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Enhancing accessibility and long-term utilization of Discrete Event Simulation models with Low-Code Development platforms

A case study of a heat treatment process at a bearing manufacturer

Master's thesis in Production Engineering

Jonathan Syrén
William Karlqvist

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

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William Karlqvist
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Supervisor: Ebru Turanoglu Bekar, Department of Industrial and Materials Science
Industrial Supervisor: Susanne Stude, SKF, Process Development
Examiner: Anders Skoogh, Department of Industrial and Materials Science

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Department of Industrial and Materials Science
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46 31 772 1000

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Abstract

Discrete Event Simulation (DES) is widely used in manufacturing for analyzing and optimizing production systems. However, many simulation models suffer from limited accessibility which limit their long term utilization due to technical complexity and reliance on expert users. This master's thesis explores how Low-Code Development Platforms (LCDPs) can improve the accessibility and sustainability of DES models by enabling broader user engagement and reducing the technical barriers connected with traditional simulation tools. The study was conducted as a case study at Swedish bearing manufacturer SKF with focus on a heat treatment process characterized by long cycle times and complex routing. A concept was developed with integration of Siemens Tecnomatix Plant Simulation and the Mendix based platform "Optimize My Plant". The concept allowed input data from SQL databases and users to be processed through Excel interfaces and transferred to the simulation model via automated application programming interfaces. Customized interfaces and visualization tools were built to support user specific simulation scenarios and key performance indicator analysis. The implementation was verified and validated through multiple tests and stakeholder workshops involving both potential users and technical experts. The findings indicate that integrating DES models with LCDPs can reduce dependency on simulation experts, increase user friendliness, and enable role specific decision support. Critical success factors include digital maturity, structured data governance, and clearly defined ownership of the model and its input data. The thesis contributes the area of simulation technology and its practical, long-term use within organizations.

Keywords: Production Simulation, Discrete Event Simulation, Low-code-development-platforms, Siemens Tecnomatic Plantsim, Mendix, Optimize my plant, Digital Twin, Data-Driven Manufacturing

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William Karlqvist, Jonathan Syrén, Gothenburg, June 2025

List of Acronyms

API	Application Programming Interface
CPS	Cyber Physical System
CRISP-DM	Cross Industry Standard Process for Data Mining
DES	Discrete Event Simulation
ERP	Enterprise Resource Planning
HTTP	Hypertext Transfer Protocol
HTTPS	Hypertext Transfer Protocol Secure
IT	Information Technology
IoT	Internet of Things
KPI	Key Performance Indicator
LCDP	Low-Code Development Platform
MES	Manufacturing Execution System
OMP	Optimize My Plant
OT	Operational Technology
REST	Representational State Transfer
SCADA	Supervisory Control and Data Acquisition
SQL	Structured Query Language
VBA	Visual Basic for Applications

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1
Introduction

This chapter provides background on the subject of Discrete Event Simulation (DES) models in manufacturing settings and highlights the need to improve their accessibility. It also outlines the aim and purpose of the master's thesis, presents the research questions, and defines the objectives and limitations of the study.

1.1 Background

DES is today a well established equipment for optimizing and improving manufacturing operations [1]. It is a useful tool for decision making in production planning and its analysis can help predict bottlenecks, starvation and throughput of production systems [2]. The range of use for DES vary from healthcare application to traditional manufacturing cases [3]. However, over time, the simulation models risks becoming obsolete and adjustments to the model can become inaccessible if internal knowledge is lacking and maintenance of the models is often expensive [4]. Production systems often has to adapt quickly to changes which require constant updates [5]. Furthermore, both the usage and updating of the model require prior knowledge and simulation experience [6]. In addition, the user interfaces of DES programs are often not adapted to suit the end users specific needs and require expertise for using end extracting information from the simulation model [6].

Data input management and interpretation of simulation statistics often demands mathematical knowledge and programming experience which the end users might not have, thus making it inaccessible to end users lacking those skills [6]. This means that simulation models are not always utilized over time and across departments as otherwise possible.

Low-Code Development Platforms (LCDP), on the other hand, is much more accessible and easy for different types of users to handle since it enables wider use of applications for digital manufacturing features without requiring deep technical expertise. More specifically they are designed with a more user friendly interface and need only a limited amount of programming [7][8]. Furthermore, data-intensive software and low code platforms can allow for better integration of data from different data sources [9]. To provide sufficient input data for simulation models, automated information flow is highly desired to reduce time and resources for keeping the model relevant [10].

The challenge with obsolescence and inaccessibility of simulation models has been noticed by Swedish bearing manufacturer SKF regarding a heat treatment process at the manufacturer's facilities. A simulation model focusing on flow and throughput was previously built by a consulting firm but has since become obsolete due to outdated data files, new machinery, and production specifications. Long cycle times through stations and complex system of routing between stations suggested simulating the throughput and efficiency based on variables such as production plan and product characteristics. During the summer of 2024, a new base model of the heat treatment process was developed with the purpose of evaluating potential effects of changing product treatment specifications and production mix. Input data such as product data and production plan was imported directly towards the simulation but parameter changes and simulation scenario preparation still needed variable changes or programming directly in the software. To better utilize the models effectively in a long-term perspective and increase accessibility for users there is a need of investigating suitable solutions such as LCDP integration and determine prerequisites in terms of data availability and model compatibility.

1.2 Aim and Purpose

The aim of this master's thesis is to develop a concept where a simulation model is integrated with a LCDP. The purpose is to evaluate and propose approaches for enabling wider utilization and access of a simulation model across an organization. The project will be conducted with LCDP application for a SKF case study. By enhancing accessibility and ensuring the model's relevance, this master's thesis project aims to suggest how the implementation can suggest practices for long term usage of the model and strategies for building a modular and flexible model that can handle changes in structure. Moreover, how the platform can allow for avoiding risk of data and obsolescence and need of extensive resource for modification. Suggested implementation will be carried out on the existing simulation model and analyzed based on their benefit to users who have little to no experience of simulation softwares.

1.3 Research Questions

To achieve the aim and purpose of the thesis outlined above, the following research questions (RQ) are formulated:

RQ1: How can LCDPs enhance the accessibility and utilization of simulation models among stakeholders with varying levels of simulation expertise?

RQ2: What design criteria and technical prerequisites are necessary for integrating simulation models with LCDPs to ensure their long-term usability and sustainability?

1.4 Limitations / Demarcations

This master's thesis only refer to DES, and the study was conducted using the simulation software Simens Technomatix Plant Simulation. Additionally, the time frame of the project was limited to 20 weeks in accordance with Chalmers thesis regulations. The aim of the master's thesis was to further develop an already existing simulation model, validation and verification of the previously built model was therefore not conducted. Instead, verification, validation, and possibly deployment were conducted on the upgraded extended model concept built during this project.

1.5 Thesis Outline

The thesis report consists of the following six chapters: Introduction, Theoretical Background, Methodology, Results, Discussion, and Conclusion. The Introduction chapter describes the background of the thesis subject and defines the aim and purpose of the project. Furthermore, it presents the RQ:s and outlines the limitations of the conducted thesis project.

The second chapter, Theoretical Background, aims to explain and state topics, strategies and subjects that are central for the thesis project. It delves deeper into some of the topics introduced in the introduction chapter, as well as presenting som new relevant subjects. The subjects presented in the chapter are: DES, LCDPs, Data, Verification and Validation.

The Methodology chapter presents the methodological approach applied during the project and the customized project methodology. Additionally, it defines the case context and the system definition of the company environment in which the project was carried out. Furthermore, the strategies applied for the qualitative studies of the project are outlined and the approach for identifying design criteria are presented. Next, the overall project concept development and evaluation phase of the thesis are explained. The chapter ends by stating the methodological approach applied for validation of the final concept.

The fourth chapter, Results, starts with presenting the findings from the conducted qualitative studies. Furthermore, it presents the established design criteria and the results of the verification of the overall project concept. Moreover, the chapter presents the developed final concept and the results from the conducted validation.

The fifth chapter, Discussion, reviews and discusses the findings of the thesis from different perspectives. The methodologies are examined as well as the execution of the qualitative study. The chapter also presents suggestions for future research and development of the concept.

The last chapter consists of a short conclusion which summarizes the content and findings of the thesis project.

2
Theoretical Background

This chapter provides the theoretical foundation necessary for understanding the key technologies and concepts that underpin the project. It covers the fundamentals of DES and its application in industrial settings, the role of digital twins, and the capabilities of LCDP in enhancing simulation model accessibility. Furthermore, the chapter discusses essential aspects of data quality and integration, as well as methods for verifying and validating simulation models.

2.1 Discrete Event Simulation

DES is a simulation technique that enables model building of real-world systems for experiments and analysis. It consists of a digital version which replicates the physical system and behaves as the physical system. Discrete event modeling is built on the principle that specific events of interest change values or states at discrete points in time [11]. Analysis and experiments performed with DES models provides results such as throughput, machine or system specific data and other relevant measurable variables. DES models can be used as a decision making tool for both design and optimization of real world systems [12]. Considering that most real systems contain variation over time, and therefore can be considered as dynamic in contrast to static systems, DES models are often stochastic and contain random input variables within pre-specified intervals [11].

From previous use cases in industries where DES has been applied positive outcomes in many different areas has been recorded [13]. Specific areas within manufacturing were DES has yielded good outcomes are within control, resource allocation, strategy, planning and design [13]. By utilizing DES, more complex system analysis such as performance during extreme scenarios or bottleneck detection can be evaluated with less effort.

2.1.1 Advantages and Limitations

DES has historically been applied in almost all industry sectors and has, in many cases yielded good results; however, there are cases where DES was not the optimal option given certain circumstances. One of the main advantages of DES is that it creates an environment where safe experimentation of different scenarios can take place, since it does not interfere with the real-world system that it represents. Furthermore, it provides opportunities for increased time utilization since simulations

over long periods of time can be performed in minutes or even seconds. Additionally, DES also enables easy sensitivity analyses [14]. A limitation related to DES is that it can be expensive to operate in terms of manpower and computational power. Additionally, the time and costs of developing DES models can be relatively extensive. Undetected errors in DES models can potentially have harmful effects if decisions are made based on simulation output [14]. Furthermore, DES models risk becoming obsolete over time without proper maintenance from simulation experts if intended to be kept relevant and reliant [4] [6]. Additionally, production systems often change at regular intervals, creating requirements for constant updates if DES models are to be used in daily operations [5]. Moreover, DES software's user interfaces are often not adapted to fit end user's specific needs and requirements, and therefore demanding quite a level of DES knowledge for the users to interpret and retrieve information from simulations [6].

2.1.2 Digital Twin Concepts and Data Flow

A Digital Twin is considered as a virtual representation of a physical object and can provide information such as optimization, evaluation, and prediction. The concept of Digital Twin dates back to the early 2000s and was first used in the Space and Aerospace industry. The Digital Twin has since been used not only to simulate a product but also manufacturing systems. However, the definitions vary and focus on certain aspects and with different views on data flow, thus leading to different levels of data automation regarding research and description of digital twins. A more nuanced way to distinguish types of digital twin is to assess the data flow between the physical object and the digital object. When data between the objects are pushed manually and there is no interaction, it would instead be called a digital model. If the data flow is automatic from the physical object to the physical object, it would be considered a digital shadow. This means that all or some of the parameters of the physical model will affect the digital model. However, data from the digital model are not sent back to the physical model automatically, and simulation result is instead used for decision making or manually adapted into the physical model. The accurate definition of the digital twin involves automatic data flow in both ways [15], thus implying that the information loop is closed. The physical model receives data from the physical model and can then manipulate the physical model based on its results. This form of data flow is often not the case for what researchers or companies claim as digital twins [15].The layers of digital twins are presented in Figure 2.1 and in table 2.1.

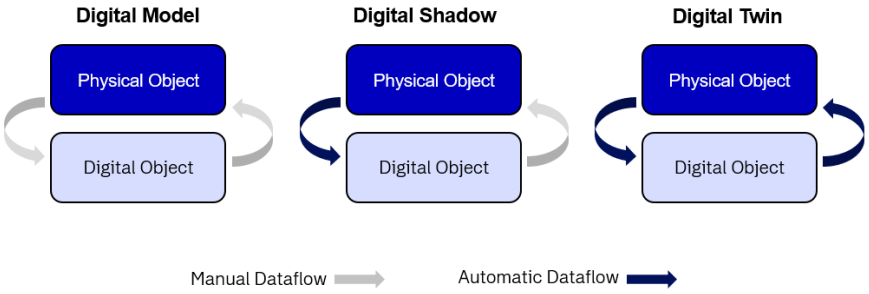

Figure 2.1: Levels of Digital Twin [15]

Table 2.1: Hierarchy of Digital Representation in Simulation Context [16]

Level	Description	Data Flow	Example
Digital Model	Static simulation without automatic updates.	Manual input only	Offline DES model
Digital Shadow	Simulation updated with real-time or scheduled data.	One-way (physical → digital)	DES with automated input
Digital Twin	Fully integrated simulation with feedback.	Two-way (digital ↔ physical)	DES with live control integration

2.1.3 Siemens Tecnomatix Plant Simulation

Siemens Tecnomatix Plant Simulation (PlantSim) is a simulation software for creations of DES models. Some of its application areas are within advanced manufacturing visualization, factory and line design, manufacturing process planning and robotics planning and simulation. By building digital twins of production lines and processes in PlantSim evaluation and optimization can be performed. Furthermore, PlantSim can be integrated and combined with other soft wears commonly used in industry settings such as Structured Query Language (SQL) databases and other Siemens software for increased connectivity [17].

2.2 Low Code Development Platforms

Increased complexity of internal operations is a challenge often faced by enterprises today [7]. However, business applications often require fast deployment which requires plenty of software development resources [18]. In the past decade LCDPs have gained popularity as a tool for enabling agility, reduced cost and time to deploy business application. LCDPs are software environments that enable the rapid development of applications through high-level graphical interfaces and pre-built

components, minimizing the amount of manual programming required. The term "low-code" dates back to 2014 as "platforms that enable rapid delivery of business applications with a minimum of hand-coding and minimal upfront investment in setup, training, and deployment"[9]. It can provide visual interfaces with "drag and drop" features, templates and other tools that simplify the development process. The platform then automatically generates much of the underlying code which accelerates development and lowers the technical barrier of creating software. Benefits of the approach is that it enables both professional developers and non-developers to create and configure applications more quickly and efficiently. Consequently, business applications can be built by non-developers and reduce the obstacles regarding scalability of company functions.[18]

In regards to simulations model and digital twins, a common problem is that domain experts often lack professional software engineering background required to implement changes in the simulation model or other cyber physical systems (CPS) [9]. The platform provides application independent parts which can be used as way to change parameters in the model. The stages of implementing the LCDP integration can be described in three steps [9]:

- The LCDP engineer creates the LCDP.
- The digital twin designer uses the LCDP to configure the digital twin to be generated.
- The domain expert uses the digital twin to observe and control the CPS.

2.2.1 Mendix

Mendix is a LCDP provided by Siemens which enables development of both mobile and web-based applications. Furthermore, it allows for web-based solution development with no manual coding needed. Pre-programmed elements can be implemented via drag-and-drop while additional adjustments can be done with Java and Javascript if needed[19]. The application can then be published in a cloud environment or locally. Mendix also allows for integrations of other Enterprise Resource Planning (ERP) systems such as SAP and other data bases for input, thus creating easy and compatible connections between organizational databases [20].

2.2.2 Optimize My Plant

Siemens has also developed a Mendix front-end application called "Optimize my Plant" (OMP) with pre-defined features that are of interest for Simulation model and LCDP integration. OMP provides a dashboard where options for adding charts, simulation results and adjusting production plans. The purpose of OMP is to present Key Performance Indicators (KPI) and statistics in simple ways and to be manageable by a larger variety of users. Furthermore, it integrates automatic live data sources from data bases, ERP systems or Internet of Things (IoT) data streams, thus allowing simulations based on real-time state of production system. The OMP package also comes with a software library called "Alexa" which is installed in Plant

Simulation to prepare the input and output of commands and simulation data between Mendix and Plantsim. One of the advantages with OMP is that it enables easy comparison and analysis between different simulation scenarios [21].

Successful cases include tire manufacturer Michelin who has used OMP and Plant Simulation for production planning. By automating data flows and providing an easy interface for production planners. The broad internal access to the simulation via the Mendix app meant that many stakeholders in Michelin could experiment with scenarios that otherwise would have been time consuming. KPI analysis was made simpler through the dashboard and became a useful tool for innovation of the operation [22].

2.3 Data

Managing input data is one of the most crucial parts of a simulation project and often the most time-consuming, which has put a lot of effort in researching solutions to reduce data-related time consumptions [23].

2.3.1 Data Quality

When working with simulation it is of importance to ensure the utilized input-data is of sufficient quality. To help evaluate the quality of data [24] has defined a framework of data dimensions and their descriptions. The proposed framework can be seen in Table 2.2.

Table 2.2: Data Quality Dimensions [24]

Dimensions of Data Quality	**Description**
Accuracy	Source errors
Reputation	Trust for data collection methods
Accessibility	Availability of data for equipment. Automated or manual data collection.
Currency	Structural changes in equipment that are difficult to track
Completeness	Data consistency. Occurrence of disturbances.
Precision	Ability to measure what is intended
Relevance	Can the data be used for the simulation model even though it exists primarily for other stakeholders
Resolution	Potential variation of disturbances in the data
Traceability	Can the origin of the data easily be traced.
Clarity	Can the data be understood by users
Consistency	Data format consistency. Uniform structure.

2.3.2 Acquisition of Input Data

The process of acquiring input data is dependent on availability and quality where the data can either be primary or secondary. It is depreciable to obtain all necessary data via secondary data sources. These include external data sources such as industry standards or industry domain experts and Corporate Business Systems such as ERP, Manufacturing Execution System (MES) and Computer Aided Design (CAD) [25]. Furthermore, project specific data such as production volumes for the model. Should this not be sufficient, manual data collection is necessary from direct measurement and observation [26]. However, when raw data are collected it needs to be analyzed and transformed into information, useful for the simulation model. Davenport and Prusak [27] highlight that transforming data into valuable information involves five methods presented in table 2.3.

Table 2.3: Methods for Analysis of Raw Data [27]

Method	**Purpose**
Contextualization	Determine the purpose for gathering the data
Categorization	Determine units of analysis or key components of the data.
Calculation	Mathematical and statistical analysis of the data
Correction	To remove errors from the raw data
Condensation	To summarize the data into a more concise form.

There are different methodologies for acquiring data to a simulation model mainly depending on the level of automation and verification [28].

- **Methodology A:**
  The data are manually asserted to the simulation model by model builder and derive from project teams.

- **Methodology B:**
  The data is put in to a computer application and the data is then read by the model. All data goes via the computer application.

- **Methodology C:**
  Data from Corporate business systems is automatically put transported into a data base. The simulation model can then automatically import the data from the data base. Nothing is done manually.

- **Methodology D:**
  The data is transferred directly from Corporate Business system to the Simulation model. No third part involved.

To achieve methodology C or D is desirable since it allows for automated data flows.

2.3.3 Governance of data and Simulation model

During the establishment of a simulation model, an important aspect is the ownership and responsibility of the model and its data. More specifically, it needs to be determined who is responsible for data accuracy and relevance. It is desirable to obtain an automatic data flow in which real-life changes in the production system or production processes result in direct updates of the input data [29]. Beyond the governance of the data, the ownership and responsibility of the simulation model is also of importance to assure assessment of update needs or other changes for avoiding obsolesce. The ownership of the simulation model may be transferred from a developer och developing team to an employee with sufficient knowledge for managing the model [29].

2.3.4 REST API

Representational State Transfer (REST) Application Programming Interface (API) is a common method used for data transfer between databases. The foundational architecture of REST-API is particularly beneficial for transferring data between databases and web applications and it is often utilized for cloud based systems. REST API makes it possible to access data via Hypertext Transfer Protocol (HTTP) and they can be constructed to be rather safe by integrating Hypertext Transfer Protocol Secure (HTTPS) for all data requests. HTTPS ensures that data is encrypted before transferring it which reduces the risk of the data being intercepted or tampered with during the transit [30].

2.4 Verification

Verification and validation is processes commonly applied when quantifying and checking the creditability of numerical models [31]. In the context of simulation models, verification can be described as checking whether the constructed model is an accurate translation of the conceptual model and making sure that the computer programming is free of errors [31] [32].

A framework for conducting verification of simulation models introduced by [32] can be seen in the list below.

1. **General good programming practice**
   By coding the program in a modular, structured and object oriented way, correctness and debugging can easily be quantified and performed.

2. **Verification of intermediate simulation output**
   By manually calculating expected results and outputs from individual processes or parts in the simulation model and comparing them to produced statistics the correctness of the code can be confirmed.

3. **Comparing final simulation outputs with analytic results**

Running a simulation scenario and comparing the final output statistics with known scenario parameters. A reoccurring problem with this verification method is that it sometimes can be very hard to find scenarios where the output is known, commonly seen in more complex cases where the output can be heavily reliant on dynamic variables.

4. **Animation**
   By visualizing the programmed sequences via animations the events can be followed and compared to what the builders of the model already know should happen. A danger with this verification technique is that it is hard to conduct for longer simulation runs where the chance of missing an error increases.

2.5 Validation

After verification of the simulation model has been completed the next step is to move on to validation of the built model. Validation is the process of determining to what extent the simulation model corresponds to the real-world system and thus to what degree the predictive capabilities are trustworthy. The process of validation is usually carried out by analyzing the output statistics of the simulation model with obtained real-world data [31] [32].

Complex simulation models can generate great ammounts of information and validation metrics must therefore be selected with care. It can be appropriate to revisit the already established requirements and the conceptual model to motivate what metrics are the most suitable [31]. The next step is to obtain real-world data to be compared to the chosen validation metrics from the simulation model. In some cases actually obtaining the data can be hard since previous observations might be non-existing, other times there can be an overload of data making it important to be selective. But in most cases some relevant and accurate data is either already prepared or the possibility exists to experimentally acquiring it [32].

The last step of the validation process is compare the simulation data and the real data to see quantify the actual model performance. One common way to do this is by trace driven simulation, the model is fed with historical input data and the generated output data from the simulation runs can be compared to the known output of the real-world system. To compare the generated simulation data with the known historical data several techniques can be applied, visualization and quantitative approaches are two examples. When visualizing the data plotting of the two datasets against each other can be applied to see how the results evolve over time and how they correlate. Quantitative studies can be performed by calculating mathematical statistics to examine the quality of the simulation results [32].

3

Methodology

This chapter outlines the methodological approach used throughout the thesis project, which combined simulation development, LCDP, and stakeholder-centered design. The aim was to develop and validate a concept where a LCDP is integrated with a DES model to enhance usability and long-term stakeholder engagement.

3.1 Overview of Methodological Approach

To support this, the project got inspiration from two established methodologies: The Banks simulation methodology, widely used in DES projects, and the CRISP-DM (Cross-Industry Standard Process for Data Mining) framework, commonly applied in data-driven projects. However, due to the customized needs of the project, those methodologies could not be applied in a strictly linear fashion. Instead, an adapted methodology was formulated by mixing selected steps from both methodologies in a way that aligned with the project's aim.

The tailored approach guided the implementation of tasks such as problem formulation, data preparation, concept design, and evaluation. It was implemented iteratively, allowing the project to remain flexible and responsive to findings from literature reviews, interviews, and both qualitative and quantitative studies. These studies informed each phase of the methodology to ensure technical feasibility, user requirements, and real-world constraints were continuously integrated into the development process.

3.1.1 Banks Methodology

When conducting simulation projects it is of importance to follow a structured work methodology to obtain satisfactory results. One commonly recognized and accepted project methodology when working with DES is the one presented by Jerry Banks, commonly referred to as Banks Methodology. The steps included in the methodology are visualized in Figure 3.1 [33].

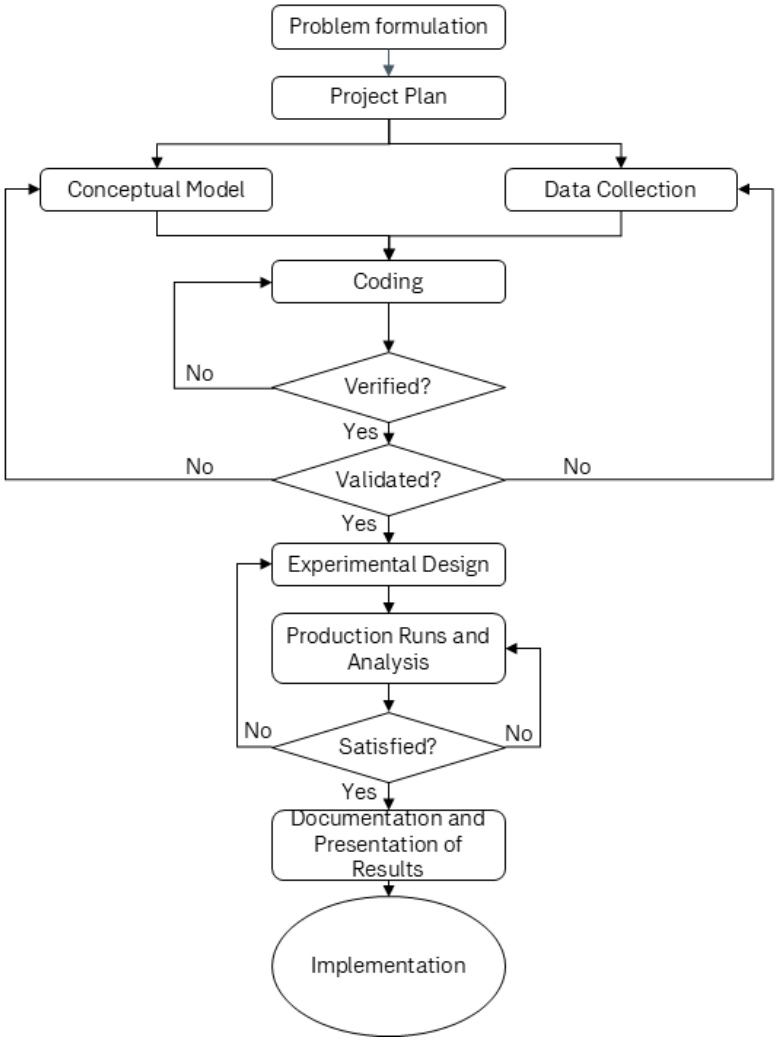

Figure 3.1: Banks Methodology [33]

The framework can be roughly divided into three main phases: Preparation, Model building and Analysis. The Preparation phase stretches form the problem formulation to conceptual model and data collection, the model building phase covers the coding to the validation and the analysis phase covers the experimental design. Given the scope of the thesis project the framework were applied to the validation step.

The problem formulation phase sets the foundation for the project by clearly stating the project objectives, defining the problem and determining the delimitation. Furthermore, it also decides the level of detail of the project, maps the involved stakeholders and sets the time frame of the project. A project plan aims to define the research questions and then break the overall goal down to specific tasks and activities. Additionally, setting deadlines for the individual activities, mapping the available resources and dividing the work into different areas of responsibility is often included in a project plan. The step conceptual model implies that a simple sketch or drawing indicating the logical relations between different components and

systems in the model. A conceptual model aims to be a basic and simple model facilitating common understanding and aiding the development of the actual simulation model. The data collection step includes defining and gathering the necessary for constructing the simulation model. The data of interest depends on the nature of the project and the end goals, but the quality and availability of the collected data has a significant impact on the end results of the project. The coding phase essentially means to translate the conceptual model with the help of the collected data into a simulation model representing the real-world system. By coding, logic and the previously conducted steps in the framework a simulation model that corresponds and behaves in line with the project objectives is created. Verification is the process of testing whether the coding and logic created for different system elements actually produces and works correct. In other words, checking that the built model acts as specified in the conceptual model. Validation is a term used for the testing whether or not the constructed model actually behaves as the real-world system it is supposed to represent. This process aims to determine if the model delivers accurate enough results for experimentation and drawing conclusions.

3.1.2 CRISP-DM Methodology

CRISP-DM is a framework for carrying out large data mining projects independent of industry sectors. The framework proposes a standard approach that via a number of process steps helps turn business problems into data mining tasks [34]. The steps of the CRISP-DM framework are illustrated in Figure 3.2.

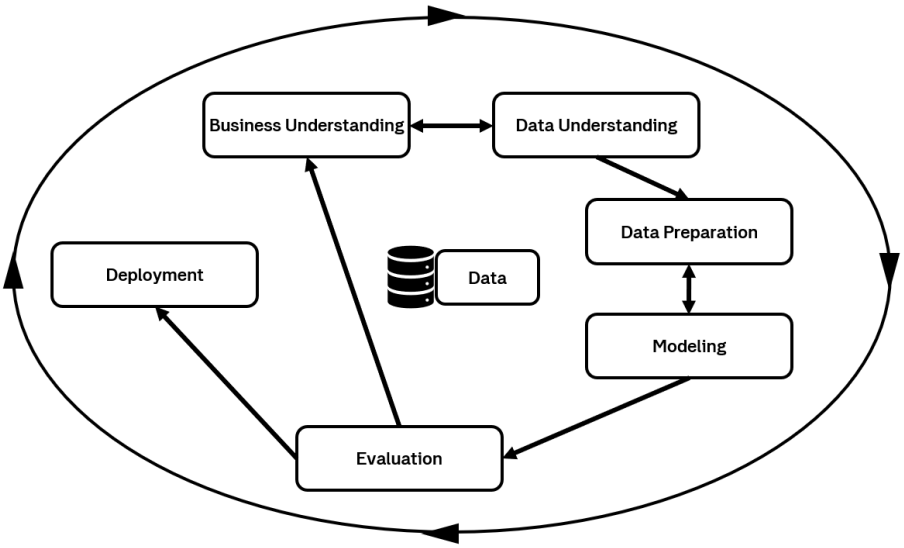

Figure 3.2: CRISP-DM Phases [34]

The business understanding phase aims to identify stakeholders and to review and understand the business objectives to formulate a mature problem definition for the data mining project. Data understanding suggests initial data collection and analysis. This phase includes activities such as familiarizing the data, initial pattern recognition, data quality analysis and a first attempt of information extraction. The purpose of the data preparation phase is to make the data ready for usage

and application. The phase includes data cleaning, structuring of the data, feature selection and data transformation. The modeling phase includes evaluation, selection and application of techniques, for example, algorithms, simulation software or data science methods. Evaluation aims to investigate to what extent the constructed model fulfills the formulated project objectives. Furthermore, it also includes sensitivity analysis to find strength, weakness and potential improvements of the model. The deployment phase may include vastly different activities depending on what the aim of the project was. If the purpose of the project was research the deployment phase may only include a final report with the findings and methods used documented. However, if the purpose of the project was to deliver a product or solution to a customer it may include many more activities associated with the actual deployment of the product or service. One of the most common pitfalls with the CRISP-DM methodology is to confuse it as a version of waterfall methodology were every step is only visited once. One of the cores and strengths of CRISP-DM is that it is highly iterative and that individual phases may be revisited many times [34].

3.1.3 Customized Project Methodology

Project methodologies has long been developed and used to help ensure satisfactory outcomes. By applying standardized tools, structures and frameworks project methodologies can help achieve successful fulfillment of project objectives [35]. Generally, there is no such project methodology that is suitable for all types of projects in all types of environments. Often times, the general building blocks of the project methodologies can be kept the same but minor alterations can be made of project steps or processes to ensure the methodology fits the intended use and can help guide the project to satisfactory outcomes [36].

The project was determined to have two main parts: the development of the simulation model and the development of the whole concept with the LCDP and the connected simulation model. Given that the two parts were quite different from each other, a mixed methodology approach was decided to be suitable. As previously presented, Banks methodology is commonly adapted within DES and CRISP-DM is often applied in data mining projects. With the attributes and characteristics of the two methods, it was deemed appropriate to use a combination of the two as project methodology for the thesis project. In Figure 3.3, the adjusted and integrated version of the two methodologies can be seen.

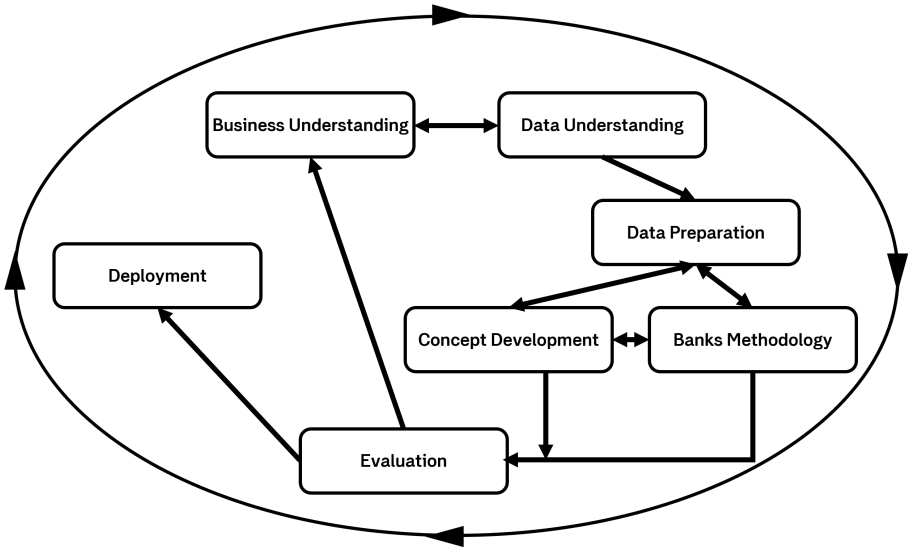

Figure 3.3: Adapted Project Methodology Inspired by CRISP-DM and Banks Frameworks

The business aspects of the project consisted of literature studies and interviews which was the base for a present state analysis, problem formulation and system description. The data understanding was formed with the help of interviews and mapping of the data flow. The data preparation phase consisted of database searches, input data management and construction of IT- infrastructure. The concept development phase contained definitions of design criteria, a stakeholder analysis and concept generation. Banks methodology was applied when modifying and preparing the simulation model to ensure accuracy and compatibility. The evaluation phase included verification and validation of the different system components. Furthermore, user surveys and workshops were carried out to evaluate the result against the thesis objectives and the formulated design criteria.

3.2 Case Context and System Definition

The thesis project was conducted with the use case of an existing simulation model over a heat treatment process at a SKF site in Gothenburg. The simulation model was initially created for helping estimate effects of increasing the product mix and changing of processes. The simulation was created in the simulation software Siemens Tecnomatix PlantSim and gets input data from a SQL data base. Some variables can be changed in the model via change of program code or user objects' parameter setting. The simulation model is built with the intention to be used by SKF employees who may have varying knowledge about simulation tools or simulation in general. Moreover, the purpose of the model is to provide information, statistics and to be a tool for decision making.

3.2.1 Problem Formulation

Since previous experiences with simulation of production flow in the heat treatment process have resulted in insufficient use over time due to complex simulation software and limited changeability and adaptability of the model, it is of interest for SKF to explore options allowing for easy and available usage and possibilities for handling input data. Challenges for the project regarded interpretation of the needs and desires from potential users and successfully present simulation results in a useful and understandable way.

3.2.2 System Description

The heat treatment process which the simulation model covers, treats rings and rollers for roller bearings. A certain amount of rings or rollers is placed in one of two parallel process-lines. The first step is Pre-wash and then followed by furnace time. The furnace time and temperature is a delicate process that does not allow for blockage in the furnace, thus only allowing for the entering of a charge when it is calculated to not rub up with the previous charge. Other contains such as maximum mass per hour or time margin are also represented in the simulation model. After the furnace and and quench the charge is picked up by a gantry crane which moves it around between different transition baths. There are many possible routings around the baths and the baths can contain several charges simultaneously which makes the process quite complex. There are normally two gantries that operate at the same time and execute movements triggered by the production line's Supervisory Control And Data Acquisition (SCADA) system. The complexity of the routing and product specific process data makes it difficult to estimate effects of changing work order or products mixes. Hence, it was requested to simulate effects of changing parameters and production plan for the system. Furthermore, there are several thousand articles that can go through the system, and they have different process variables and routing. This required automated data flow from data bases were actual process data was stored. Moreover, it required a secure way to import the data.

3.3 Conducted Qualitative Studies

The qualitative study conducted during the project consisted of two major parts, a review of the literature and interviews. Reviews of literature were conducted continuously throughout the project, while interviews were limited to several independent occasions.

3.3.1 Literature Review Strategy

With the purpose of gaining a fundamental understanding of the topics investigated in the thesis project, reviews of literature were contiguously applied. The literature studies were carried out in a systematic way in where articles with different opinions, both popular and unpopular, were examined [37]. The reason behind the strategy

was to reduce the selection bias among the authors and to build an as unbiased understanding of the topics as possible [37]. The literature reviews of the thesis project were carried out in accordance with the framework illustrated in Table 3.1.

Table 3.1: Framework for Systematic Literature Review [38]

1	Define clear objectives and questions to be addressed.
2	Establish inclusion and exclusion criteria.
3	Conduct a comprehensive search among published and unpublished studies.
4	Evaluate the quality of selected studies.
5	Analyze the extracted data.
6	Present and synthesize the findings.
7	Provide transparent reporting of the methodology and methods used to conduct the review.

To find literature with sufficient quality and reliability, accepted academic web sites, for example, Scopus and Google Scholar were used. In addition, several criteria were established to help sort out appropriate literature from web sites. The criteria presented in Table 3.2 were applied for most of the searches for literature, however, when it came to more technical fields, for example, simulation, older sources of information were used since they were still considered relevant.

Table 3.2: Criteria for Literature Selection

1	Minimum of 20 citations in other published scientific papers.
2	Preferably published in the past 10 years.
3	Provide enough information regarding authors and publication so that the origin and authenticity can be confirmed.

3.3.2 Interviews

With the aim of gaining more in depth-knowledge and to capture information linked to experiences, interviews were conducted throughout the thesis project [39]. The interviews served two purposes, to learn about the opinion and views of potential users and to gain knowledge from technical specialists. The interviews with potential user were conducted in a semi-structured way to enable comparison between the different interviewees responses [40]. The purpose of the interviews with the technical experts was to obtain information within their areas of expertise which required the interviews to be less structured to allow them to speak freely about their views and opinions. Since the purpose of the interviews was to capture the respondents unique knowledge and experiences semi-structured interviews were conducted to create space for the interviewees to elaborate freely while still keeping a structured set-up of the interview [41]. During the interviews some guiding questions were asked to the interviewee who then could answer freely, the interviews were kept flexible and additional questions that arose were added to the list of questions.

To protect the respondents, permission to conduct the interviews, and later publish the results was always asked of the interviewees. Additionally, the interviewees were offered the opportunity of anonymity to ensure the safety of the individuals [41]. To draw conclusions and analyze the qualitative data obtained from the interviews, the sample size of the qualitative study was set to a minimum of 10 interviews. The reason behind the number 10 was that the purpose of the qualitative study was determined to be theme saturation, since the goal was to capture the many different views that the respondents had on the topics of the interviews [42].

To analyze and interpret the collected qualitative data from the interviews coding was applied on the generated transcripts [43] [44]. Due to the relatively few interviews conducted, it was decided to perform the coding manually, as opposed to the option of using software as a tool [44]. The coding process was applied in several steps, starting at the lowest level and moving upward towards higher levels [43]. The first step of the coding was to identify relevant text from the transcripts, then, the relevant text found was grouped into aggregate dimensions based on shared themes identified between the different relevant text [43]. The identification of relevant text and themes was conducted with the more abstract, higher level RQ:s in mind. The process was repeated three times, thus yielding three levels of interpretation of the qualitative data.

3.3.3 Stakeholder Analysis

The aim of the interviews was to gain an understanding of what people in different parts of the organization considered important for the thesis project considering several different aspects. An aspect was how the organizational view on simulation was and what the thesis project could offer. Another was to learn more about potential users thoughts regarding the area and what they considered important. Stakeholder analysis is a tool often applied with the intent of mapping different actors and their behaviors, interest and resources associated with an organization. Information gained from stakeholder analysis can be translated into project objectives or strategies with the aim of satisfying the identified needs of different actors categorized as stakeholders [45]. The stakeholder analysis for the thesis was conducted through the qualitative study and the interviews. The list of the identified and interviewed actors selected as stakeholders of the project can be seen in Table 3.3. Furthermore, since the aim of the interviews differed the interviewees were divided into two respondent groups based on their work areas: Potential User or Technical Experts.

Table 3.3: Interviewees

Work Area	**Respondent Group**
Supply chain Manager	Potential User
Heat Treatment Manager	Potential User
Process development	Potential User
Simulation Expert	Technical Expert
Data Integration	Technical Expert
Scalable Manufacturing	Technical Expert

3.4 Identification of Design Criteria

In projects where a design process is applied one crucial step is to set up and define design criteria. The key role of the design criteria is to ensure that the main objectives of the design are actually achieved [46]. A process that can be followed when creating a design is the Questions, Options and Criteria method. The first step involves finding and defining the key design challenges, the second step regards inventing different options to solve these challenges and the third step is to evaluate the different options using design criteria [47].

The design criteria for the thesis were created from collected data regarding the area of the implementation. The data were collected via two different methods: literature reviews and interviews with stakeholders. Based on the data and information collected, aggregate dimensions that covered the range of important topics that formed the basis for the selected design criteria were constructed. The main purpose of the design criteria was to guide the design phase of the concept to ensure that all the project objectives were met, and to be used as an evaluation metric when the design had been finalized.

3.5 Overall Project Concept Development and Evaluation

To ensure that the thesis criteria were met, deadlines followed and project management kept efficient, a concept development process was applied [48]. The basis of the conceptual development was the design criteria that were used to continuously evaluate different options and make decisions. The first step carried out during the conceptual development phase was to outline and define different critical areas, after careful consideration a list of items was formulated.

3.5.1 Overall Conceptual Model

To get an overview and understanding of the systems different components and their relations to each other, a simple conceptual model was drawn up. The major components included in the system were: The users, the data bases containing operational information, OMP, the plant simulation DES model and the web interface

between OMP and the end user. The data flow and logic relations between the system components can be seen in Figure 3.4.

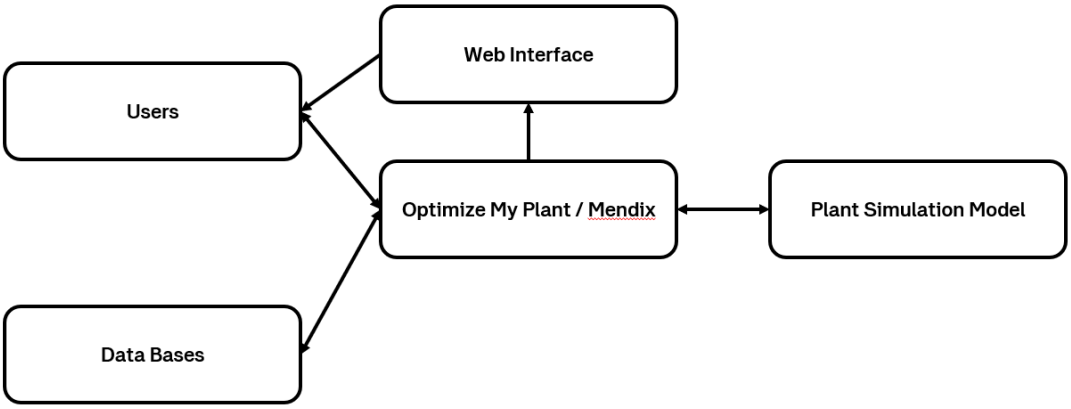

Figure 3.4: Overall Conceptual Model

Furthermore, to compliment the simple and rough conceptual model the subsystems to the identified components were mapped and summarized to get a deeper understanding of the total system. Below, the findings of the mapping are summarized for each of the major system components.

Users:
The users of the system were determined to have two main functions: generators of input data and interpreters of the simulation results. The users would input data to be used for the simulation and set initial parameters of the simulation run. The input data provided by the users would be fed into OMP, then the simulation would be run, and lastly the results would be displayed to the users via the web interface.

Data Bases:
The data bases would, similar to the users, function as an enabler of input data to the simulation. The data bases would send standard data, for example, product data and production plans that needed no modification. Similar to the users, the data would go into OMP and then into to simulation model.

OMP:
OMP powered by Mendix in the background would be the core of the system. It would be the primary processor of input data, responsible for running the simulation model and communication of the results displayed to the users via the web-interface.

Plant Simulation Model:
The Plant Simulation Model would function as the information generator in the system. Based on the input data sent from OMP and user exposed parameter it would run and return simulation statistics back to OMP.

Web Interface:
The Web Interface would be the part of the system that the user interacted with. It would be customized to fit the intended users and enable easy and logic interaction. One of the main focus areas of the interface was the selection of KPIs and the simulation statistics it would display to users.

3.5.2 Adjustments of the Existing Simulation Model

Since the simulation model was not designed with OMP integration in mind there was a need to make certain changes. However, since both softwares were under the Siemens umbrella and intended to be compatible, plenty of pre-built functions could be utilized from the plug-in OMP which reduced the need for adaptation in several aspects such as input and output data and initiation of simulation runs. Furthermore, to make the simulation model compatible with the OMP interface a custom made library, Alexa, built by the developers of OMP could imported into the model. It's main function was to connect the simulation model with OMP to allow for data transfer in both directions. The most basic level of data transfer could, for instance, be that the web interface sends input data to the simulation model and the simulation model then sends back simulation statistics and results to be displayed in the web interface.

Additionally, the simulation model had to be modified from certain aspects to be able to handle and act on the input data and to send back the results to the user interface. One example of modifications made to the simulation model was that all the input data had to be imported and sorted into tables inside the simulation model before a run or experiment could be initiated. Additionally, methods in the simulation model that initiated a simulation run previously cleared and reloaded input data from data bases before each simulation run. This needed to be changed since data would instead be pushed into the simulation model via OMP before a simulation was initiated. Thus, the simulation model needed to be designed with blank tables ready to be filled with input data and not to clear and trying to reload before each run. Other changes required regarded method variable changes, that previously were chosen in the simulation model itself. The variables needed to instead be selected in OMP by the user to set the desired circumstances for a simulation scenario. When connecting the simulation model and OMP a rough outline of the steps required were provided by Siemens, the summarized steps and their order are presented below.

1. Determine required input for the simulation model
2. Define KPIs and statistics relevant for the users
3. Create end - user controlled parameters

3.5.3 Data Flow Mapping and Integration

One key part of the concept development phase was the mapping of the data flow between the different systems, programs and data bases. In Figure 3.5 the network architecture behind OMP, as depicted by [21] is shown.

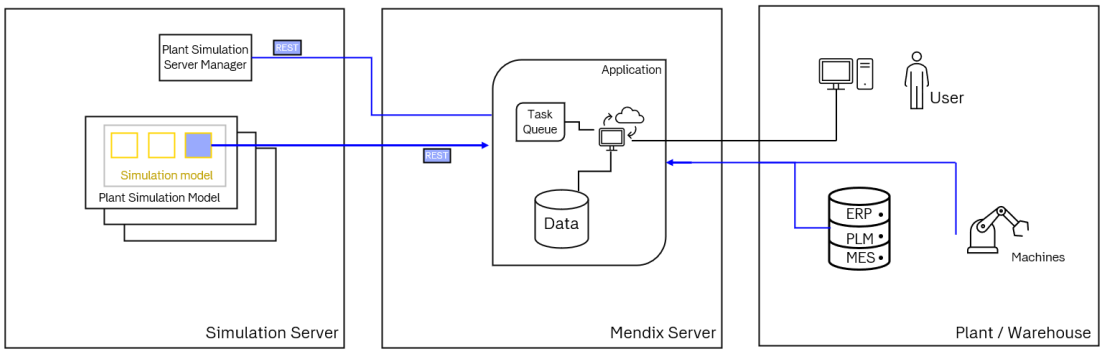

Figure 3.5: OMP Network Architecture [21]

As depicted in Figure 3.5 the web application consists of three major parts: the Mendix Server, the Simulation Server and the Plant that provides input data and parameters in different formats. For the scope of this thesis project the following parts were identified in relation to three different areas:

Simulation Server:
Consist of the built and modified Plant Simulation Model with the Alexa library included.

Mendix Server:
For the duration of the thesis project Siemens granted access to Mendix servers, thereby allowing access to the OMP solution.

Plant:
Several SKF data bases and programs were identified as important information and input data sources. The SCADA and the SQL databases were detemrined to be the most crucial ones, since they contained vital input-data for the simulation model.

3.5.4 Input Data Management via Excel and SQL

After mapping the data flow and identifying from what local databases important information could be retrieved, a more extensive list of required input data and their storage data bases was compiled: see Table 3.4.

Table 3.4: Overview of Input Data

Input Data	**Data Origin**
Production History	SQL
Product Data	SQL
Production Plan	SQL
Work in Progress	SCADA
Current system limitations	SCADA

As previously stated in the conceptual model, both the users and the local SKF databases were going to act as generators of input data. Considering that, it was decided that an Excel interface was to be designed with the intent of creating a shared environment between the input data from the databases and from the users. An advantage of using Excel was that its already compatible with SQL, thus enabling easy and customized ways of connection. Additionally, it was established that the Excel Workbook had to make it possible for the users to alter, or insert their own data for testing and experimenting. Another benefit of using Microsoft Excel was that it came with the in-buil option to export data as CSV-files. This was practical for the concept since Siemens Technomatix Plant Simulation is effective at treating input data as CSV-files. Microsoft Excel also comes with the built-in feature to connect Workbooks to Macro Commands by writing custom Visual Basic for Applications (VBA) code. VBA coding makes it possible to alter, manipulate and export sheets from a workbook and send it to other applications via REST-API. After reviewing the OMP program structure it was determined that the most appropriate way to export the input data from Excel would be to push the data from the Excel Workbook. What that practically meant for the concept was that the input data could only be sent from the Excel Workbook to OMP, however, sending the data from OMP back to the Excel Workbook would not be possible.

3.5.5 Web Interface Design and User Parameters

The Web Interface of OMP needed to be modified in several different ways to ensure that it was comfortable for the user and so that it could treat the input data and the simulation output statistics. It was also necessary that the user could review the input data sent from the Excel sheet and that the parameter settings for the simulation were clearly communicated. As previously determined, the users needed to be able to set simulation parameters inside OMP that controlled the simulation environment for different simulation scenarios. The best solution found was to create global user exposed parameters that would be connected and communicated from OMP to the simulation model. When designing the user exposed parameters for the web interface boolean values and integers was implemented, creating a logical and easily interpreted environment for the users. Additionally, descriptions of the parameters and input formats were added to decrease the cognitive ergonomic load on users. The qualitative study was determined to be used as the basis for what user exposed parameters that needed to be constructed and how the design would look.

Furthermore, the other main purpose of the web interface would be to visualize and communicate important simulation output statistics to users of the concept. The OMP package came with some limited built in KPIs and visualization strategies, however, there was a need for custom made KPIs and visualization to be able to display all the relevant info. To determine what statistics, KPI and information that would be relevant for the users questions targeting that specific area was incorporated in the interview questions. In addition, the literature study was also utilized to find potentially interesting information to display for the different stakeholders using the concept.

3.5.6 Verification of Simulation Model

When verifying that the system functioned as intended all four of the steps presented in section 2.4 was utilized. The first step of the process was to ensure that the simulation model behaved as intended, this was done by debugging and checking all of the code and logic implemented in the model. Furthermore, the coding was done in a structured and modular way with the intent of making it easy to debug and understand. Next, the different processes were controlled individually by manually calculating total throughput for different scenarios and then checking that the actual outcome were close to the predicted one. The processes was also visually inspected when they were ran to see if any anomalies would appear. Lastly, the whole system was simulated and the statistical results was compared to calculated expected values. Additionally, the simulation system was ran with several different combinations of the variable parameters to ensure that it was robust and trustworthy.

3.5.7 Verification of the Overall Project Concept

The scope for the verification of the whole concept differed quite substantially from the verification of the simulation model itself. For that process, the aim was to ensure that the data flow and the parameter settings inside OMP actually produced the expected results from the simulation model. In other words, the goal was to check that the connection between the uploaded simulation model and OMP was working as expected. To control this several different actions were performed, the first thing to be checked was that the data sent from the excel-file ended up in the right place and had the right structure inside OMP. To see whether or not this was the case numerous different data sets were transferred from the excel-file to OMP, whereas the corresponding CSV-files were searched for errors. Next, the simulation output based on the in data sent from the macro excel-file and the user exposed parameters where controlled. This step was carried out by running the simulation model with a set of parameters and input data, after those results were recorded the simulation model was run via the OMP interface with the same input data sent from the macro excel-file and the same parameters. Lastly, the two outcomes were compared to each other to investigate the accuracy of the concept.

3.6 Validation of Final Concept

To ensure that the LCDP implementation worked as intended and met the end users expectations, it was tested against the design criteria and user surveys were conducted. The first evaluation step was to test if the previously built simulation model could simulate scenarios and give results with such accuracy that it satisfied the intention of the simulation. Simulation scenarios in which given production plan and parameters that represented historical data to validate the model produced sufficiently close throughput as reality. The reason for the validation was to ensure that the final concept was not based on an inaccurate simulation model, thus leading to unusable KPIs and statistics. The second validation phase regarded validation of the LCDP implementation in comparison to the model. Comparison of possibilities of performing the same scenarios directly in the model and in the web interface was made to determine that the outcome of the simulation was not compromised. Both parameter changes and input data changes were tested simultaneously to determine that the data transfer and connection between the two components functioned as planned. Different extreme scenarios such as immediate or infinite process time were tested as direct parameter changes in the model and also via OMP to determine that changes were leading to the same outcome, both when made directly in the model or via input data. Certain scenarios of input production data were also tested to ensure that input data was accurately pushed from the web interface to OMP.

A user survey was conducted to assess the LCDP implementation. The survey was conducted through workshops where stakeholders from different areas could express their opinion and experience of trying out the implementation. One reason that workshops were used as evaluation tool was that interactive evaluation methods have been shown to increase the engagement of participants and yield more accurate results compared to passive methods, for example questionnaires [49]. Furthermore, workshops are a commonly applied tool for evaluating and co-creating design and information system concepts, quite similar to the aim of the thesis project [50]. The questions and areas of discussion during the workshops were based on the design criteria and the aim was to identify positive aspects of the concept as well as areas for improvement. The participants were also asked to describe potential issues or drawbacks based on their intended usage. The findings from the workshops were then compared to each other and matched against the design criteria. Furthermore, it was also investigated wether the survey could sufficiently provide a comprehensive evaluation or if it would benefit from being conducted again after a the user had gained more experience. In total, two workshop sessions were held with two respective groups of stakeholders. The first workshop was held with a group of potential users of the constructed platform while the second one was held with one technical expert. The participants of the two workshops and their corresponding work areas are shown in Table 3.5.

Table 3.5: Workshop Participants

Work Area	**Workshop 1**	**Workshop 2**
Heat Treatment Manager	X	
Process Engineer	X	
Data Integration		X

4
Results

The following sections present and explain the outcomes of the activities conducted during the thesis project. First, the findings of the qualitative study are summarized, followed by the established design criteria. Finally, the results of the verification and validation of the overall project concept are presented.

4.1 Results from the Qualitative Study

The qualitative study gave insights from both interviews and literature review. The interviews provided insights into how potential users believe they would benefit most from the implementation, while technical experts shared their views on key prerequisites and characteristics of the implementation. The literature review explored a range of topics relevant to the scope of the thesis project. The following sections highlight key areas that were identified as particularly important and beneficial to the development of the project, and which helped inform the creation of the LCDP concept.

4.1.1 Results from Interviews

The interviews were categorized into two main areas: potential users and technical experts. The approach helped capture several critical aspects of areas surrounding the implementation. To gain an overview and summarize the content, the collected qualitative data were coded. The results of the coding for both interview groups are presented in Figures 4.1 and 4.2.

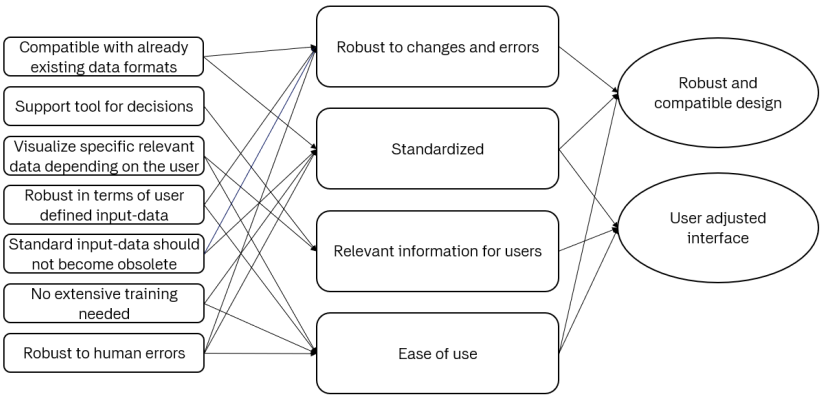

Figure 4.1: Coding from the Interviews with the Potential Users

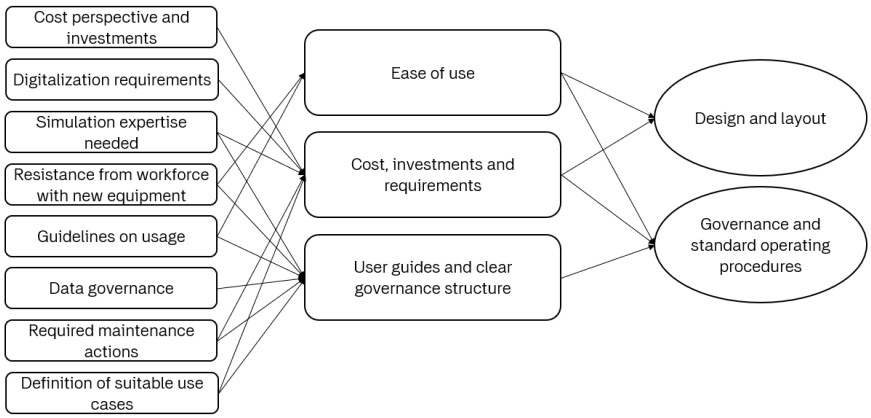

Figure 4.2: Coding from the Interviews with the Technical Experts

The potential users expressed that it would be beneficial if the application was compatible with, and resembled, their usual workflows. For example, by allowing input data to be formatted in the same way as in their standard databases and Excel sheets. When asked how the LCDP implementation could support their work, they responded positively. They saw value in using it as a decision making tool, provided it could deliver sufficient information and statistical output from the simulation. This was considered especially useful in complex situations and in the evaluation of extreme scenarios within the heat treatment system, where calculations and experience alone were sometimes insufficient to predict outcomes. The interviewees also revealed that potential users had varying needs and preferences regarding simulation scenarios, as well as the types of KPIs and results they wished to receive. Another important aspect raised was the risk of human error, such as incorrect formatting or unintentional changes made during setup for simulation scenarios. Additionally, some respondents worked with databases that were updated continuously. This raised concerns about how to manage changes to master data, to ensure that the input data used for simulation remained valid and up to date.

One key takeaway from the interviews with the technical experts was the importance of including cost and investment calculations when considering implementations of this kind. When the scalability of the platform was discussed, it was noted that a relatively high level of digitization and data collection is required for such a solution to be feasible. The topic of required technical expertise also emerged, particularly regarding the need for experience in simulation to successfully implement and operate the system. Additionally, interviewees pointed out that new technological applications are sometimes met with resistance from shop floor workers, who may not perceive the need for such tools and therefore fail to recognize their potential benefits. The experts also emphasized the importance of clear user guidelines, robust data governance, and well defined maintenance strategies when launching new digital initiatives. Finally, they highlighted the value of identifying and outlining which specific use cases are most suitable for applications of this nature.

4.1.2 Results from Literature Review

The literature review explored a range of topics relevant to the scope of the thesis project. The following sections highlight key areas that were identified as particularly important and beneficial to the development of the project, and which helped inform the creation of the LCDP concept.

4.1.2.1 IT/OT integration

With the growing demand for enhanced planning and monitoring in manufacturing, the concept of IoT has become central to many organizations [51]. A critical factor for successful adoption of IoT in manufacturing environments is the convergence of Information Technology (IT) and Operational Technology (OT), which enables more seamless analysis of data across these traditionally separate systems [51] [52]. In general, IT is categorized as the hardware and software systems used for processing information [53]. IT can also be defined as the processing, storage, and transfer of electronic data, and is often associated with key principles such as privacy, authentication, data integrity, and non repudiation [52]. OT is commonly defined as systems used for the monitoring and control of physical devices, typically comprising both hardware and software components [52] [51]. A primary purpose of OT is to generate information that enables adjustments to processes for improved performance. A common implementation of OT in the industrial sector involves the use of sensors, switches, and motors to collect data from physical assets. This data, once processed and interpreted, can provide valuable insights for operational optimization [53].

When integrating OT and IT systems, several important factors must be considered. A critical step is to identify all machines and software components affected by the convergence, as well as their interrelationships. Another key aspect is designing the connectivity structure between IT and OT systems to ensure efficient communication. Additionally, the potentially large volumes of data generated must be compiled and managed in appropriate and effective ways [54]. In Table 4.1 some recognized

advantages and disadvantages proposed by [52] are presented.

Table 4.1: Advantages and Challenges [52]

Advantages	Challenges
More direct control	Extent of integration
Complete monitoring	Cyber Security
Asset management	Bandwidth requirements
Productivity improvement	Interface integrations

4.1.2.2 Suggestions for Using LCDP

LCDPs enable companies to improve resource utilization by significantly accelerating the development and deployment of business applications. These platforms provide high level graphical interfaces, drag-and-drop functionality, templates, and other visual tools that simplify the development process [18]. By minimizing the need for manual coding, LCDPs allow applications to be developed more quickly and with fewer technical resources. This rapid development capability is particularly valuable in the face of growing complexity in internal business processes and the increasing demand for fast deployment challenges that traditionally require substantial software development efforts [27]. By automatically generating much of the underlying code, LCDPs reduce both the time and cost associated with application deployment.

4.1.2.3 Digital Twin Viewpoint

The academic literature on digital twins emphasizes their advantages in test running process changes within a digital model, particularly when supported by automated data transfer. This highlights the need for sophisticated data management. Among the various levels of digital twins, the concept of a Digital Shadow is particularly relevant to a Simulation Model/LCDP implementation. In this context, establishing a fully or partially automated data flow is desirable to accurately mirror real world conditions during simulation scenarios [15]. However, advancing toward a full digital twin is significantly more demanding. It requires rigorous model verification and seamless integration with control systems for production lines which may be delimited PLC systems. The information flow from a digital shadow should ideally be presented as statistical output, either in statistical reports or directly in the software interface. This should mainly support decision making of the physical system. The literature suggests that a suitable solution for such integration is the use of encrypted data transfer via API, allowing secure communication between the database and cloud based LCDPs, typically utilizing HTTPS protocols [30].

4.2 Identified Design Criteria

Based on insights from both the interviews and the literature review, a set of design criteria was developed to align with the proposed research objectives and address

the expectations expressed by the interviewees. Table 4.2 introduce indexation of the established design criteria for further referencing.

Table 4.2: Design Criteria

Index Nr	Description
DC1	Ease of use
DC2	User adjusted interface
DC3	Robustness
DC4	Compatibility
DC5	Governance and Ownership

Ease of use:
To maximize accessibility in the use of the LCDP implementation, simplicity is essential in order to reduce hesitation associated with complex simulation tools. By removing the need for direct interaction with the simulation software, the LCDP interface should display only the most relevant features and information. Furthermore, instructions for using the implementation should be clear and easy to follow, and any potential simulation errors should be easily identifiable and correctable by the user.

User adjusted interface:
The interface should be designed to present only the minimum necessary information, variables, and functions to the user focusing on user centered design and displaying only the information that is relevant or requested. If the implementation is intended for use by multiple stakeholders with varying needs for information and KPIs, it is advisable to create separate interfaces tailored to each user group's specific requirements.

Robustness:
The implementation should be designed to withstand unintended changes and allow for the resetting of variable selections or functions within the interface to ensure safe and reliable usage. Furthermore, input data representing the physical system and production plan should be seamlessly imported from actual system data sources. For variables and parameters that are directly programmed into the model, appropriate safeguards and validation mechanisms should be in place to maintain consistency and accuracy.

Compatibility:
Before implementing the LCDP platform, it is important to assess the conditions for implementation and determine what modifications to the simulation model may be necessary. The model should be designed or updated to accommodate the required data inputs. Parameters that reflect the current state of the physical system, as well as those intended to be modified by the user, must be imported into the model in a standardized format. As such, these variables should not be directly coded into the

model but instead defined as input data.

Governance and Ownership:
A common challenge and obstacle to the long term use of simulation models is the risk of obsolescence and reliance on outdated or inaccurate data. Therefore, parameters that change continuously should either be imported directly from the ERP system or be adjustable by the user. To ensure the model remains accurate over time, clear responsibility for maintaining the simulation model must be established. In addition to assigning ownership of the simulation model itself, there should also be defined ownership of the LCDP implementation. This includes ensuring the accuracy of data flows and adapting the platform to reflect any changes in either the simulation model or the physical system it represents.

4.3 Results from Verification of the Overall Project Concept

The verification of the concept involved a series of tests in which different scenarios were simulated using both the standalone simulation model and the implemented concept. Each scenario was first run directly in the simulation model, and the results were documented. The same scenario parameters were then configured in OMP, and the simulation was executed again, with those results also documented. Finally, the results from the two simulations were compared, and any discrepancies were identified and analyzed.

After conducting a series of tests involving various setups and scenarios, it was concluded that the simulation model and the OMP interface consistently produced identical results across all trials. This confirmed that the connection between the input data and the user exposed parameters was functioning as intended.

4.4 Results from Final Concept

Following the steps outlined in the methodology chapter, along with several iterations, a final concept was developed. The concept consists of multiple components, each individually designed to meet both internal requirements and external criteria related to integration with other building blocks. The following sections aim to describe and explain the structure and functionality of the final concept.

4.4.1 Input Data Management Results

Input data management was mainly handled using Microsoft Excel through a specially designed workbook. The workbook consisted of seven distinct sheets: Recipe, Production History, Future Production, Recipe Test, Production Plan Test, and Send to OMP. The Recipe sheet was linked to SKF's SQL databases and contained the latest confirmed and validated recipes for production. The Production History

sheet, also connected to the SQL database, included over ten years of historical production data. Similarly, the Future Production sheet was linked to SQL and displayed upcoming production data from the present onward. The two test sheets "Recipe Test" and "Production Plan Test" were designed to allow users to manually input their own data. These sheets were intentionally left blank but formatted with predefined headers to ensure that user entered data followed the correct structure.

The Send to OMP sheet was the first sheet in the workbook and contained two buttons, each linked to a macro commands developed using VBA. The macros performed two critical tasks. The Send to OMP button encrypted the data in the workbook and exported the relevant sheets as CSV files to the OMP platform. The Refresh button was connected to a macro that reloaded the data from the SQL database into the relevant sheets. This ensured that the most up-to-date information was used and helped prevent any manual errors in the downloaded data. The layout of the excel sheet is shown in Figure 4.3

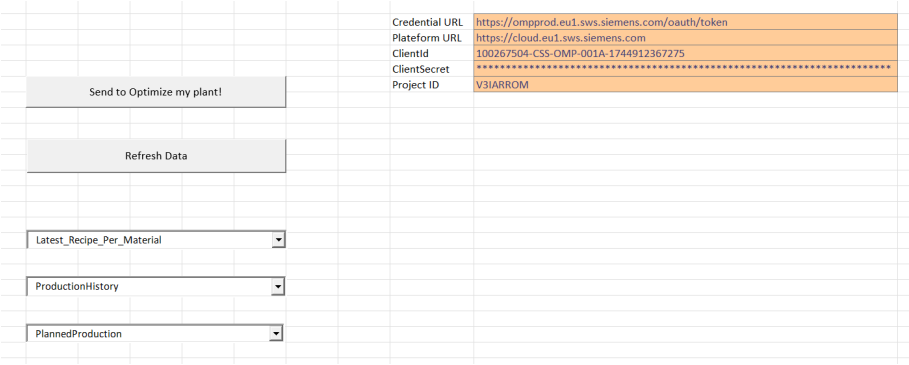

Figure 4.3: Excel Sheet where Input Data are Compiled ant Pushed to Mendix

4.4.2 Simulation Model Results

Several adjustments were made to the simulation model to ensure compatibility with the other components of the concept. One of the most critical modifications was the implementation of a custom Initiation method, designed to import input data from OMP. Figure 4.4 illustrates this Initiation method, where input data is retrieved from OMP and stored in internal tables within the simulation model.

```
-- import file in loadedFile table
if existsFile(ProductDatapath) then
-- insure separator is ;
     ProductData.columnSeparator:=";"
    if  ProductData.readFile(ProductDatapath, true) = false then
        print to_str("[Alexa Error] error in loading  ProductData.csv file")
    end
else
    print to_str("[Alexa Error]  ProductData.csv data files does not exists")
end
```

Figure 4.4: Init Method

To facilitate data exchange between the simulation model and OMP, the Alexa library developed by Siemens was utilized. Additional adjustments were necessary to ensure that all tasks before, during, and after simulation execution occurred in the correct sequence. For example, when simulating multiple scenarios in a single session, the original model required an automatic cleansing of tables between runs. However, in the LCDP integrated version, the model had to be initialized with empty tables that were populated by OMP through the Alexa library. In this case, table cleansing was not appropriate, as data needed to be imported prior to the simulation run.

Further modifications were made to the global user exposed parameters to ensure they functioned as intended. Most of these parameters were set as Boolean variables, enabling the use of if-statements to control simulation behavior. For example, the Boolean variable FurnaceA, selected in OMP, determines whether Furnace A should be activated or deactivated during a simulation run with the help of if-statements. Another example of the use of global variables was the method used to generate the production plan for a simulation run. The method first checked whether to base the plan on historical or future production data, as indicated by the Boolean variable FutureProduction set in OMP. Then it looped through the selected production list and populated the production plan table using the StartDate and EndDate parameters.

In addition, several customized methods and strategies were required to calculate and transmit KPIs and statistics back to OMP after the completion of a simulation run. Certain KPIs and statistics related to standard objects within the simulation model could be returned to OMP by populating pre-configured components provided by the Alexa library. However, other KPIs such as production logs—required more advanced handling. These types of data needed to be processed through custom methods designed to convert simulation internal tables into CSV-files, which could then be exported back to OMP.

4.4.3 Optimize My Plant Results

The OMP interface was structured in multiple layers. The first screen presented to the user was the Scenario Dashboard, which displayed a selection of KPIs along with a list of previously executed simulation scenarios. This served as the start page of the OMP interface, providing users with a quick overview of recent activity and key metrics. An example of the start page is shown in Figure 4.5.

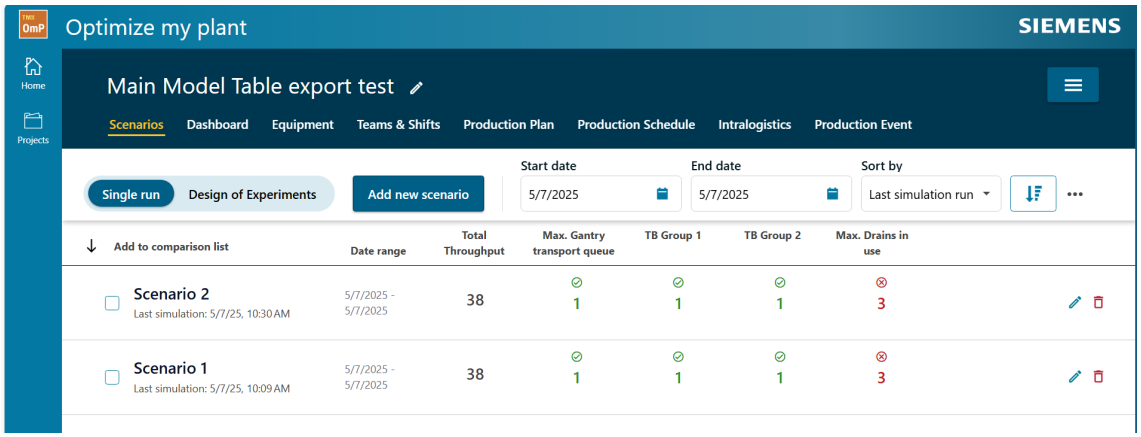

Figure 4.5: Dashboard of OMP Interface

To create a new scenario, the user would click the Add New Scenario button. The next step involved entering the start date and defining the duration of the simulation. Additionally, the users could enter their own description and name of the scenario to note what parameters or input data that was used for the scenario, if the scenario were to be revisited in the future. The design, layout, and format of the page used to input these parameters are illustrated in Figure 4.6.

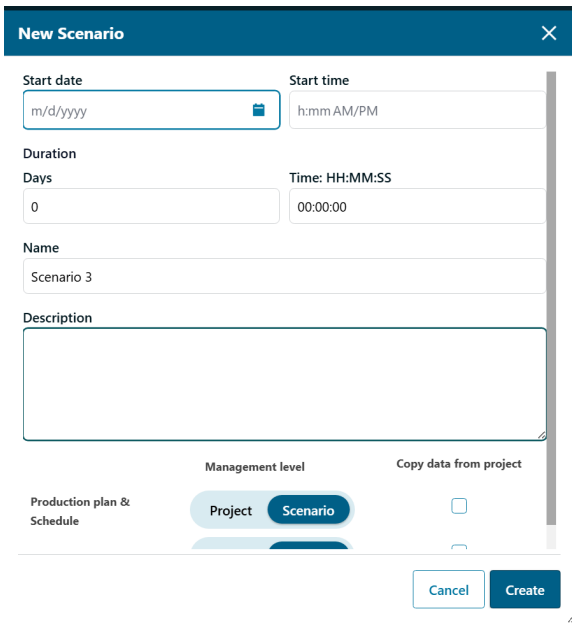

Figure 4.6: Selection of Date and Length of Simulation

After selecting the simulation start date and duration, the user was directed to a page dedicated to configuring the initial simulation settings. Under the Scenario Parameters tab, users could adjust a range of global variables that defined the conditions under which the simulation would run. These global parameters were selected based on insights from the qualitative study, particularly the interviews conducted with the two stakeholder groups. The set of global variables exposed to end users, their function and their formatting is presented in Table 4.3.

Table 4.3: Global Parameters

Name	Function	Type of Value
StartDate	Start Date of Simulation	Date (YYMMDD)
EndDate	End Date of Simulation	Date (YYMMDD)
FutureData	Historic or future production plan	Boolean
FurnaceAStatus	Furnace A Active/Not Active	Boolean
FurnaceBStatus	Furnace B Active/Not Active	Boolean
GantryNorraStatus	Gantry Norra Active/Not Active	Boolean
GantrySodraStatus	Gantry Sodra Active/Not Active	Boolean
BlockageStatus	Blockage in System Active/Not Active	Boolean
InitialChargeStatus	Initial Charges in the System Active/Not Active	Boolean
SortingVariable	Defines variable to sort the production plan after	Drop down Menu

Once the user had defined the simulation conditions, the final step was to select the input data set on which the simulation would be based. Under the Scenario Parameters tab, users could upload input files and choose the specific data collection to be used in the simulation. This functionality also enables users to send multiple sets of input data, allowing for quick testing and comparison of different scenarios. The interface displaying the available input data collections is shown in Figure 4.7. Important to note is that input data could be loaded into OMP in two ways: from the specially designed Macro Excel file or by directly uploading documents straight into OMP.

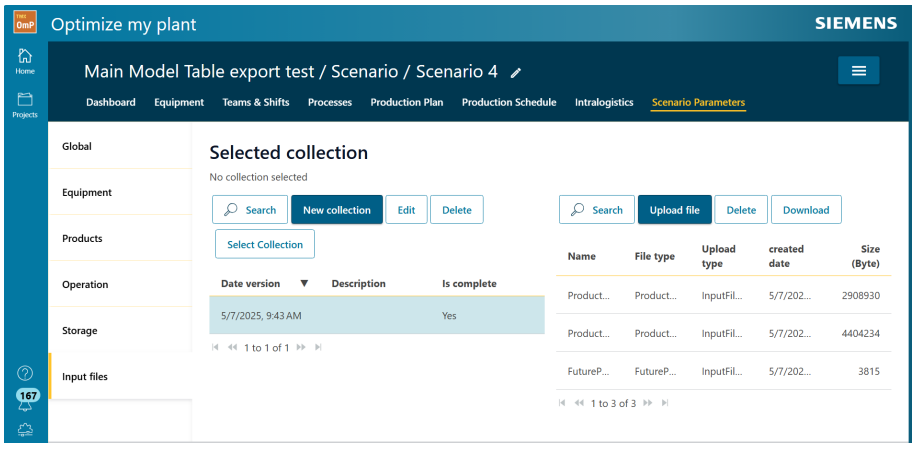

Figure 4.7: Collections of Pre-Defined Input Data

The final step in configuring a scenario was for the user to navigate to the Dashboard tab and click the Run Simulation button. Once the simulation run was completed, statistical data were transferred from the simulation model to OMP and presented in various formats and KPIs. The interface displaying the controls for initiating the simulation run is shown in Figure 4.8.

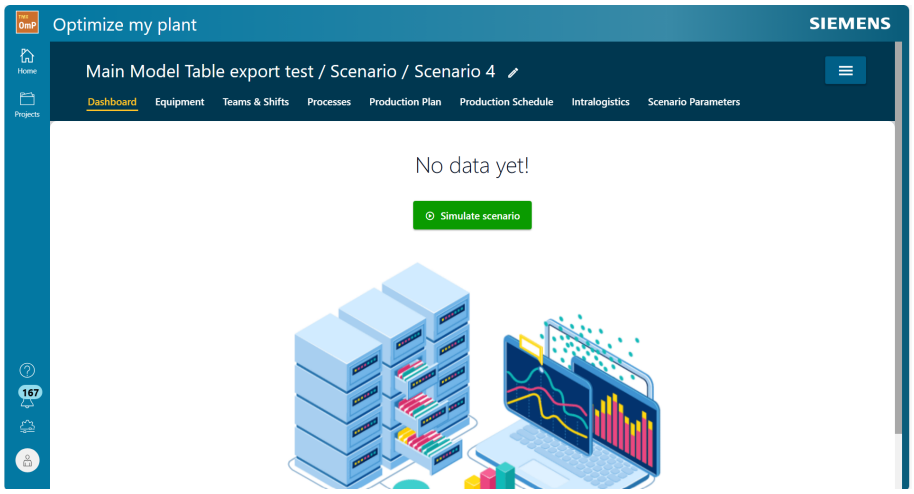

Figure 4.8: Interface for Starting a Simulation

4.4.4 Visualization of Simulation Output

The simulation output was visualized in several formats, tailored to different levels of detail and types of information. Most of the KPIs displayed in OMP were obtained either through built in functions provided by the Alexa library or through custom methods developed to calculate specific statistical metrics. Furthermore, the statistical data was sampled and collected at varying intervals some continuously and others at discrete points during the simulation. Table 4.4 summarizes the collected statistics, their definitions, and their respective sampling frequencies.

Table 4.4: Simulation Outputs

Name	Meaning	Sampling Frequency
Max Gantry Transport Que	The maximal length of requests to the gantry system	1/hour
TB Group 1	The maximal amounts of baths full at the same time	1/hour
TB Group 2	The maximal amounts of baths full at the same time	1/hour
Max Drains in Use	The maximal amounts of drains in use at the same time	1/5 min
Tank Occupancy	The number of products in each tank	1/0,5 hour
Production Log	List of finished products with time log	1/Simulation

Once the simulation output was collected and transferred to OMP, the statistics were displayed in various formats depending on their nature. Metrics such as Max Gantry Transport Queue, TB Group 1, TB Group 2, and Max Drains in Use were presented as color coded text blocks, where the text color reflected the value of the statistic. The color scale was designed to highlight value ranges, helping users quickly identify potentially critical or problematic conditions. An example visualization of those explained KPIs can be seen in Figure 4.9.

Figure 4.9: Example of the Color Coded KPIs

Tank Occupancy was visualized using a time series chart, allowing users to select which of the 12 tanks to display or hide within the chart for clearer analysis. Meanwhile, the Production Log was exported from the simulation model to the OMP interface as a downloadable CSV-file, enabling users to review the data externally. Figures 4.10 and 4.11 provide examples of how the Production Log and Tank Occupancy statistics were visualized within the interface for an example scenario.

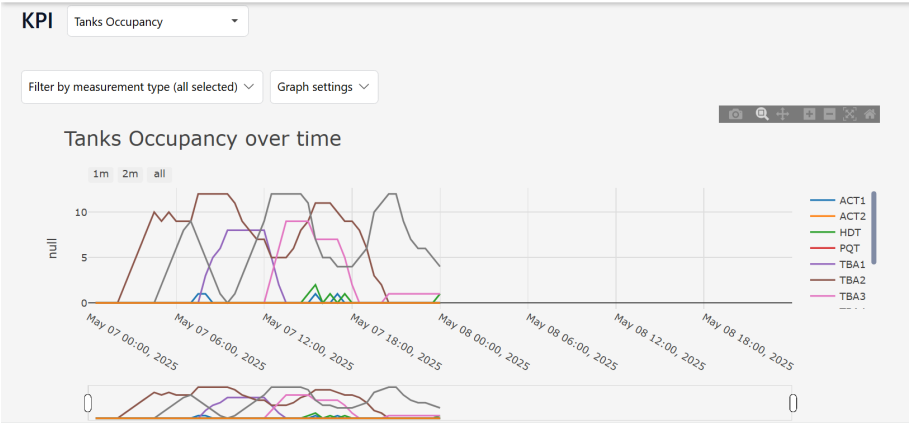

Figure 4.10: Example Time Series Chart for Tank Occupancy

C	D	E	F
Location	Time of Entry	Time of Exit	Actual Time
*.Models.Model.Tank3	2:05:16.8092	4:35:16.8092	2:30:00.0000
*.Models.Model.Tank3	3:25:35.7101	5:55:35.7101	2:30:00.0000
*.Models.Model.Tank3	3:40:24.1077	6:10:24.1077	2:30:00.0000
*.Models.Model.Tank3	3:55:13.1077	6:25:13.1077	2:30:00.0000
*.Models.Model.Tank3	4:13:03.2553	6:43:03.2553	2:30:00.0000
*.Models.Model.Tank3	4:27:52.2553	6:57:52.2553	2:30:00.0000
*.Models.Model.Tank3	4:47:19.9297	9:47:19.9297	5:00:00.0000
*.Models.Model.Tank3	5:01:32.9297	10:01:32.9297	5:00:00.0000
*.Models.Model.Tank3	5:15:45.3273	10:15:45.3273	5:00:00.0000
*.Models.Model.Tank3	5:29:58.3273	10:29:58.3273	5:00:00.0000
*.Models.Model.Tank3	5:57:32.2873	10:57:32.2873	5:00:00.0000
*.Models.Model.Tank3	6:16:16.7249	11:16:16.7249	5:00:00.0000
*.Models.Model.Tank3	10:30:20.6797	13:00:20.6797	2:30:00.0000
*.Models.Model.Tank3	11:24:40.6797	16:24:40.6797	5:00:00.0000
*.Models.Model.Tank3	11:37:03.2023	16:37:03.2023	5:00:00.0000
*.Models.Model.Tank3	11:57:23.2023	16:57:23.2023	5:00:00.0000

Figure 4.11: Example CSV-File of the Production Log

4.5 Results from Validation of Final Concept

The validation of the thesis project was conducted through user surveys with identified stakeholders, carried out during two separately organized workshops. The first workshop targeted stakeholders identified as potential users, while the second focused on technical experts. Prior to engaging in discussion and collecting feedback,

a thorough and standardized walkthrough of the concept and its various components was presented to the participants in each workshop. The following sections summarize the key discussions from the workshops, structured around the previously established design criteria.

4.5.1 Results from the First Workshop

The first workshop were performed with two of the identified stakeholder classified as potential user. Present at the workshop were two stakeholder, one of the participants worked as a process engineer and the other one as a production supervisor. The discussed topics during the workshop revolved around the design criteria and summaries of the discussions are presented in the following sections.

Ease of Use:
The respondents found the management of input data to be intuitive and logically structured. Their reasoning was based on the fact that the input data was handled in Excel a tool they regularly used in their daily work tasks and that much of the process was automated. One particularly appreciated feature was that the standard data in the Excel sheets was directly connected to SKF's SQL database, allowing users to refresh the data via a custom built button. This functionality was seen as beneficial because it reduced the risk of unintentional data alterations and ensured that the input data remained up to date and valid. An important topic of discussion during the first workshop centered on the selection and presentation of KPIs. One potential user found some of the simulation outputs difficult to interpret when visualized in OMP. This was largely attributed to the unfamiliarity of the KPIs, which differed from those typically used in the participant's previous experience. The conclusion of the discussion was that each KPI should be accompanied by a clear explanation, and that it may be appropriate to allow different KPI views depending on the type of user interacting with the interface. The two participants in the workshop worked in closely related fields but within different disciplines, one as a production manager for the hardening process and the other as a materials engineer. As a result, their informational needs from the concept differed in some aspects, although several areas of common interest were also identified.

User adjusted interface:
During the workshop, the potential users expressed that they found the layout and design of the OMP interface to be clear and easy to navigate. One suggestion they raised was the potential benefit of developing a Swedish language version of the concept, as shop floor workers have varying levels of English proficiency. The respondents also appreciated the approach of keeping most manual inputs within the OMP interface itself, noting that this made the process easier to manage and reduced the risk of accidental errors. Additionally, they emphasized the importance of having a clear and well structured user guide. However, they did not believe it needed to be overly extensive, as the interface was largely self explanatory. Both participants felt confident that a colleague could begin using the concept as a deci-

sion support tool with minimal training or guidance.

Robustness:
The purpose of the discussion on the concept's robustness was to capture the potential users' perspectives on long term usability and flexibility. Both participants agreed that the available global parameters provided sufficient flexibility to test relevant scenarios and extract the necessary information. Given the built in adaptability and automated handling of input data, the respondents saw strong potential for successful long term use of the concept. However, questions were raised regarding the ownership structure of the solution. Since the simulation model, input data, and web interface would all require updates over time as the modeled system evolves, the respondents emphasized the importance of clearly defining ownership and maintenance responsibilities to ensure continued relevance and usability.

Compatibility:
The values and parameters that users were most likely to modify regularly such as production plans and product data were compatible with integration between local SQL databases and the LCDP via an Excel file. This solution was considered suitable, as it allows users to input and review data before it is transferred to the implementation. During the workshop, it was noted that the desired information and KPIs may vary depending on the specific purpose of the simulation. As the output requirements evolve over time, adjustments may be necessary in both the LCDP interface and the simulation model itself. While changes to the LCDP typically require little to no coding and can be implemented relatively easily provided appropriate instructions are available modifications to the simulation model are more complex. These changes demand greater programming expertise and familiarity with the simulation software. Larger updates would likely require involvement from individuals with dedicated simulation or software development skills.

Governance and Ownership:
Ensuring the long term usability of the model places importance on establishing a clear governance and ownership structure. While the direct users of the implementation have valuable insights into the model's current configuration and its relevance to ongoing operations, participants in Workshop 1 discussed that ownership might be more appropriately assigned to the IT/OT section of the process development team. This team would be well positioned to manage minor updates, particularly those related to data handling and integration. More substantial updates, such as structural changes to the simulation model would instead be carried out by a centralized simulation team with the necessary technical expertise.

4.5.2 Results from the Second Workshop

The second workshop was held in conjunction with one of the stakeholders previously identified in the group technical experts. The design of the workshop was kept as similar as possible to first one to create a certain level os standardization of the results. It started out with a in depth explanation and demonstration of the concept

followed by discussions of the concept with topics related to the design criteria.

Ease of Use:
The respondent expressed how the concept was relatively simple and that the steps required to simulate and compare scenarios were not to extensive. The participant also explained how the concept could be a way of exposing the workers on the shop floor to simulation as a tool for decision making. In the respondents opinion, he found it unlikely that shop floor workers would consistently use simulation software in their everyday work tasks. One area of improvement identified from the technical expert was the need for a standardized and meticulous user guide, or perhaps even several different user guides depending on the level of expertise among the user groups.

User Adjusted Interface:
The respondent found the user interface to be clear and logical. Furthermore, the participant expressed how the need for interpretation and reflection regarding the simulation outputs visualized could have positive effects. Given, that the user of the concept would need to think and reflect regarding what is really important which could, in the respondents view, facilitate learning and deeper understanding of the system. One important aspects found during the workshop was that the user interface would have to be updated as time passes, given that factors change continuously.

Robustness:
The participant found strength in the robustness of the concept given the flexibility around changing the structure and layout. Additionally, the respondent urged on the need for continuous updates and maintenance work to ensure that the concept did not become obsolete. The technical expert explained how previous projects had become obsolete as a result of improper standardization and actions to maintain and update the solution. An specific area that the respondent identified would need to be updated at some time in the future was the user exposed parameters. Since the system is going to change at some point the parameters and the simulation model will have to be updated.

Compatibility:
During the discussions it was concluded that the concepts level of compatibility was considered as high, since it was built on programs and packages commonly applied at SKF. The technical expert expressed that the connection between SQL, Microsoft Excel and OMP was clear and that it is good to automate such processes when the possibility exists.

Governance and Ownership:
The most prominent topic of the workshop regarded the governance and ownership of the model. It was described that software solutions it often becomes an issue when their is lack of ownership or division of responsibility. Regardless of whether a simulation implementation like this is created by consultants or by internal specialists, there must be a clear plan regarding who is responsible for ensuring the model's rele-

vance and adequacy. Potential risks associated with unclear ownership may include expectations that developers will take on the responsibility for initiating updates and being available for all minor modifications. However, this can be problematic in cases where the model has been developed by consultants or a group of specialists within a global company like SKF. On the other hand, ownership should not necessarily rest with users if they lack sufficient expertise to make changes or to specify more comprehensive modifications in detail. The optimal solutions would instead be if the ownership was allocated to someone with an understanding of production software within the process development department, preferable with at least intermediate simulation experience. This role can thus serve as primary support for the main users and owners of the processes represented by the simulation implementation. Minor updates in OMP or in PlantSim can be made by this individual as they possess an understanding of the manufacturing process as well as foundational knowledge of the implementation. If the process owners signal the need for changes, the product owner may contact senior experts at a global level if necessary, who have expertise in the simulation tool and LCDP. The role of the product owner thus serves as a bridge between users and specialists for implementation.

4.5.3 Summary of Results from Workshops

The findings of the workshops with potential users and technical experts are presented and compared to each other in Table 4.5 The suggested user structure established to ensure continuous maintenance of the concept is presented and compiled in Table 4.6.

Table 4.5: Comparison of Workshop 1 and Workshop 2

Aspect	**Workshop 1 (Potential Users)**	**Workshop 2 (Technical Experts)**
Participants	Process Engineer, Production Supervisor	IT/OT Expert
Focus Area	Usability, ease of use, interface interaction	Technical sustainability, governance, and maintainability
Interface Feedback	Intuitive and self-explanatory	Clear and logical, but needs standardized user guides
Training Needs	Minimal training needed, but KPI explanations required	Emphasis on role-based documentation and instructions
Input Management	Excel was familiar and useful for data handling	Stressed future-proofing of data interfaces
Suggestions	Add Swedish language option, improve KPI clarity	Assign ownership to someone with both production and simulation skills
Perspective	Day-to-day operational use	Strategic, long-term system governance

Table 4.6: User Structure

Attribute	**Level 4 (Global Specialist)**	**Level 3 (Local Super User)**	**Level 2 (Strategic User)**	**Level 1 (Operative User)**
Simulation Expertise	Senior	Intermediate	Beginner	None to Beginner
Responsibility	Significant updates and technical support	Smaller Updates / Product Owner	Strategic end user / Process Owner	Operative end user
OMP Interaction	Designing interface	Update interface	End user / Process verification	End user
PlantSim	Building models	Minor updates	None	None

5
Discussion

This chapter aims to critically review and discuss the findings of the thesis project from multiple perspectives. It starts by comparing the project outcomes with the initially presented research questions. Furthermore, the methodologies and the execution of the qualitative study are then examined and discussed. Finally, the chapter finishes with recommendations for future research and areas for improvement.

5.1 Answering RQ1

The combined findings from the qualitative study emphasized the importance of a simple interface with a robust data flow, enabling users to benefit from the simulation model with little to no simulation experience. This insight shaped the first design criterion: making ease of use a cornerstone of the project. The simulation model, implemented using LCDP is currently presented only as a concept and has not yet been tested for practical application. Although it would have been challenging to quantify increased utilization through simple prediction, the workshops provided valuable insights. Feedback from potential users indicated optimism regarding the model's implementation. Since users are not required to have the simulation software or model installed locally, the system effectively reduces dependency on simulation experts. Instead, users only need to understand the simulation parameters and interpret the results, creating an environment where simulation experimentation can be conducted safely. In the long term, this could promote more frequent use of the model. However, the level of utilization is likely to vary among different user types. Those responsible for overarching processes may use the model less frequently than those involved in daily operations. By supporting a range of user profiles, the simulation model has the potential to gain broader organizational acceptance. This, in turn, could reduce the risk of obsolescence, as adoption across various departments with different usage patterns would sustain its relevance.

Furthermore, the findings of the thesis project relate to previous studies and research in several aspects. The thesis project established how domain experts often lack the software experience and skills required to maintain and manage simulation models. This is in line with previous research published by M. Dalibor et al. [9]. Moreover, the findings of the thesis suggest that the use of LCDPs is beneficial when it comes to increasing the accessibility and utilization of complex software among different user groups. These findings align well with previous research conducted by R. Sanchis [7].

5.2 Answering RQ2

The thesis project established five critical design criteria for integrating simulation models with LCDP for increased long-term utilization. The design criteria were formulated through interviews with stakeholders and literature reviews of existing research, the gathered data was combined and concatenated down to the final design criteria used for the thesis projects concept generation and final validation. After validating the final design of the concept via workshops to evaluate the degree of fulfillment towards the design criteria it was evident that results pointed towards potential successful long-term usage with the help of LCDP integration. The literature review and qualitative studies unveiled several important prerequisites when integrating simulation models and web interfaces with the intent of increasing long-term utilization. The level of IT/OT integration lays the foundation for creating concepts like the one developed during the thesis project. Gathering and storing production data is crucial to secure correct and usable input-data for simulation purposes and greatly impacts the outcome and reliability of simulation output. Furthermore, the higher the degree of data management, the easier and more efficient the development and results of digitalized solutions will be. Additionally, a framework aimed at creating clear governance and ownership was established based on the interviews, literature findings and workshops.

In relation to previous research there are both alignments and contradiction towards the findings of the thesis. Research presented by A.C. Bock et al. [18] suggest that development of LCDP applications could be delegated to non-developers within an organization. However, the findings of the thesis project rather claim that development and major updates should be executed by people with development skills and only minor updates or adjustments carried out by regular users. On the other hand the thesis findings resonate with F. Bachinger et al. [29] which emphasizes how clearly defined ownership to avoid obsolescence and ensure long-term usage is critical. However, contradictory to Bachinger et al. [29] who claims that simulations experts should be responsible for both deployment and ownership, the thesis suggests that ownership can be awarded to someone with only basic simulation training if a simulation team is ready to support during updates. The owner will act as a bridge between simulation experts and regular users. Moreover, commonly shared among several studies, maintenance and data management are crucial for securing long term usage. While A. Skoogh et al. [23] emphasizes that input data management is the most time consuming part of simulation, thus should be automated and well prepared. N. Robertson [28] and F. Bachinger et al. [29] highlights that automatic data flow is needed for using less resources and minimizing risk of data errors. This is also in line with the findings of the thesis which claims that an important prerequisite is well managed data preparations and data flows.

5.3 Reflection on Methodological Approach

The methodological approach played an important role for the outcome of the thesis project. By introducing standardized tools and structures our methodology can be considered as an important aspect of the realization of our concept [35]. Given the methodological impact it is of relevance to critically review the chosen strategy, and its effect on the results.

5.3.1 Reflection on the Results of Qualitative Study

The Qualitative study conducted during the thesis project consisted of interviews and literature reviews. For both areas guidelines and standardized strategies were established and followed to ensure conformity, reliability and repeatability [38] [40]. The results from the qualitative study laid the foundation for the concept development and answering of the thesis projects research questions. The interviews conducted as part of the qualitative study had a sample size of six people although the planned size was ten. The reason behind the lower amount of conducted interviews where mainly due to the time constraint of the project but also since it was determined that the six interviews provided sufficient information regarding the research areas. To interview more than one person with the same job could have strengthened the results but was not deemed crucial, since the purpose of the interviews where to investigate more general opinions on the topic. Furthermore, the interviews conducted were of high quality and provided a lot of substance, valuable experience and knowledge within the required areas. All of the interviewees were employees at SKF, either in global positions or local positions in connection to SKF Gothenburg. These two factors create a certain degree of unreliability of the outcomes of the qualitative study, firstly, since the possibility of company bias may affect the views communicated by the interviewees, lastly, the sample size was smaller than what previous research has deemed appropriate for the intended purpose of the gathered data.

5.3.2 Reflection on the Customized Project Methodology

The thesis work followed a constructed mixed project methodology given the wider scope of the thesis, both regarding simulation, and data management, CRISP-DM and Banks methodology where the foundation of the methodological approach given their common application areas [33] [34]. The integration of the two methodologies helped structure the project and guide it towards satisfactory outcomes [35] [36]. The iterative process of creating the concept was deemed a successful strategy since the adjustment and changes were often needed during the development phase. However, there were several other available project methodologies that could have been chosen for the constructed mixed project methodology, which may or may not have resulted in other outcomes of the project. In conclusion, it can be determined that the constructed mixed project methodology was suitable for the research area of the thesis but that other project methodologies could have been applied which could

have affected the results of the thesis.

5.3.3 Reflection on the Concept Evaluation

The evaluation of the final concept was conducted through interactive workshops with different stakeholders to create engagement among respondents, yield reliable data, and to jointly evaluate the design [49] [50]. Potentially there could have been more participants in the evaluation work shops to broaden the perspective on the insights. Furthermore, the time constraint did not allow for evaluating the concept during a deployment phase where operative capabilities could have been further investigated. In conclusion, the workshop provided valuable insights regarding the concepts, but additional workshops with more participants could have strengthened the reliability of the result.

5.4 Prerequisites for Implementation and Simulation Case Relevance

The results from interviews and workshops show that it is possible to replicate the LCDP integrated simulation model under certain conditions. Key among these are the availability and quality of data, the compatibility of the simulation model with standardized input data and a clear governance structure. In this case, SKF Gothenburg had a solid and well structured data set that enabled simple data management. Integration through Excel and SQL databases proved to be both flexible and user friendly, making it a replicable option provided that similar infrastructure is available. However, the ease of replication will decrease if IT/OT integration is missing. For example, if the implementation is expected to be carried out in a less prepared factory. In that case, the scope of the implementation would need to be expanded and the data may need to be compiled once more before the OMP.

The chosen simulation case of a heat treatment system at SKF showed clear relevance. It involved complex routing and long cycle times, which made it difficult to predict results without simulation and only with experience or calculations. This use case is exemplified where simulation integrated with LCDP can provide significant decision making support for process experts who can identify known risks and indicators of capacity limitations in the system in simulation scenarios. Being able to work with different production scenarios is essential in production environments with high variability. For production channels with a more linear flow that do not involve major operational or strategic decisions regarding product mix and work processes, it can be assumed that creating a similar implementation was redundant. An important advantage of the implementation is precisely that it can enable the simulation tool for people with process expertise rather than the simulations having to be managed by simulation experts who need to put more focus on experimenting with parameters and interpreting results.

5.5 Optimal Use Cases for Concept Implementation

The evaluation of the developed concept, including stakeholder interviews and practical tests, highlighted the conditions and environments where the LCDP integrated simulation model is particularly well suited. Identifying these optimal use cases is essential for guiding future implementations and maximizing the value of the concept. The concept proved to be useful and desirable in production environments characterized by high variability for example, systems with complex flows, long cycle times, or frequent changes in product mix. In such cases, simulation becomes a valuable decision support tool for predicting system behavior under various scenarios something that is difficult to achieve solely through experience or static calculations. The selected use case of SKF's heat treatment process illustrates this well, where simulation enables a better understanding of capacity limitations and system bottlenecks. A key prerequisite for successful implementation is a relatively high degree of digital maturity. Facilities with structured data collection processes and centralized databases, such as SQL, are better positioned to benefit from the concept. Since the concept heavily relies on standardized input and automated data flows, it is best suited for environments with well established ERP systems and a robust IT/OT infrastructure. In less digitally mature environments, implementation may require more extensive work in data standardization and system integration.

The flexibility of the LCDP concept allows for use across different roles with varying information needs. During the workshops, it became evident that production managers and process engineers, for instance, requested different KPIs and scenario configurations. Therefore, the concept is particularly suitable for organizations where multiple departments or professional roles collaborate in planning or process development. By enabling role specific interfaces or customized outputs, the system can provide targeted decision support for different user groups. Another suitable use case is in production sites that already possess simulation expertise. LCDP reduces the need for direct interaction with simulation software, making it possible for users at the local level to engage with the system efficiently.

5.6 Contributions of the Thesis

The significance of the results can be evaluated from academic, industrial, and sustainability perspectives.

5.6.1 Academic Perspective

The academic contribution addresses the gap in the literature concerning the integration of DES and LCDP. While both fields have been extensively studied individually, there is a lack of research on their combined use particularly in terms of suggested practices, advantages, and limitations. The findings of this thesis contribute to filling that gap by evaluating the establishment of a user oriented digital shadow and

analyzing the prerequisites necessary to achieve it.

5.6.2 Industrial Perspective

From an industrial perspective, particularly for SKF, the results can support more effective utilization of simulation models by a broad range of stakeholders, including process engineers, production managers, and operators. Improved user-friendliness reduces the need for extensive expertise when creating simulation scenarios. This enables simulation results to be more readily used as a basis for decision making, such as in production planning, recipe development, and process evaluation. Moreover, it promotes greater scalability of simulation technologies and may increase both acceptance and interest in simulation within the organization.

5.6.3 Sustainability Perspective

DES has in the past proven efficient at reducing waste in production environments and help create more sustainable production systems by its ability to evaluate and analyze alternative solutions [55] [56]. The generated concept can hopefully help SKF make more informed and efficient decisions in their production which may increase their energy and material efficiency, thus positively impacting the environment. In addition, as expressed during the workshops, the concept will probably have a higher utilization rate than normal simulation models which in turn may increase the positive effects.

The findings from the thesis project could potentially also be beneficial in the aspect of economical sustainability. The generated concept is, as previously explained, easily integrated with already existing simulation models. This could potentially increase the lifetime of already existing simulation models, that often are decommissioned rather soon after commissioning phases. Since simulation models could imply quite the investment to build, this effect may have positive financial impact given the increased utilization rate and the longer life cycle. If the concept is successfully incorporated in the company's everyday work, the cost savings from potential material reductions and energy savings might be noticeable as well.

5.7 Recommendations for Future Work

Although the concept presented in this thesis has demonstrated promising results, there are several opportunities for further development, refinement, and validation. The concept has been developed and tested in a specific use case at SKF. To evaluate its generalizability, future studies should implement and validate the LCDP integrated simulation model in other industrial environments particularly those with varying levels of digital maturity, production complexity, or organizational structure. As highlighted during the workshops, different user roles have varying needs for KPIs and simulation outputs. Future development could therefore focus on creating adaptive user interfaces that automatically adjust based on the user's role or purpose. This could improve the user experience and increase adoption across

different parts of the organization. Given the feedback regarding varying levels of English proficiency among operational staff, future work should also include the development of localized versions of the interface. This would improve accessibility and usability, especially in operator focused environments. To enhance maintainability and scalability, future work could focus on modularizing the simulation model. This would allow individual components to be updated independently and increase the system's resilience to changes in the physical process or production environment. Although the technical feasibility has been addressed, future work should also include an economic evaluation of the concept. A structured cost benefit analysis or return on the investment study could strengthen the business case for broader implementation within organizations.

6
Conclusion

This master's thesis investigated how LCDPs can improve the accessibility and long-term utilization of DES models in industrial environments. The case study, focused on a heat treatment process at SKF, revealed both technical and organizational opportunities for utilizing LCDPs to fill the gap between simulation models and operational decision makers with varying simulation expertise. Through a combination of literature reviews, stakeholder interviews, and concept development, the study identified development opportunities associated with traditional simulation model usage, lack of accessibility and risk of becoming obsolete. To address these issues, a concept was developed that integrated a Siemens Tecnomatix Plant Simulation model with the Mendix based OMP platform. The integration allowed for the development of a web interface that simplified user interaction, automated input data flows, and provided desired simulation outputs. The final implementation demonstrated that DES models could be made more accessible without compromising the accuracy or decision support potential. The validation, conducted through two stakeholder workshops, further highlighted the concept's usability and relevance. The potential users emphasized the clarity of the Excel-based input interface, appreciated the automation of data handling. Furthermore, they recognized the potential to conduct scenario analysis without extensive simulation experience. Feedback also emphasized the need for role specific KPIs, user adapted interfaces, and a clear ownership structure for sustainable long term usage. Findings suggest that such implementations are most effective in digitally mature environments with existing data infrastructure and organizational enthusiasm for simulation supported decision making. The concept's flexibility and adaptability to different user roles make it potentially scalable across departments and broader aspects of production planning and development.

In conclusion, the thesis shows that by leveraging LCDPs it is possible to improve and convey the use of simulation models in industry as well as reducing dependency on simulation experts. It also supports more frequent and informed operational decisions. However, long term success is highly dependent on robust governance, continuous model maintenance, and user centered interface development. These insights offer guidance for future efforts of integrating simulation technologies into operational and strategic industrial decision making.

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