 2011). This approach is described to be aimed at standardising the interview process to reduce variation and ensure that every interview is conducted in exactly the same way for each interviewee.

In contrast to qualitative interviewing, the structured interview often contains closed questions, which means that the interviewee is given a limited choice of possible answers to the questions (Bryman & Bell, 2011). While closed questions reduce interviewer variability and enable easier processing of the interview data, there is a risk that important aspects of the interviewee's replies are not captured in the pre-defined selection of answers.

2.4.4.2 Unstructured interview

One type of qualitative interviewing approach described by Bryman and Bell (2011) is an unstructured interview, which can be seen as similar to a conversation or discussion. A predefined question or topic could be the initiating factor for the interview to start, but as it is conducted there is a limited interference from the interviewer and the interviewee is allowed to answer freely. Three of the main uses for unstructured interviews are described by Gillham (2005) as follows:

- As an initial technique to examine aspects which have to be investigated in a more structured way at later stages of the research.
- When the interviewee is hindered by a more structured interview approach.
- If the personal experiences of the interviewee are of significant interest and a structured questioning could hinder the interviewee to fully communicate this information.

2.4.4.3 Semi-structured interview

A semi-structured interview is described by Bryman and Bell (2011) to be a more structured approach within qualitative interviewing than the unstructured interview. Within this approach, an interview guide should be prepared ahead of the interview and should contain a specification of topics or questions which are to be used. While this interview guide is the general baseline for the interview and all topics should be covered, the semi-structured interview is still a flexible approach for interviewing and the interviewer and interviewee are able to converse quite freely (Bryman & Bell, 2011). Further, it is possible to add additional interview topics depending on the responses from the interviewee as the interview progresses.

Gillham (2005) argues that the flexibility, balanced by structure and quality of the obtained data, makes the semi-structured interview the most important approach towards conducting a research interview. It is further stated that the approach works with precision while still maintaining openness in the level and range of the interviewee's responses.

3
Methodology

This chapter introduces the methodology of the performed thesis. It describes the approach through which a new simulation project methodology has been developed, applied and evaluated.

3.1 Procedure

The structure of how the thesis was performed is visualised in Figure 3.1. Initially, a research phase was performed with the aim to create a framework of theory related to the application of simulation within the development of new production systems. This was initiated with a literature review divided into two parts; one with the purpose to review theory related to common simulation project methodologies that are used today, and one with the purpose to collect theoretical data of important aspects within the development of new production systems. From the theoretical foundation built during the literature review, a number of challenges with applying simulation during the development of new production system concepts were identified and mapped.

Based on the analysis of the theoretical framework, an adapted simulation project methodology was developed and proposed with the aim to better deal with the identified challenges. To be able to evaluate the new methodology and how it functions in its intended context, it was applied and evaluated during a development project of a new production system concept in an industrial case. Lastly, this evaluation was further supported by interviews with some of the key stakeholders involved in the development project.

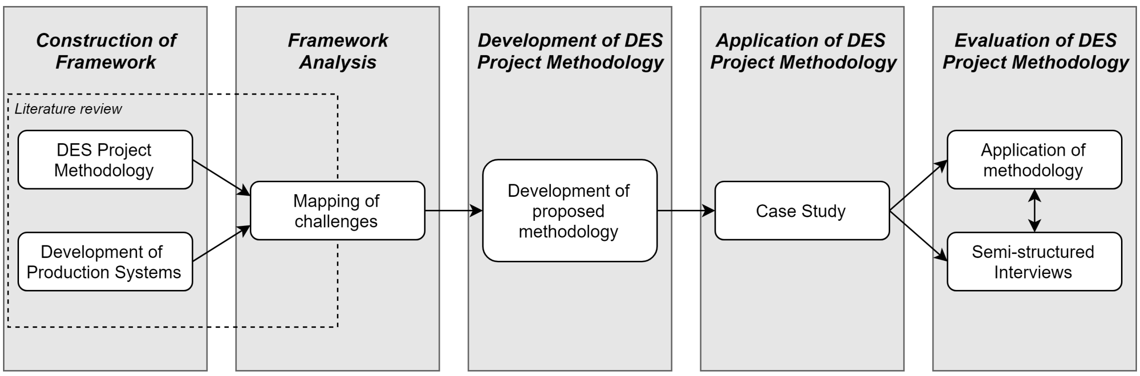

Figure 3.1: Methodology procedure of the performed thesis.

3.2 Construction of framework

This section presents how the framework for analysing the application of simulation within the development of new production system concepts was created. This part of the methodology was aimed at building an initial foundation to answer the first research question: "*What challenges signifies the use of DES within the development of new production system concepts?*"

3.2.1 Literature review

A literature review was conducted to create a foundation from which an adapted simulation methodology could be developed. Within this, the study was divided into two parts; one with the purpose to collect theoretical data about commonly used simulation methodologies and the other with the purpose to collect theoretical data about the processes of developing new production systems. The process of the conducted literature review followed the presented procedure from Hart (2018), with the literature review divided into two phases and four stages.

In the first stage, relevant sources such as scientific papers and books were searched for, with the main focus on reading abstracts. The two methods that were used for finding relevant sources were to search for keywords in line with the *Building blocks* strategy presented by Rowley and Slack (2004), and by using the reference lists in the literature as a direction to find more literature in line with Jesson et al. (2011). The key topics that were searched for within the area of simulation at this stage were the methodologies of a simulation project in general, as well as a more detailed focus on common steps within these methodologies. Within the field of production system development, the key topics were related to production systems in general, the development of new production systems and potential challenges with a simulation application.

In the second stage, literature that was seen as relevant after reading the abstract was read more thoroughly and critically. This was done with the purpose of extracting material based on themes within the two search tracks. This led to stage three where the material was extracted and notes about the material were taken. The extracts were then categorised within the different themes with the grid method, as described by Timmins and Mccabe (2005), and summarised in a more comprehensive way than the list in stage one. In the fourth and final stage, different sections were written based on the themes that were extracted from the literature sources.

3.3 Framework analysis

This section presents how the reviewed literature on simulation methodology and development of new production system concepts was analysed to identify potential challenges within this type of application. This part of the methodology was aimed at finding an answer to the first research question: "*What challenges signifies the use of DES within the development of new production system concepts?*"

3.3.1 Mapping of challenges

Based on the body of reviewed literature on simulation methodologies and the development of new production systems, a mapping was performed to identify potential challenges and conflicts between these two literature fields. To be able to identify and analyse the connections between concepts and arguments within the two fields, a relationship map was created in line with the theory presented by Hart (2018).

The relationship map was based upon the categorisation of literature performed during the literature review and was mainly aimed at establishing connections between arguments within these categories. As an initial step of the mapping, the identified arguments concerning potential challenges within the context of developing new production system concepts where summarised and listed. These were then mapped against the key steps within simulation methodology identified in the review literature with the aim to identify how these relate to each other.

3.4 Development of DES project methodology

This part of the thesis methodology was aimed at developing a new simulation project methodology and provide the basis for finding an answer to the second research question: "*How should DES methodology be adapted to deal with challenges presented during the development of new production system concepts?*". The development of a proposed simulation project methodology was mainly based on the identified challenges and accumulated knowledge related to the application of simulation during the development of new production systems. From these challenges, countermeasures were developed and incorporated within the new methodology with the aim to bridge the gap and create a better adaptation to the context of developing new production systems. The countermeasures were mainly developed based on the findings from the review and analysis of literature.

The basic procedure and steps within the proposed methodology were based on acknowledged existing simulation project methodologies, and adaptations of the methodology steps were performed where this was required.

3.5 Application of DES project methodology

With a basis in the proposed simulation project methodology, this part of the thesis methodology was aimed at establishing the required context for evaluation in order to address the second research question of the thesis: "*How should DES methodology be adapted to deal with challenges presented during the development of new production system concepts?*".

In line with the theory presented by Yin (2003), a case study was considered to be a suitable research method to evaluate the proposed simulation project methodology within this purpose. This consideration related to the importance of covering the specific contextual conditions of a simulation methodology application with a focus to answer *how* and *why* questions.

With a case study decided as a suitable research methodology, a case needed to be determined that could provide answers to the specified research question. Based on the research question, the scope of the case was set to be an analysis of the use of simulation with the proposed simulation project methodology during the development of a new production system concept. This type of application was aimed at enabling an analysis of implications from applying the theoretically constructed methodology in a real and ongoing project. The studied case was set to be within the development of a new production system concept. As described by Bellgran and Säfsten (2010), this is a type of production system development where fundamental changes are required, and these conditions were a basis for the selection of the case company.

As described by Bellgran and Säfsten (2010) and Flores-Garcia et al. (2018), uncertainties and frequent changes are often present during the development of new production systems. To study a case company within this context was consequently seen as a potential risk for the case study to become more time consuming and extensive than feasible for one study, in line with the case study pitfall described by Baxter and Jack (2008). To avoid this situation, time boundaries were placed on the case study as a countermeasure. Based on the definitions by Yin (2003), the type of case study that was decided to be performed at the case company was of an exploratory approach. This type suited the case and the aim to evaluate the proposed methodology during its application, which had no clear single set of outcomes.

3.5.1 Studied case project and company

The case study was conducted at the manufacturing company PowerCell Sweden AB, which operated a manual production of fuel cell stacks and systems. The simulation project was performed within an ongoing development project of a new production system concept, aimed at transitioning from the manual to automatic production. The new production system concept was planned to mainly be composed of a number of robots, processing equipment and some limited manual work. The material flow between these resources was handled manually and by various types of material handling equipment, such as conveyor systems. As the development of the concept progressed throughout the case study, the amount, type and composition of the automated resources varied.

The development project was composed of five different actors that influenced the simulation project including the customer, development team, external resources, process experts and simulation team. The interactions between these actors are illustrated in Figure 3.2. The roles for each actor are described as follows:

Customer
Representatives from the manufacturing company PowerCell Sweden AB, for which the new production system concept was developed. They were the buyers of the de-

velopment project and had extensive knowledge about the product, and the existing manual manufacturing processes and production.

Development team
The development team mainly consisted of representatives from Semcon AB, mixed with some concept developers from the customer. They were responsible to develop the new production system concept and plan how the transition from a manual to automated production should be designed and conducted. The development team had important knowledge about automation and automated resources, as well as the future processes of the new production.

External resources
The external resources consisted of different equipment vendors and representatives from other areas of expertise, aimed at supporting the developing team with the technical solutions and specifications needed in the development of the new production system concept.

Process experts
The process experts consisted of key representatives from different parts of the project organisation, including the customer, development team and external resources. They had extensive knowledge about the current and future production processes, as well as expertise within key areas such as automation and new production equipment.

Simulation team
The simulation team had the task to create and analyse a simulation model of the new production system concept in order to evaluate and contribute to the development of the concept.

The simulation project was conducted during 20 weeks of the overall development project as a part of this thesis, with the aim to support the development of the new production system concept and evaluate the proposed simulation methodology. The created simulation model was meant to cover the full concept and all of its resources and processes.

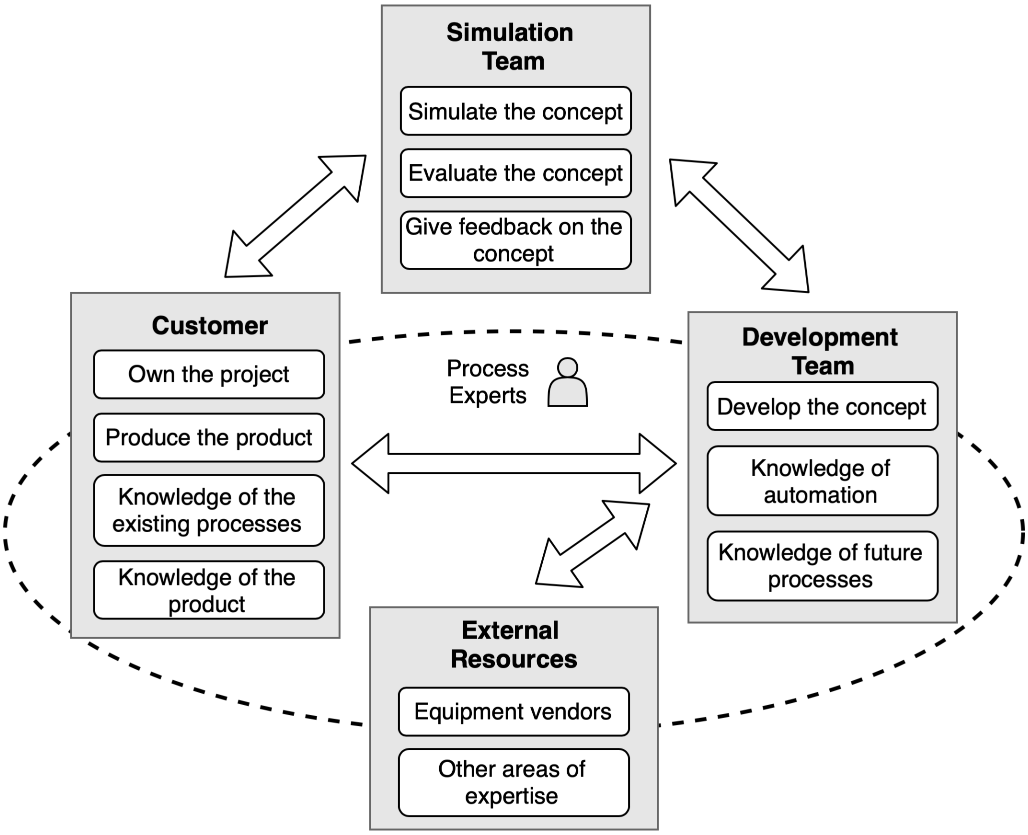

Figure 3.2: Project organisation within the development project.

3.6 Evaluation of DES project methodology

Based on the findings from the case study, this part of the thesis was aimed at finding an answer to the second research question: "*How should DES methodology be adapted to deal with challenges presented during the development of new production system concepts?*". The evaluation of the proposed simulation project methodology was performed through an application of the methodology in the simulation project in the case study and further supported by interviews with key stakeholders from the development project.

3.6.1 Application in case study

Based on the possible advantages presented by Hartley (1994) and Gummesson (1988), a case study was performed to analyse and evaluate how the new methodology dealt with the identified challenges presented in Section 4.2. The evaluation was mainly based upon perceived experiences and observations which had been obtained during the study, and these were used to examine the relations between the proposed simulation project methodology and outcomes from the case study.

The observations from the application of the methodology were documented continuously throughout the full span of the conducted case study and analysed collectively at later stages of the project.

3.6.2 Semi-structured interviews

To provide additional perspectives to the evaluation of the proposed simulation methodology and support the findings from the application, interviews were conducted with key stakeholders who had been involved in the development project within the performed case study. These interviews were performed in a semi-structured manner, as described in Section 2.4.4.3. This qualitative approach towards interviewing was aimed at providing a broad and detailed understanding of the interviewee's perspective and perceptions from the case study, in line with Gillham (2005) and Bryman and Bell (2011).

Two interviews were conducted with important representatives from the development project within the performed case study. One person representing the customer and one person representing the development team, as two key stakeholders. The number of conducted interviews was set to give a good enough representation of the small group of people involved in the development project. As part of the semi-structured approach towards interviewing, a flexibility in the asked questions and provided responses was encouraged. The interviews were held in Swedish, which was the native language of both the interviewers and interviewees, with the aim to avoid having language as a limitation for how the questions and responses could be expressed. The interview guide is presented in Appendix A and has been translated into English for presentation purposes in this report.

The questions in the interview guide were divided into four different categories, each with a different purpose for the conducted interviews. The questions in the categories *Introduction* and *Background* were meant to set the conditions and provide a context for the interview, while the *Summary* was meant to conclude and sum up the interview before it ended. The key questions for the interview were located within the category *Main topics* and the challenges, which are presented in Section 4.2, which each question was meant to cover are presented in Table 3.1. More specifically, each question has a ticked box for each challenge that it covers.

The findings from the performed interviews were weighed in together with the results from the application of the methodology in the case study for a final evaluation of the proposed simulation project methodology. The results are presented in Chapter 6 and further discussed in Chapter 7.

Table 3.1: Challenges covered by the semi-structured interview.

Main topics	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**
Question I	X	X	X	X			X		
Question II		X	X						
Question III				X		X			
Question IV	X	X				X			
Question V					X		X	X	X
Question VI		X				X			

Challenges from literature:
C1. Context uncertainty
C2. Challenges in setting and understanding objectives
C3. Challenging to specify conceptual model inputs/outputs
C4. Model uncertainty
C5. Challenging to achieve data validity
C6. Challenging verification and validation
C7. Input uncertainty
C8. Challenging data acquisition
C9. Challenging to achieve data completeness

4

Development of DES Project Methodology

This chapter introduces the results from the development phase of the proposed simulation project methodology. The key findings from the performed literature review on simulation project methodology and development of new production systems are presented initially, followed by the identified challenges from the mapping and analysis of literature.

4.1 Literature review

The performed literature review resulted in a theoretical framework containing key literature within the fields of simulation project methodology and the development of new production systems. The body of literature consisted mainly of scientific papers and books, from which material was extracted and categorised in sub-themes within the two areas. The literature review resulted in a total of 29 unique sources from which material was extracted and categorised in 14 different themes. The resulting themes from this categorisation and how they relate to the reviewed literature within simulation methodology and development of production systems are presented in the following two sections.

4.1.1 DES project methodology

The extracted material from literature within the field of simulation project methodology was based on literature from 25 different sources and categorised in 10 different themes, which are presented under the header *Literature themes* in Table 4.1. The table further illustrates the relationship between the authors and the literature themes to which their literature has provided key findings. More specifically, all sources of literature have a ticked box for each of the themes that they cover.

Table 4.1: The reviewed literature within simulation project methodology.

Author(s)	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Balci (1997)								X	X	
Banks (1999)	X			X						
Banks et al. (2005)		X	X					X	X	
Barker and Zupick (2017)								X	X	
Bärring et al. (2018)					X					
Carson (2005)	X	X	X							
Fishman (2001)	X									
Fowler and Rose (2004)						X				
Freiberg and Scholz (2015)	X									
Hatami (1990)					X					
Law and Kelton (2000)		X								
Musselman (1994)		X	X	X						
Negahban and Smith (2014)	X									
Robertson and Perera (2002)						X				
Robinson and Bhatia (1995)			X				X			
Robinson et al. (2011)				X						
Roy and Oberkampf (2011)										X
Sargent (2013)								X	X	
Scheidegger et al. (2018)										X
Skoogh and Johansson (2008)					X		X		X	
Skoogh et al. (2012)					X	X				
Trybula (1994)		X			X					
Walker et al. (2003)										X
Wang (2013)									X	
Xie et al. (2014)										X

Literature themes within simulation project methodology:
S1. Discrete event simulation
S2. Simulation project methodology
S3. Problem formulation and setting objectives
S4. Model conceptualisation
S5. Input data management
S6. Challenges with data acquisition
S7. Classification and collection of simulation data
S8. Verification and validation
S9. Techniques for verification and validation
S10. Uncertainty quantification

4.1.2 Development of production systems

Within the field of production system development, the literature was categorised in four different themes based on material from 12 different literature sources. The findings are presented in Table 4.2, where the relationship between the authors and the literature themes to which their literature has provided key findings is illustrated. More specifically, all sources of literature have a ticked box for each of the themes that they cover.

Table 4.2: The reviewed literature within production system development.

Author(s)	**P1**	**P2**	**P3**	**P4**
Banks et al. (2005)			X	
Barker and Zupick (2017)				X
Bellgran and Säfsten (2010)	X	X		
Carson (2005)			X	
Flores-Garcia et al. (2018)		X	X	X
Fowler and Rose (2004)				X
Kühn (2006)			X	
Law and Kelton (2000)			X	X
Negahban and Smith (2014)			X	
Rogalski (2011)	X			
Skoogh et al. (2012)			X	X
Wang (2013)				X

Literature themes within production system development:
P1. Production systems
P2. Challenges with production system development
P3. Simulation within production system development
P4. Challenges with simulation within production system development

4.2 Mapped challenges

The mapping of potential challenges with applying simulation during the development of new production systems was performed based on the literature review findings presented in Section 4.1.1 and Section 4.1.2. The resulting relationship map is presented in Figure 4.1. From the literature on the development of new production systems, four key conditions were identified and each of these related to a minimum of three potential challenges which they could create within a performed simulation methodology. The potential challenges caused by each condition are described as follows:

Uncertainties in project prerequisites
As the new production system is under development there are uncertainties related to how the structure and processes of concept will function, and the final concept design when the project finishes. This leads to difficulties in setting clear objectives of the project, establishing an understanding of the simulated system and knowing what is required and will be produced from the simulation model.

Frequent changes of system and concept
The constant development of the new production system concept means that several aspects are expected to change throughout the project. The changes in the production system over time leads to a variation in the required inputs, outputs and design of the simulation model, and creates difficulties maintaining its verification and validity.

Limited availability and quality of input data
As part of the development of a new production system concept, there are new and potentially not yet developed manufacturing processes, equipment and production principles. This leads to a limited availability in input data to the model and creates uncertainties related to its quality. As a consequence, data estimations are required which causes difficulties in assessing the validity of both input data and simulation model behaviour.

No historical data of real system
As the new production system concept has not yet been implemented, no data of its performance can be collected. Consequently, there is no available reference for assessing the simulation model validity and creates difficulties in ensuring that the data and model are representing the real world and system.

The identified challenges with using simulation during the development of a new production system concept have been summarised in nine different categories, which were identified as critical to consider as the new simulation project methodology was developed. These are: *Context uncertainty, Challenges in setting and understanding objectives, Challenging to specify conceptual model inputs/outputs, Model uncertainty, Challenging to achieve data validity, Challenging verification and validation, Input uncertainty, Challenging data acquisition* and *Challenging to achieve* *data completeness.*

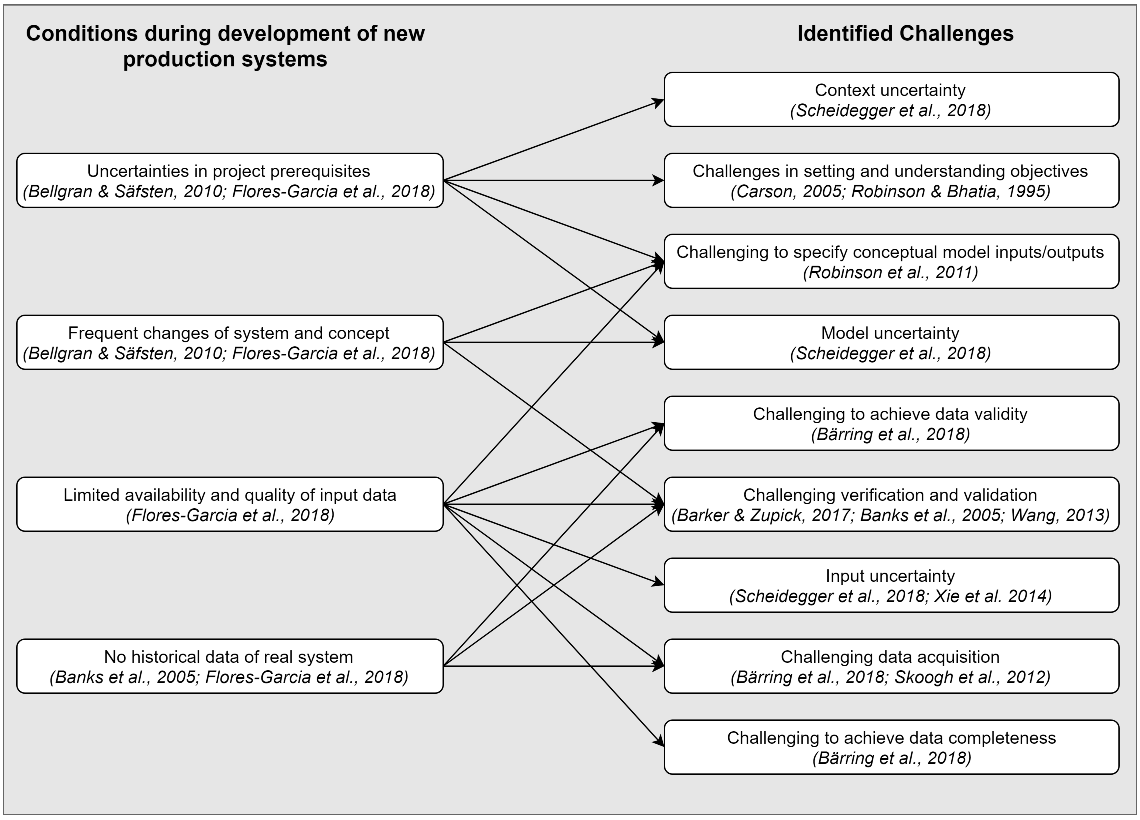

Figure 4.1: Resulting relationship map with the identified challenges.

4.3 Proposed DES project methodology

Based on the identified challenges with applying a common simulation methodology within the development of new production systems, a proposed simulation project methodology was developed. The complete proposed methodology is presented in Chapter 5, with detailed descriptions of the adapted methodology steps and the countermeasures which they have incorporated.

5

Proposed DES Project Methodology

This chapter presents the proposed simulation project methodology. Initially, a general introduction is given to the methodology and each step is then explained in more detail.

The proposed project methodology is visualised in Figure 5.1 and has been adapted based on the identified challenges in Section 4.2, with revised methodology steps from the simulation project methodologies which have been summarised by Musselman (1994). To better suit the development of a new production system concept, the steps of the proposed methodology have been separated in two focus areas with different scope and purpose. These areas are *Overall Concept Focus* and *Iterative Multi-Process Focus*.

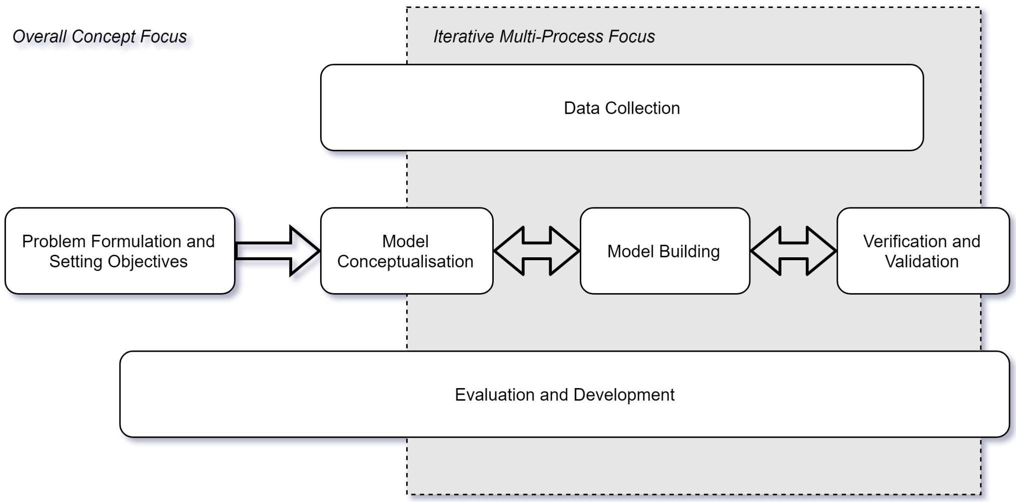

Figure 5.1: Overview of the proposed simulation project methodology.

The methodology steps located within the first focus area, *Overall Concept Focus*, are aimed at working with the production system concept as a whole and aspects which set the prerequisites of the simulation project.

Iterative Multi-Process Focus is the second focus area and should be targeted at specific sections of the production system concept, based on their current stage of development and uncertainties. Additionally, the methodology steps within the scope of these sections are to be performed in parallel, meaning that multiple aspects of the simulation model are developed simultaneously. The following sections describe the methodology steps within the two focus areas in more detail.

5.1 Problem formulation and setting objectives

The initial step of the simulation project, illustrated in Figure 5.2, should be to perform a problem formulation and setting of project objectives in close collaboration with the involved stakeholders. This is in line with Musselman (1994), Carson (2005) and Banks et al. (2005) and is meant to support the stakeholders and simulation team to straighten out all expectations and prior knowledge regarding the new concept and simulation. The end result should be an agreement and mutual understanding of the project scope and objectives.

The importance of this agreement and understanding between all parties involved in the development of the concept is of further emphasis within the proposed project methodology. This connects to the identified challenges related to uncertainties in project prerequisites, as presented in Section 4.2. With a common understanding and agreement of the scope and objectives, the impact from the challenges of context- and model uncertainties can be reduced.

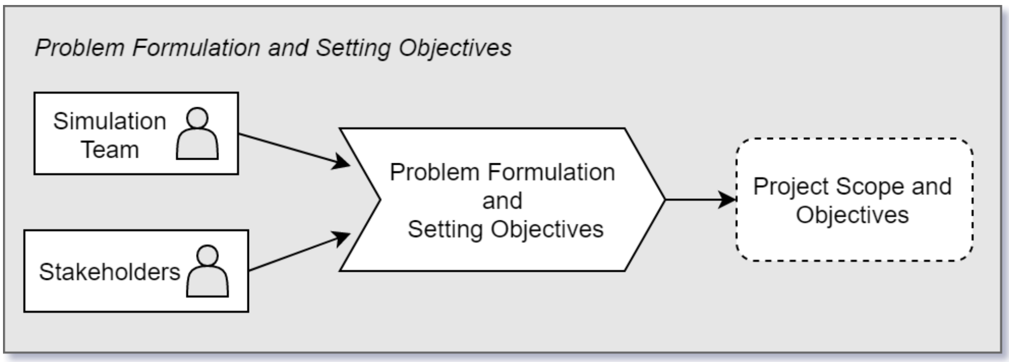

Figure 5.2: Overview of the proposed methodology for problem formulation and setting objectives.

5.2 Model conceptualisation

Based on the set project scope and objectives, a conceptual model should be created to facilitate an early overall understanding of the new production system concept and how it should be modelled. This process and methodology step is illustrated in Figure 5.3. In line with Robinson et al. (2011), it is important that the inputs and outputs are specified in the conceptual model and these should be based upon the agreed objectives of the project. This is aimed at creating a better understanding of the possibilities and limitations of the simulation model, and enables a better adaptation to different accuracy requirements and the identified challenges with this step of the methodology.

Depending on the current stage of development of the new production system concept, there are different methods that could be used to create a better understanding of the required inputs to the conceptual model. As described by Musselman (1994), two examples are initial factory visits or discussions with process experts. In line with Robinson et al. (2011), it is however of importance that the conceptual model is created with a depth of detail which is adapted to the identified model uncertainties. Additionally, the data collection at this stage should be limited within the boundaries of the input uncertainty.

One important difference with the proposed simulation project methodology compared to the simulation project methodologies which have been summarised by Musselman (1994) is that the conceptual modelling should be performed iteratively and in parallel processes with other project methodology steps. Further, these processes should be targeted at the aspects of the new production system concept which are more certain at the time rather than including the full production system in the conceptual model. This focus is aimed at reducing the impact from future changes in the concept and the potential modelling rework that these would require, meaning that the areas which are least likely to change should be modelled first. As the certainty of the different areas of the new production system concept increases, or changes which impact the conceptual model are introduced, the model should be updated accordingly to ensure that its development matches the development of the concept.

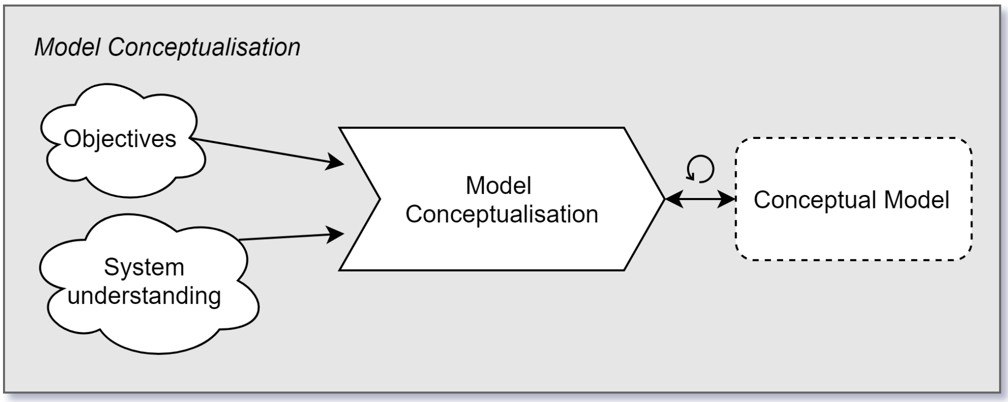

Figure 5.3: Overview of the proposed model conceptualisation methodology.

5.3 Data collection

An overview of the methodology step of data collection is illustrated in Figure 5.4, and should be initiated by a specification and classification of the required input data. This should be done based on the availability and collectability of the data, in line with the theory presented by Robinson and Bhatia (1995) and Skoogh and Johansson (2008). This process is aimed at establishing an initial understanding of what types of input data that will be required throughout the simulation project. Further, the classification can give insights in how the input data could and should be collected.

Within the proposed simulation project methodology there is an increased importance of a consideration to the limited availability and quality of input data during the development of new production systems, and the possibility that no system exists to use as a reference and source of data. As a result, it is of importance to establish a close collaboration with process experts and people with extensive knowledge during the data collection. This is described by Carson (2005) as a suitable approach to aid in the estimations of data, which is required when a substantial part of the classified input data is located within category C.

In line with the approach described by Skoogh et al. (2012), a proposed additional use for this collaboration is to formulate accuracy requirements on the input data before collection is initiated. In addition to ensuring an efficient and targeted data collection within the right areas, this specification should also support the formulation of a suitable detail level of the conceptual model as described by Robinson et al. (2011).

As visualised in Figure 5.1, the step of data collection is located within the *Iterative Multi-Process Focus* and should consequently be focused at the areas of the new production system concept which are furthest developed at the time. Further, this methodology step should be carried out iteratively and in multiple processes which are run in parallel. Additionally, the data collection should support and be initiated simultaneously with the step of model conceptualisation.

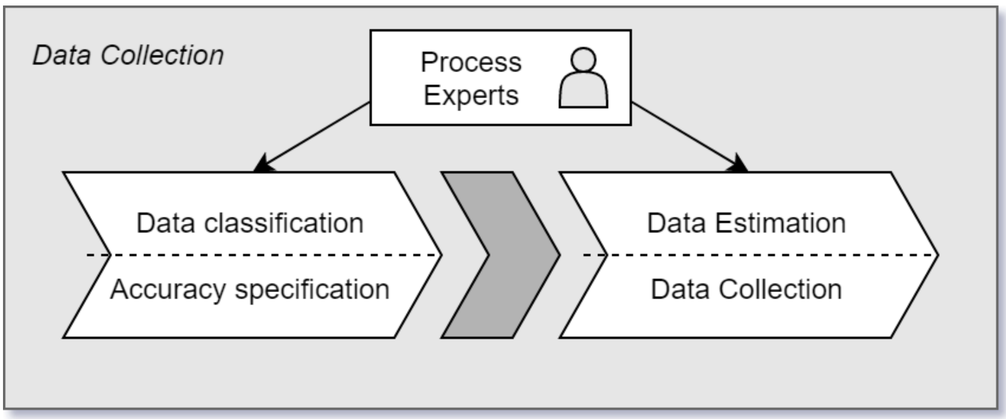

Figure 5.4: Overview of the proposed methodology for data collection.

5.4 Model building

In line with theory presented by Robinson et al. (2011), the simulation software should not be specified prior to the methodology step of model building. Consequently and as illustrated in Figure 5.5, the initial step of the model building should be to perform a choice of software unless this has been specified previously throughout the project. The choice should be based on the previously specified inputs and outputs of the simulation model, as well as the set objectives and expectations in accordance with Banks et al. (2005).

As an additional support in the selection of simulation software, the classification of input data should be used to establish an understanding of the possibilities and limitations in the choice. In line with Skoogh and Johansson (2008) it is suggested that the focus is placed on simulation software which are able to generate data from running simulations, based on the limited availability and quality of input data. This is aimed at creating better possibilities in estimating input data which cannot be collected. When the classification indicates an increased amount of available and collectable data, it could however enable the possibilities of using simulation software which rely more heavily on input data quality and are able to output simulations over a longer period time. Consequently, when this is the case consideration should be taken to these possibilities in software.

When the selection of simulation software has been completed, the coding or modelling of the simulation model should be initiated. To deal with the identified challenges related to model uncertainty, the focus should initially be to create a model which captures the overall view of the concept. As the development of the concept details progresses and these become more certain, the focus should be transitioned towards fine-tuning details. A close collaboration with the development team of the new production system is of importance to ensure frequent updates of the current state of development for the new concept, thus increasing the detail level of the model as the project progresses.

Further, as the methodology step of model building is located within the focus area *Iterative Multi-Process Focus*, it should be carried out in parallel processes and iteratively between other methodology steps based on the certainty and current development of the new production system concept.

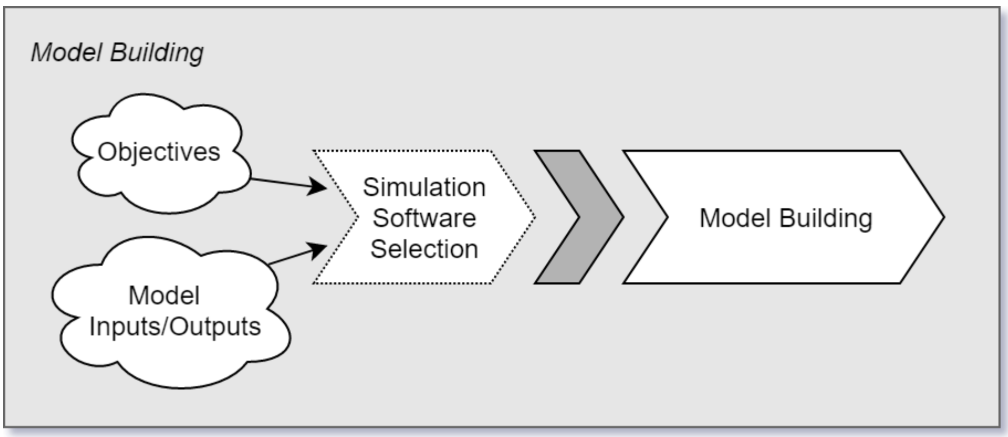

Figure 5.5: Overview of the proposed methodology for model building.

5.5 Verification and validation

In order to ensure that the simulation model is aligned with the current version of the conceptual model, the process of verification should be performed continuously, which is in line with the theory presented by Banks et al. (2005) and Barker and Zupick (2017). This is further illustrated in an overview of the methodology step in Figure 5.6. Within the proposed project methodology, the importance of this continuity of verification is further emphasised and functions as a tool for dealing with the identified challenges related to frequent changes in the new production system concept. A recurring verification of the simulation model enables swift adjustments to any changes in the conceptual model as a result of developments of the new production system concept.

Further, as a part of the focus area *Iterative Multi-Process Focus*, the verification and validation should be performed iteratively and in parallel processes with other steps of the project methodology. This is partly aimed towards ensuring model functionality through an iterative process of building and verifying parts of the simulation model before they are merged into one model.

As a consequence of frequent changes and continuous verification, there is a possibility that already verified sections of the simulation model have to be re-modelled and re-verified as the new production system concept is developed. Thus, this should be considered and further emphasises the importance of prioritising the modelling to the sections of the concept which are the most certain to avoid future adjustments.

With regard to the assessment of simulation model validity, a comparison between simulation model performance and historical data from an existing system has been described by multiple authors as one of the preferable techniques for validation (Banks, 1999; Carson, 2005; Robinson & Bhatia, 1995). On the contrary, it is suggested that the step of validation within the proposed methodology is more focused on the use of the informal validation techniques described by Sargent (2013) and Balci (1997). This is aimed at dealing with the challenges related to the limited availability and quality of input data, which can be expected as a new production system is developed with the use of simulation (Flores-Garcia et al., 2018). Some of the proposed approaches for validation are *Animation, Face validation* and *Structured walkthroughs*.

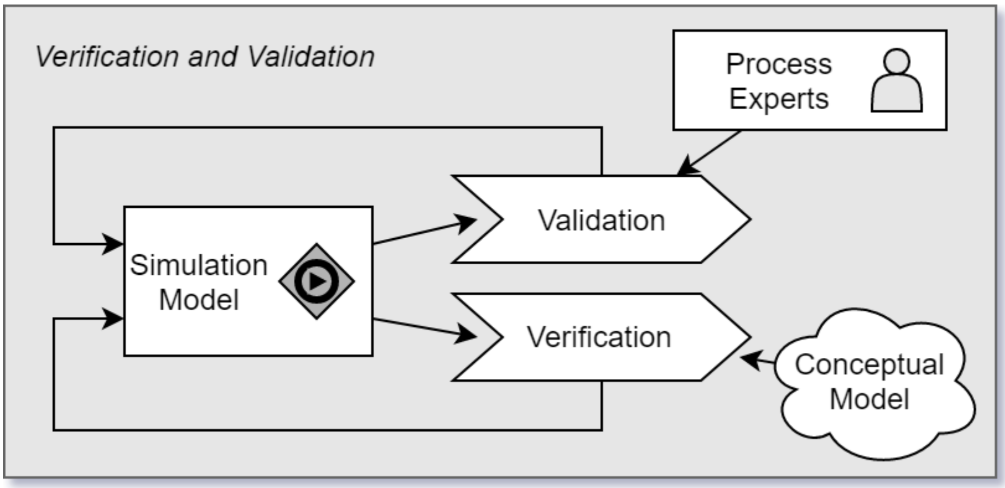

Figure 5.6: Overview of the proposed verification and validation methodology.

5.6 Evaluation and development

Within the proposed simulation project methodology, the step of evaluation and development should be performed continuously and in parallel to other methodology steps throughout the project. This is an important difference compared to the approach to simulation model analysis presented by Musselman (1994) and Banks et al. (2005), which is performed after the simulation is built, verified and validated through a set of experiments. The proposed alternative approach towards evaluation and development is aimed at enabling the simulation team to contribute and support the development of the production system concept, which is illustrated in Figure 5.7. This should be done through close collaboration with the development team to which continuous feedback on the performance of the concept can be provided, which is in line with the importance of performing evaluations during production system development as presented by Bellgran and Säfsten (2010).

A close collaboration between the simulation team and development team is further supported by Carson (2005) and Musselman (1994) as an important step towards bringing competencies together and sharing critical knowledge regarding the business, processes and products of the new production system concept. Additionally, this enables a better ability to deal with the identified challenges related to context uncertainty. Within the proposed methodology, the step of model building is one area identified to have significant potential to provide insights which can support the development of the new production system concept. Consequently, an additional focus should be placed on providing feedback as a part of this step.

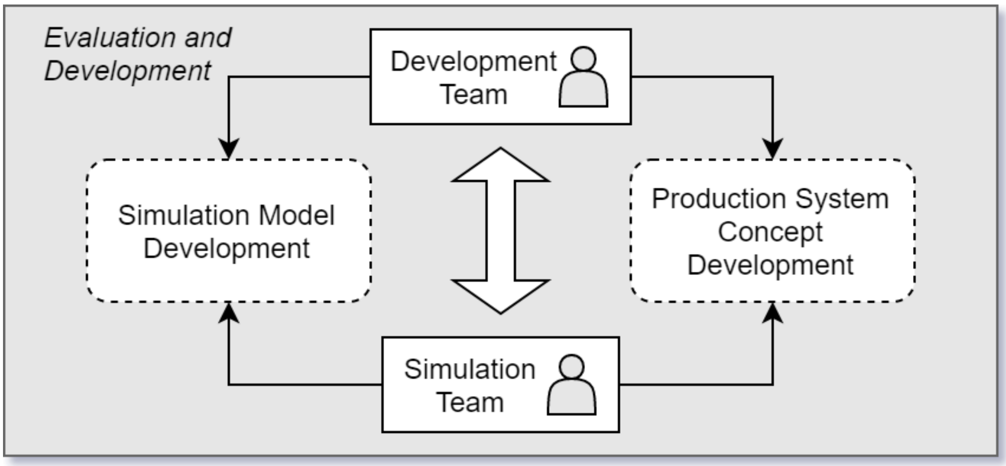

Figure 5.7: Overview of the proposed methodology for evaluation and development.

6
Evaluation of DES Project Methodology

This chapter introduces the evaluation phase of the proposed simulation project methodology. The outcomes from its application in a case study are presented initially, followed by the results from the semi-structured interviews at the end of the project.

6.1 Application of DES project methodology

This section presents the results from the application of the proposed simulation project methodology in the industrial case study at PowerCell Sweden AB, and the outcome from each step of the methodology is explained in more detail in the following sections.

6.1.1 Problem formulation and setting objectives

An uncertainty in how the new production system concept would perform if it was implemented was one important factor which was identified during the initial problem formulation. The purpose of the simulation model, and consequently the problem to solve during the project, was to evaluate the feasibility of the new concept and investigate if and how it would meet its requirements. The identified uncertainties were mainly related to technical solutions of the new manufacturing processes and overall capacity of the production system.

With a set problem to solve the project transitioned into the step of setting objectives, where a number of different expectations on the project and simulation model were identified. The two main stakeholders who provided input during this phase were the customer and development team of the new production system concept, and this was performed through discussions and unstructured interviews with the project objectives as a key topic. The identified expectations are summarised in Table 6.1.

Table 6.1: Identified expectations on the simulation project and model.

Expectations	**Customer**	**Development team**
Detailed layout	X	X
Process cycle times	X	X
Selling visualisations	X	X
Continuous concept feedback		X
Simulations over long time period	X	
Statistics of uncontrollable factors	X	
Simulation model scalability	X	

An aspect which was found to be seen as important and contradicting between stakeholders was the detail level at which the simulation model should be built. On one hand, the simulation model was expected to be used to generate cycle times and test the clearances between resources as they operate, thus requiring great visual details of the model performance. On the other hand, there were expectations to be able to simulate the behaviour of the concept over a longer time period and perform statistical analysis of the outputs. Two examples of the outspoken metrics and trends to be analysed were Mean Time Between Failure (MTBF) and Mean Time to Repair (MTTR). Further, the graphical representations of the simulation model were in this case expected to provide selling visualisations of the new production system concept. An additional request on the simulation model functionality was to be able to test several different variants of the new production system concept against a set of various scenarios and capacity demands. This consequently put a requirement on a scalability of the simulation model.

The significant spread and occasional contradictions between simulation model expectations led to additional discussions from which the scope could be narrowed down and agreed upon. The main objective was set to be a simulation model with enough detail to be able to evaluate and improve the processes of the new production system concept while providing good graphical visualisations of the system. Additionally, the involvement of the simulation team in the development of the new concept was seen to be an aspect of critical importance and was an expectation related to the simulation project as a whole. A point of view which was expressed by the development team was the importance of using feedback from the simulation team to support the development of the new production system concept.

6.1.2 Model conceptualisation

With a basis in available 3D-models of the current stage of the new production system concept, an initial collection of data for the conceptual modelling could be started. The findings led to an initial understanding of the system, which was further supported by discussions and unstructured interviews with the development team and experts on the production system's products and processes. Knowledge related to critical manufacturing processes and the current stage of development for each section of the concept are two examples of the input information which was obtained and had been discussed with stakeholders at the prior step of problem formulation and setting objectives.

Further, it was possible to carry out an introduction to similar and existing manual process at the case company which gave additional support in the understanding of the new production system concept. The findings from this introduction mainly provided insights related to the possibilities and potential difficulties in the transition from a manual to automated production. Two identified key aspects within the case company and the new concept were the critical and tight accuracy requirements on certain assembly processes and material properties of the products, which could create difficulties during material handling and processing. In spite of the uncertainties which were presented with regard to the new production system concept, a general consensus about the future process flow could be achieved and functioned as a basis for the conceptual modelling.

With this background and the set objectives from Section 6.1.1, the required outputs and inputs of the simulation model could be specified. A selection of these is summarised in Table 6.2.

Table 6.2: Specified inputs and outputs for the model conceptualisation.

Inputs	**Outputs**
Equipment processing data	Process cycle times
Resource dimensions	Detailed layout
Layout of new production system concept	Throughput capacity
Accuracy requirements	Graphical visualisations
Process flow of new production system concept	

Based on the inputs and outputs, the conceptual model was created in sections targeted at the parts of the new production system concept which were furthest developed at the time. In spite of this approach and an adaptation of the detail level to the uncertainty of the concept, there were cases where the conceptual model had to be adjusted as a result of developments of the production system concept. While these updates in the conceptual model occasionally required changes in the simulation model, these where often minor adjustments of the process layout which had a limited impact on the process of model building.

6.1.3 Data collection

The required input data for the simulation model was classified in the three categories A, B, and C, and some of the important results are presented in Table 6.3. The classification was based on a set of 31 different data points and indicated that the type of input data and its possible source for collection varied between each category of data. Some examples of these data types and sources are summarised in Table 6.3. Further, the distribution shows that a majority of the input data was classified within category B and category C, which indicates that it is not available and has to be collected or estimated.

Table 6.3: Results from the input data classification.

	Category A	**Category B**	**Category C**
Common data type	Product data	Equipment data	Process details
Common data source	Case company	Available equipment	Process experts
Collection method	Available	Collected	Estimated
Distribution	13 %	23 %	65 %

A substantial part of the input data which was classified in category A was related to the product which was to be produced in the new production system concept. The product was an existing resource within the new concept and already well developed at the start of the simulation project. The dimensions and bill of material of the product are two examples of input data within this category, which were available within sources at the case company.

The input data classified in category B was mainly related to available machines and other standard equipment, such as processing times and equipment dimensions. The collection of this data was primarily carried out through video analysis of manufacturing processes and time studies at the existing manual production.

Lastly, a significant majority of the classified input data was neither available nor collectable and thus defined within category C. The data was mainly related to the process details of the manufacturing processes which were developed as a part of the new production system concept. The collaboration and unstructured interviews with process experts from the customer and experts on the new automation equipment from the consulting part of the development team was a key support to the estimations of the data within this category. This was performed throughout the project to ensure data validity as the new concept was developed. Further, similar manufacturing processes and equipment which were considered to be of a good enough resemblance to represent the processes of the new production system concept were used for data estimations. Data was collected from these processes and used as indications for the processes in the simulation model. Additionally, the simulation model could be used to generate some of the process cycle times as it was running.

One approach to dealing with the input uncertainty was to build the simulation model with default simulation software data as an initial step. Two examples where default data initially was used as a replacement are cycle- and material handling times. With increased certainty of the developed processes and new production system concept, the data collection was continued and the results were used to replace the standard data. As a result, the cases where the collection of data had to be redone due to changes and developments of the manufacturing processes were reduced.

6.1.4 Model building

Within the thesis project, Process Simulate (Siemens PLM, 2011) was used as the simulation software. Based on the available resources within the project, this software was selected before the initiation of the simulation project and the selection process was thus performed earlier than what is suggested in the proposed simulation project methodology. Consequently, the methodology step of problem formulation and setting objectives was partly influenced by the capabilities of the selected simulation software.

Another notable software is Sketchup (Trimble, 2019), which was used as a 3D modelling software. Within the development project of the new production system concept, a 3D model was created in the software and updated as the concept was developed. This 3D model of the concept functioned as a library for the CAD models which were used to build the foundation of the simulation model. Consequently, the effort put on creating new CAD models was limited and more focus was shifted towards importing and placing simulation model resources rather than creating them. Additionally, the Sketchup 3D models often functioned as a basis for discussion between the development team and simulation team regarding developments of the concept. As the concept had been developed and adjusted, these changes were frequently accompanied by an updated version of the 3D model which gave the possibility to update the simulation model without extensive work on the CAD models. Lastly, the simulation team was able to provide some feedback regarding the concept based on the provided 3D model, before the simulation model was built. An illustration of how the built simulation model was represented in Process Simulate is shown in Figure 6.1.

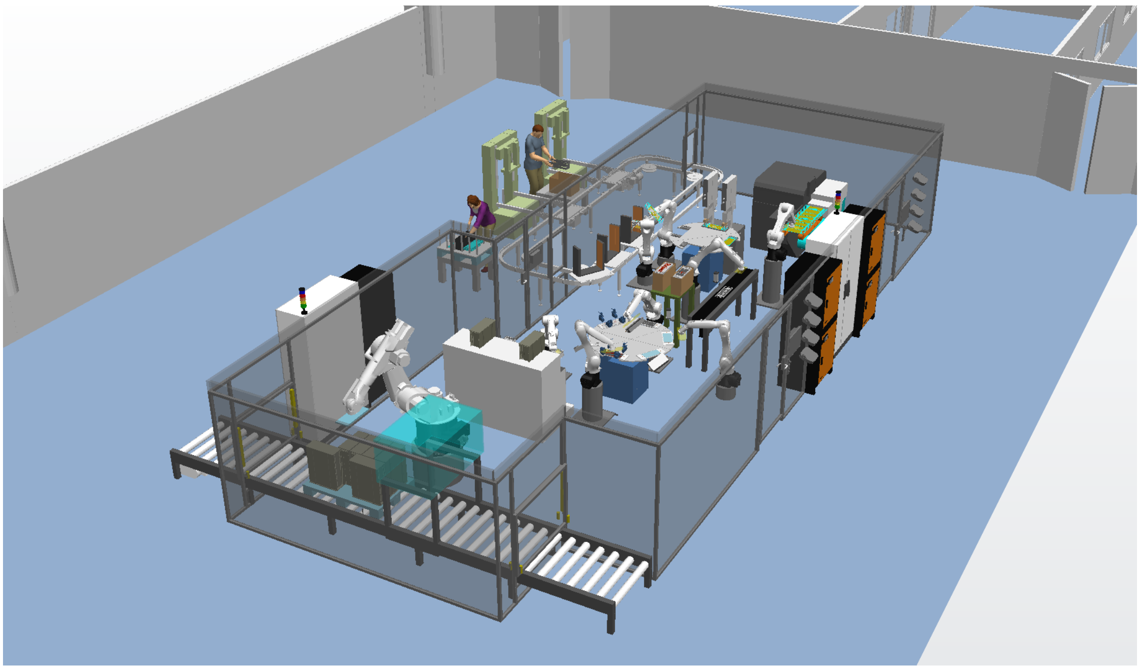

Figure 6.1: Visual representation of the simulation model in Process Simulate.

As the model building was initiated there were some processes which were seen as developed enough to be built in the simulation model, and as the project and concept progressed the number of processes at this level of certainty increased. Initially, the processes were mainly related to material supply and material handling, while layout- and process details became more certain at later stages of the project.

During the project, it was however apparent that the development of the new production system concept progressed at a slower pace than the building of the simulation model. As a result, an increased amount of the processes which were built in the simulation model had not yet reached the desired level of certainty, which introduced a higher risk that these would have to be re-modelled as a result of concept changes. As the project progressed, the required re-modelling work in the simulation model from concept developments became more frequent, often related to critical processes and the layout design.

6.1.5 Verification and validation

During the continuous process of verification, some differences between the conceptual model and simulation model were identified and adjusted in the simulation model to ensure that these were matching and kept up to date. These discrepancies were mainly related to the continuous development of the new production system concept which caused changes in the scope and content of the model. As a result, there were cases when there was a need to adjust and re-verify already verified sections of the simulation model.

As a result of the lack of historical data from production or existing systems, as described in Section 6.1.3, the techniques used for validation of the simulation model were more limited to be of a more informal character. With the graphical visualisations, which were available in the selected simulation software, the validation techniques using animation and face validation were well facilitated.

With the steps of model building and verification being performed in parallel processes on sections of the new production system concept, one of the most frequent types of validation activities was the one carried out for each section of the simulation model as it was completed. The main approach towards validation was to use face validation, where the behaviour of the simulation model was displayed to parts of the development team who collaboratively inspected and discussed the processes in that section. Additionally, developers, process experts and people with extensive knowledge within the new automation equipment supported a more in-depth validation of the behaviour of these resources using face validation and structured walkthroughs.

Further, in collaboration with several of the production system concept developers, a number of larger validation sessions were held as the project progressed. These sessions included discussions and unstructured interviews with a broader focus on a selection of multiple sections of the simulation model. The results from these validation activities gave input which contributed to the development of both the simulation model and the new production system concept. In line with this overall concept focus, a validation which was targeted at the whole simulation model and thus production system concept was performed as the model had been finalised.

6.1.6 Evaluation and development

At an initial stage of the project, a close collaboration and feedback loop between the simulation team and development team was established. One factor behind this setup was related to the importance of providing feedback from the simulation team to support the development of the new production system concept, as the expectations expressed in Section 6.1.1. Feedback related to restrictions of the manufacturing processes due to layout design, indications of process cycle times and general suggestions on process improvements are some examples of key inputs that were presented to the development team throughout the project.

As the certainty of the new production system concept increased and a larger portion of the processes was modelled, the behaviour of the simulation model could be used to draw more conclusions. Consequently, there was an increased frequency in the provided suggestions to the development team as the building of the model progressed. Additionally, the resulting impact and improvements in the concept as a result of feedback from the simulation increased with a more detailed simulation model and knowledge of the system behaviour. As a complement to the continuous evaluation and development, a final evaluation of the full concept and completed simulation model was performed at the end of the project.

6.2 Semi-structured interviews

The results from the performed semi-structured interviews with representatives from the customer and development team provided insights for the evaluation of the proposed simulation project methodology. The relations between the findings from the interviews and the identified challenges in Section 4.2 are summarised in four different categories as follows:

Uncertainties regarding new production system concept
The representatives from both the development team and customer described a clear difference between the certainty of the new production system concept and its processes at the start of the simulation project compared to when it was completed. The overall scope was the same, but as new solutions were developed during the project the concept became more certain.

In spite of the uncertainties related to the new production system concept, this aspect was not seen as a problem. According to both interviewees, the simulation team appeared to be handling the uncertainties well in their work and this was believed to be based on that the uncertain conditions were communicated at an early stage of the project, and that the simulation team focused on the right aspects from the start. A contributing factor to the ability to control the effects of uncertainties was to focus on modelling the most certain aspects of the new production system concept.

Additionally, both interviewees expressed that there were no experienced issues related to the setting of objectives, and the representative from the customer emphasised that the discussions between stakeholders proved valuable in expressing and refining expectations.

Frequent changes of system and concept
The common view of both the development team and customer was that changes in the new production system concept existed to a significant degree and frequency. These changes were seen as inevitable when a new concept is developed with support from simulation, as the simulation project is meant to provide feedback regarding the production system concept and aid in the concept development. The customer representative stated that the changes in the concept to a large extent were based on challenges with certain concept alternatives which were identified from the simulation model.

Additionally, both interviewees stated that the changes and feedback that were presented to the simulation team seemed to be well incorporated in the simulation model. The customer representative further expressed that the high frequency of communicated changes could be a result of the close collaboration between the simulation team and other stakeholders. The simulation team was also described to have been clear with the possibilities and challenges with the presented concept changes based on the boundaries of the simulation project, such as simulation software capabilities and time limitations.

Resemblance between simulation model and production system concept
With regard to how well the simulation model was matching the objectives and intended production system concept, the representatives from the development team and customer both expressed that there was a great resemblance between the simulation model and concept.

Confidence in simulation model
The representative from the development team expressed confidence in that suitable input data had been used for the simulation model. One of the reasons behind this was stated to be that the development team had been closely involved in the process of acquiring input data, and occasionally functioned as the data source. This view was supported by the representative from the customer who expressed great confidence in the used input data, mainly due to that the majority of data came from people with good knowledge of the new production system concept and its processes.

In relation to the simulation model behaviour, great confidence in the simulation model was expressed by the development team and it was seen as an accurate and suitable representation of how the new production system concept would function in reality. The customer representative expressed the same point of view, but also emphasised the importance of assessing the validity based on the context and objectives of the simulation model. The interviewee stated that the early stage of development of the new concept inevitably leads to a more difficult verification and validation.

Summary
To conclude, both of the interviewed representatives from the development team and customer expressed an overall satisfaction with the conducted simulation project. Based on the findings from the interviews, the challenging conditions within the development of new production systems presented in Section 4.2 were confirmed to exist during the development project. Two conditions emphasised by the interviewees were uncertainties in the concept and project prerequisites, and a significant amount and frequency of changes in the new concept.

The findings from the interviews further indicate that the challenges that existed during the development project seemed to have been dealt with by the proposed simulation project methodology. The interviewees described a limited impact from uncertainties on the creation of the simulation model and stated that discussions aided in setting objectives and expectations. Further, the changes of the concept were incorporated in the simulation model, and both representatives expressed good confidence in the used input data and simulation model behaviour.

7
Discussion

This chapter presents a discussion on the identified challenges with simulation during the development of new production systems, how the proposed simulation project methodology is set to overcome these and the outcomes from its evaluation. Further, sustainability, methodology trustworthiness and future research are discussed.

7.1 A challenging context

The findings in the thesis point towards a number of significant challenges with the application of simulation during the development of a new production system concept. In addition to being strongly rooted in the studied literature regarding simulation methodology and development of production systems, the identified challenges were also shown to exist in reality as a part of the development project within the conducted case study. The challenging context was confirmed by both the simulation team and stakeholders with leading roles within the development project of the new production system concept. With regard to uncertainties in the new production system concept, a notable aspect is at what stage of the development of the concept that the simulation project is initiated. At an early stage, the uncertainties are more significant, which could lead to a simulation model which represents something that is too far from the final production system concept. At later stages, the certainty is greater and simulation can be of better support, but the cost for changes in the concept could be more significant.

While the identified challenges have shown to be present and important to consider within the scope covered by this thesis, it is important to consider that these challenges have their basis in a simulation team point of view and mostly point towards difficulties related to the work of that team. If the application of simulation within the development of new production system concepts was to be considered from the point of view of a different stakeholder within the development project, there is a possibility that another emphasis and set of challenges would be of focus.

7.2 From challenges to solution

The proposed simulation project methodology was developed to include a number of important adaptations, which were identified as critical for dealing with the identified challenges that arise when simulation is applied during the development of new production system concepts.

Adaptations to uncertainties and changes
Through a parallel and iterative approach of performing the steps of the proposed methodology, it has been adapted to be better aligned with the continuous development and changes of the new concept. With this approach, the aspects of the concept that are the furthest developed can be target initially before transitioning towards including more parts of the concept as these have reached a suitable level of certainty and development. The same guidelines apply for the detail level of the simulation model, and it should be adapted accordingly. An initially basic detail level supports the visualisation of the concept, and the level of detail should increase to be more targeted at fine-tuning modelled aspects of the concept as these become more certain.

Close collaboration
The close collaboration between the simulation team and development team is crucial to take full advantage of the proposed simulation project methodology. This is achieved partly by incorporating the simulation team to be part of the development team. This collaboration is aimed at enabling the possibility to use the insights from the simulation model to support the development of the concept, as well as communicating changes in the concept back to the simulation team. Consequently, a feedback loop between these two teams is established and this could be further supported by the use of good graphical visualisations of both the simulation and production system concept, which assist in creating a better system understanding.

The proposed simulation project methodology is not limited to promoting communication between the simulation team and the development team as this extends to all involved stakeholders in the development project, especially at the beginning of the project. The set expectations of the simulation project must be in line with the conditions in which the simulation project is conducted. If a significant part of the required input data for the simulation model has to be built on estimations, the expectations on the simulation model's ability to represent reality have to be adapted accordingly.

7.3 Evaluation outcomes

The proposed methodology has shown to be well adapted to limit the impact from all of the identified challenges in Section 4.2. However, these are not completely eliminated from these types of applications and projects with simulation and must still be taken into consideration. Some identified key aspects related to the ability of the proposed simulation project methodology to deal with the identified challenges are discussed in the following sections.

Setting the direction of the project

The application of the proposed simulation project methodology showed that the impact from identified challenges regarding context- and model uncertainty was possible to reduce by adaptations in the simulation project methodology. At an early stage of the simulation project, a collaborative setting of the project and simulation model objectives established a better understanding and clarity of the expressed expectations. This further relates to the challenge of setting and understanding objectives. The view of a successful adaptation is further supported by the conducted interviews, where it was stated that significant uncertainties existed but had a limited impact on the project as a result of clear communication and focus by the simulation team. Additionally, a clearer understanding of the availability and quality of data could be established based on the conducted classification of input data. This enabled better possibilities in setting realistic expectations of the inputs and outputs of the simulation model, thus dealing with the identified challenge of specifying conceptual model inputs and outputs.

Dealing with frequent concept changes

In addition to previously mentioned challenges, the challenging verification and validation of the simulation model is another aspect which was managed during the application of the proposed simulation project methodology. In spite of the frequent changes of the production system concept, these were considered by the development team to be well incorporated in the simulation model. The main reason behind this was seen to be the incorporation of an iterative and parallel execution of the steps in the proposed methodology, with a significant reduction in the risk for major adjustments in the simulation model at later stages of the simulation project. Additionally, the flexibility towards changes in the concept was further improved by the frequently performed verification.

An increase of the simulation model detail in parallel to the development and increased certainty of the new production system concept was an additional contributing factor in being able to deal with the challenges related to frequent changes. However, the application of the proposed simulation project methodology also showed that the modelling of processes which are still uncertain could provide insights which are valuable for the development of the concept. In spite of the increased risk that the simulation model of these uncertain sections could lead to a need to adjust the model if the concept changes, the adjustments could also assist in eliminating potential alternative solutions for the new production system concept and support its development. As a consequence, there is a difficult balance to consider between modelling in greater detail with a higher risk for future time-consuming adjustments in the model, or modelling in less detail with a higher risk of failing to capture important aspects of the new processes.

Validating the simulation model

In spite of the limited availability and quality of data, the use of informal validation techniques in the simulation project enabled a possibility to assess the validity of the simulation model. With a higher dependency on human reasoning than data, these techniques could however create difficulties in achieving confidence in the validation. When the availability of data is limited, the importance of early involvement of the development team and process experts is consequently emphasised to be of critical importance to be able to build credibility of the simulation model provide feedback during the project.

The findings from the interview support that these potential difficulties have been dealt with, and both the customer and development team expressed confidence in the input data and simulation model. Consequently, this indicates that the proposed simulation project methodology deals with aspects related to the challenging validation and challenges related to the uncertainty and limited availability and quality of input data. Additionally, the findings from the interviews and application of the methodology collectively show that an enabling factor for the informal validation techniques could be the capabilities of the used simulation software. Through the use of good graphical visualisations and a simulation model behaviour which is a good representation of reality, the confidence and understanding of the simulation model can be improved.

7.4 Thesis methodology

The created framework of studied literature constitutes a large part of the foundation upon which the thesis project is built. As a consequence, the specific literature sources which have been reviewed could heavily dictate the outcome of the project. To avoid a possibly biased body of literature, the literature review followed a structured methodology and included multiple reviewed sources of literature for each theme within the two areas of study. Further, the literature with connections to Chalmers University of Technology have been used based on the contributions to their respective scientific field and not due to possible relations to the university or performed thesis. The analysis of the framework through a mapping of literature further mitigates the risk of having findings which are too influenced or biased by specific sources of literature, as the findings are isolated and compared against other literature. There is however a limitation of the analysis and evaluation within the boundaries of the reviewed literature, and there is a possibility that a more representative view of the available theories and concepts could be achieved by including more literature sources in the creation and analysis of the framework.

The choice to perform a case study as the main basis for the evaluation of the proposed simulation project methodology is well supported by the studied literature on case study methodologies. Further, this support extends to the selection and context of the studied case company and project. The limitation to one case study does however restrict the possible conclusions that can be drawn from the findings. Additionally, the development, application and evaluation of the proposed methodology have been performed as part of the thesis, which could create difficulties in an unbiased evaluation of the methodology.

To perform evaluating interviews with external sources was one approach to target possibly biased results and to add another dimension of credibility to the findings in the thesis. By interviewing stakeholders with significant experience from both the development project and simulation project, a more holistic perspective could be achieved. While the interviews induce a risk of being subjects to misinterpretations and bias, these risks have been targeted with the use of structured and non-leading questions while leaving room for the interviewee to fully express their point of view.

With regard to the trustworthiness of the thesis methodology, the findings are rooted in both theory and practice which indicates a credibility of the research within the scope of the thesis. Additionally, the review of the findings with involved stakeholders was aimed to support the credibility further. With regard to transferability, the methodology does however only include one specific case study and the findings could be different in another context and studied case. To mitigate the risk of context-specific findings, the proposed simulation project methodology was developed based on theory and without consideration of the conditions of the specific case study. While different interpretations and starting points in the literature review and analysis could lead to a variation in the developed methodology, the findings should be similar and indicate low dependability. Regarding confirmability, complete objectivity of the findings in the thesis cannot be achieved, but the possible influence from personal values have been targeted through a focus on systematical and structured approaches within each phase of the thesis methodology.

7.5 Sustainability aspects

There are many manufacturing companies that are interested in using modern technologies that are becoming more and more affordable, however, the profitability in investing in these are often complex to evaluate (Freiberg & Scholz, 2015). Further, this complexity often leads to that the investments in these technologies get rejected or postponed. A simulation project methodology that is adapted to suit the development projects of new production system concepts creates an improved possibility in using simulation to test the concepts virtually, before moving forward with investments and an implementation of the system. Consequently, the concept can be evaluated to see if it meets the set requirements and also give valuable insights to its development. The minimised risk of making poor investments has the potential to lead to an improved economic and environmental sustainability, as costly changes and material waste after the system implementation can be avoided.

Fuel cells are one example of a technology which could contribute to better environmental sustainability in the future. However, they are expensive and complex to produce. With modern technologies, it can be possible to start mass producing fuel cells to lower the price and be competitive but it is a high-risk investment as it would be performed in a greenfield environment. An application of the proposed simulation project methodology can support the development of a new production system, thus reducing the uncertainties related to how the system would perform in reality. With this virtual assessment of the system, the risk of an investment in the new and sustainable technology can be reduced.

The proposed simulation project methodology promotes cross-functional work and close collaboration between the different parties involved during the development of a new production system concept. This is an important step towards including competencies and achieving better social sustainability. However, this collaboration also means that more parties are able to question and influence the work, which can be beneficial but could also cause complexity and difficulties in arriving at a common solution. A close and cross-functional collaboration is however an approach which is considered as essential to fully be able to utilise the competences of all persons in a development project and it should be encouraged.

7.6 Future research

Within this thesis, the proposed simulation project methodology was developed, applied and evaluated. To establish a more nuanced view on each of these three aspects it would be beneficial with future research, where the proposed methodology is applied and reviewed critically by an external simulation team. Additionally, it is suggested that the methodology is applied and evaluated in multiple cases with a different setting compared to the studied case company in this project. This would enable a broader analysis and give more comprehensive insights regarding the applicability and outcomes of the proposed simulation project methodology, which complements the findings from this thesis.

8
Conclusions

This thesis has shown that the application of simulation within the development of new production system concepts induces a number of challenges which are of significance within this context. The identified challenges are grounded in literature and have been confirmed in practice, with a main basis in uncertainties in project prerequisites, frequent changes of the production system concept, and limited availability and quality of input data.

Through an adaptation of the simulation project methodology, the identified challenges can be targeted and reduced. Two critical aspects within this adaptation are the parallel and iterative processes, in which the steps of the proposed project methodology should be performed. These processes should be targeted at the furthest developed aspects of the new production system concept, with increased detail as the certainty and development of the concept progresses. Additionally, the collaboration between the simulation team and other stakeholders in the development project is of critical importance for a successful project. An incorporation of the simulation team in the concept development at an early stage greatly facilitates the possibilities in developing both the simulation model and new production system concept.

The proposed simulation project methodology's capabilities to deal with the identified challenges are well supported by findings in both theory and practice, including literature reviews and analysis, an application in a case study and evaluating interviews with key representatives from the development project. Consequently, this thesis has provided a suitable exploratory first iteration of how simulation can and should be applied during the development of new production system concepts.

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A

Interview Guide

This document presents the interview guide that was used as a baseline for the conducted semi-structured interviews. The presented topics were the starting point for all interviews but additional topics may have been added depending on the responses from each interviewee.

A.1 Guide for semi-structured interview

A. Introduction
   I. Can we record this interview?
      (a) This is aimed at supporting our work with the thesis report. For this purpose, we are also taking notes during the interview.
   II. The interview will cover some aspects related to the simulation project within the development project of the new production system concept. It will take roughly 15 minutes.
   III. Do you wish to be anonymous?
      (a) Yes - Could we use your title/role in the project instead?
      (b) No - What is your name?
      (c) No - What is your working title?
   IV. Which company do you work for?
   V. What has been your role during the development project?

B. Background
   I. Background to the interview
      (a) We are Hannes and John and have been taking part in the development of the new production system concept. As part of this, we have assumed the role of a simulation team, with the aim to perform a simulation project and create a simulation model of the new system.
   II. Purpose of the interview
      (a) Throughout the simulation project we have applied and evaluated a new methodology for simulation projects. This interview is meant to provide additional insights for the evaluation and support the findings in our thesis report.

C. Main topics
   I. How would you say that the certainty of the new production system concept and its contents has changed during the project?

    (a) What impact have you experienced that this has had on the work of the simulation team?

II. What possibilities have there been to set the expectations and objectives of the simulation model and simulation project in general?
    (a) How have these possibilities changed during the duration of the project?

III. To what extent would you say that changes in the new production system concept, e.g. regarding layout design or process details, has occurred during the project?
    (a) How were the changes received and considered by the simulation team?

IV. Based on the set expectations and objectives, how well would you say that the behaviour of the simulation model represents the new production system concept?

V. How confident are you that the data which has been used as input for the simulation model is good enough for the model's purpose?

VI. Based on the current project conditions, how confident are you that the behaviour of the simulation model is an accurate enough representation of how the production system would behave in reality?

D. Summary

I. Is there anything else that you would like to add?

II. Thank you for your time.