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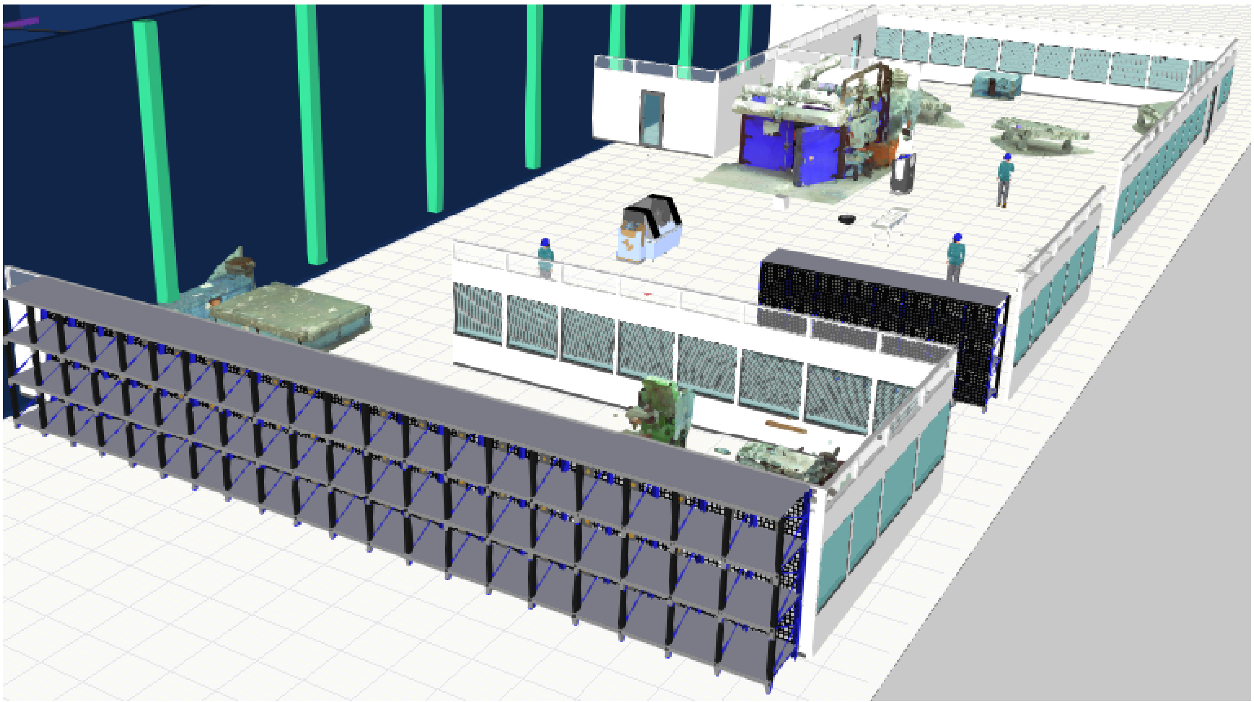

Using Discrete Event Simulation as a Step Towards Creating a Digital Twin

A Pre-Study for Creating Digital Twins in a Highly Labor-Intensive Production System Using Simulation Modelling

Master's thesis in Production Engineering

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Cover: The front cover illustrates a side view of the simulation model built to achieve a digital representation of the real-world system, for the sake of this thesis.

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Abstract

With Industry 4.0 emerging as the trend that is taking over the manufacturing industry, there is a rapidly increasing demand for industries to turn towards digitalization. The digital twin is a concept that has come to the forefront of digitalized systems and is supported by research that validates the advantages it can yield in the manufacturing industry. With research focusing on the abilities, advantages and disadvantages that digital twins possess, there seems to be a scarcity of focus in terms of the means to establish a digital twin. This thesis work proposes a methodology which identifies a step-by-step procedure for establishing digital twins. This methodology was built with reference to the digital twin levels of maturity which elaborate on the evolution of a digital twin from conception to an ideal state. The focus also lies on understanding how discrete event simulation can be used as a tool to support the process of establishing a digital twin. The proposed methodology was implemented in an industrial case study. The case study focused on building a simulation model of one of the production systems in focus. The simulation model was designed in order to support the first step in the evolution of a digital twin. The findings from this case study were then evaluated in order to determine the reliability of the proposed methodology for establishing digital twins.

Keywords: Digitalization, Digital Twins, Levels of Maturity, Discrete Event Simulation, Digital Models.

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Hitesh Narayana Atreya & Sathyajith Sridhar
Gothenburg, November 2019

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1
Introduction

This chapter provides an introduction to the master thesis in terms of the background to the topics followed by a brief description of the company and the production systems that are focused in the thesis. The chapter then provides the aim and objectives of the thesis and the research questions posed, finally concluding with the scope and delimitation.

1.1 Background

The ever changing needs of the customer markets pose increasing demands for better quality at lower costs. There is a need for manufacturing industries to keep up with the constantly changing dynamics of the customer market, in terms of both expectations and requirements (Rojko 2017). This pushes industries to turn towards new technologies such as automation and lean manufacturing, to cope with the need for improving product quality and variety while minimising the costs (Delkhosh 2012). With the help of new advancements in technology, industries are identifying ways to incorporate new technologies that push towards digitalization (Erol et al., 2016). The increasing customer demands require industries to re-evaluate their productivities (Wagner et al., 2019) as well to improve the level of efficiency in utilizing their resources and raw materials. Digitalization in the manufacturing industry yield numerous benefits, with the most critical benefits being in terms of productivity, safety, customization, costs and quality (Seebo 2019).

One concept under the broad spectrum of digitalization is known as the digital twin. A digital twin is a digital representation of a product or system. This representation portrays the state of the real-world product or system through a digital model (Rosen et al., 2015). The accuracy of these digital representations of the physical model determines the capabilities of a digital twin. A digital model that possesses the ability to enable collection of real-time data from the physical system (Rosen et al., 2015). The collection of real-time data for the digital model enables an accurate representation of the state of the physical system at all times. Connectivity and compatibility between the different manufacturing execution systems and the digital model can be essential when considering the digital twins. Digital representations of different phases of products or systems can be done with the help of simulation modelling (Rodic 2017). Digital twins can create opportunities for industries to increase productivities (Wagner et al., 2019) as well ways to improve the level of efficiency with respect to utilizing their resources and raw materials.

Simulation modelling is a tool that can be used to understand the production systems and their product flow. Simulation has moved from models that are analytical in nature whose primary goal is optimization to models that are integrated as decision support tools (Rodic 2017). Simulation provides the ability to evaluate the capabilities of production systems (Mohamed et al., 2014). A simulation model could be beneficial towards future development of integrated production systems. Strategic changes to production layouts, which involve significant financial investments, can be assessed thoroughly using simulation modelling prior to making changes in the real-world setup. Changes such as introduction of new variants/products into the production line, increase of takt time of the line and reduction in lead times can be implemented in the virtual model first to analyze their effectiveness in the manufacturing process.

The decision-making and production evaluation capabilities provided by simulation modelling enables its application as a tool in industries working towards improving productivity and reducing costs (Rodič 2017, Mohamed et al., 2014). The more complex production systems contain many variables and hence the decision-making process becomes more difficult (Mcafee et al., 2012). Complexity of a production system can increase depending on the level of manual labor involved within the production process (Mishev 2006). Another factor contributing to complexity in a production system is low production volumes, which means that the manufacturing processes possess large lead times and require highly-skilled manual work. High levels of manual labour in production systems make it more difficult to introduce automation (Jackson et al., 2016). The aerospace industry is one example of an industry where production volumes are low and manual labor is high. SAAB AB is a Swedish aerospace and defence organization focused on identifying new tools to evaluate changes their production systems. Introduction of new products, increase of takt time and reducing costs are the focus when it comes to the changes that need to be evaluated. Changes in the production layout, in the form of new workstations/machinery, has raised questions in terms of the changes in levels of productivity. At the moment there is no tool or system in place which aids in evaluating the productivity changes that will occur based on changes made to different production-relevant variables such as number of stations, personnel, product variants, sequences, etc.

The SAAB production facility at Linköping is the case company used to conduct this thesis, and will be referred to as the company for the remaining portion of the report.

1.2 Aim and Objectives

The aim of the thesis is to assess and analyse the process of creating a digital twin in a highly labor intensive production system. This thesis work will focus on the step-by-step procedure that can be taken to implement digital twins for a production system by following a project methodology. The methodology is based on the literature review followed by identification of problems in this scenario of creating digital twins. The project methodology is developed as an adaptation of several researches relevant to the field of digital twins. Once developed, this project methodology is applied to a real-world context with the help of a case-study to tackle practical problems and identify potential solutions to overcome them. The development and application of the adapted project methodology is to determine a better approach of creating digital twins for a production system involving high level of manual labour. This new approach can help reduce potential setbacks that may have occurred if standard practices would have been followed.

The potential use of modern tools such as discrete event simulation to enable an easier method for creating the digital twins is also part of the scope of this thesis work. This new approach to create digital twins of production systems could also enable a more sustainable approach to production in the future.

The research questions chosen after considering the aim and objectives to be achieved with the help of this thesis are as follows:

1) What are the steps to be achieved in order to establish a digital twin?
2) How can DES support the process of establishing digital twins?

1.3 Delimitations

The scope of this thesis includes studying two separate production systems at the company. No other department of the company are considered in detail for the sake of the thesis. In the process of creating the simulation model, the actual production with continuously changing data is not considered. Instead, a sample set of data regarding the production systems is obtained for building the model. Lastly, no cost analysis in terms of creating and implementing a digital twin are considered.

2
Theory

This chapter provides a theoretical background to the work done in this thesis. It contains a literature study covering the important topics and ideas that drove this thesis work under the broad framework of digitalization and simulation.

2.1 Digitalization

Digitalization is ushering in a trend which establishes an impetus on production systems that are re-configurable, which enable them to adapt their hardware and software interfaces in order to cope with the constantly changing requirements imposed by the market such as product design and quantities (Koren and Shpitalni, 2010). In such a manufacturing setup, the elements of the production system such as the product itself, the equipment and other active elements possess a virtual representation (Rojko, 2017). This representation is associated with data ranging from product information, 3D models, operational status and maintenance information to name a few. Due to the disruptive changes in customer demands created by new digital business models, an impetus on flexibility within production systems has been created (Enke et al., 2018). The Internet of Things (IoT) and automation are known to be drivers of digitalization as a concept and enable process digitalization which in turn, creates a foundation for an industry's digital transformation (Kagermann et al., 2013). One of the key factors to establish a flexible production system can be the implementation of an IoT integrated system (Lasi et al., 2014).

Digitalization can be used to reduce the level of physical human effort in production and simultaneously increases quality of products (Monostori et al. 2016). The markets are demanding innovations to be faster and products to have shorter life-cycles (Stoldt et al., 2018). From a long term perspective, industries need to stay competitive in this rapidly changing market scenario. Manufacturing industries often use lean principles such as continuous improvement to stay competitive in the market (Tóth et al., 2018). The concept of digitalization can drive industries towards their philosophy of continuously improving (Enke et al., 2018).

Digitalization helps create opportunities for access to real-time data which was a drawback in earlier production systems (Enke et al., 2018). With access to new and continuously updated data, a compromise in terms of production variables such as takt-time can be avoided. In industries that follow the make-to-order strategy and manufacture products in batches with the help of digitalization, the processes can be adjusted on an individual level without affecting the overall production process (Enke et al., 2018).

2.2 Digital Twins

A digital twin can be defined as "an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin." (Tao et al., 2017)

The digital twin concept has moved to the forefront in industry due to the rise of digitalization and the Internet of Things (IoT). An increase in digitalization when it comes to manufacturing has generated opportunities for expanding productivities and effectiveness of production systems. Digital Twins can be perceived as a concept which creates a digital representation of the various different areas of a products' life cycle (Rosen et al., 2015). With that being said, digital twins are not simply a collection of digital representations of different variables throughout a products' life cycle. They form a network of connections between the different digital representations which engage in information sharing as well as real-time data updates (Rosen et al., 2015).

The digital twin concept was first introduced in 2002 during an industrial presentation regarding product life-cycle management (PLM) at the University of Michigan (Grieves and Vickers, 2016). This concept was introduced in the context of two systems, one that exists in the virtual world and one that exists in the real world, being linked in order to continuously share data. The system in the virtual world is a system that represents, in the virtual world, the variables of the system in the real world (Grieves and Vickers, 2016). In essence, digital twins can be described as the digital equivalent of a physical product, resource, system, etc. These digital equivalents are used to describe and design the physical equivalent through digital data sets (Grieves and Vickers, 2016).

Traditionally speaking, static models of a system are constructed before the production phase. These models are likely to be independent from different phases such as design, production and maintenance (Bao, et al., 2018). In the modern dynamic environment, occurrence of multiple uncertainties could lead to the disruption of these static models. The digital twin model is a concept which expands the abilities of these traditional static models. It enables the model to communicate with all the different phases of a system, playing a key role in making design-based decisions as well as a validating the system as a whole (Rosen et al., 2015).

2.2.1 Digital Model, Digital Shadow and Digital Twins

Within the domain of digitalized models, the terms digital model, digital shadow and digital twin are often used interchangeably. But there is a difference between these three terms with respect to the data integration levels of the physical and the digital systems (Kritzinger et al., 2018). A digital model is a concept where the digital representation and the physical model do not undertake any automatic exchange of information. In case of a digital model, any form of information exchange is done manually. Digital shadows are different from digital models in that they enable a one-way flow of data from the physical model to the digital representation (Kritzinger et al., 2018). Any real-time changes that affect the state of the physical model will ensure that the change of state is depicted immediately on the digital model as well. Digital twins lie at a step above the digital model and the digital shadow in that it enables an automatic bi-directional data flow (Kritzinger et al., 2018). In case of digital twins, a change in the physical model due to its interaction with an entity, will lead to a change in its digital representation as well. On the other hand, the digital representation can also act as a controlling agent when it comes to regulating the physical model.

2.2.2 Maturity Levels in Digital Twins

A digital model or representation of a product or system can be at different states in terms of its capabilities. Based on their capabilities and functionalities, digital twin representations can be classified into four levels as can be seen in the figure below. These levels are also known as the digital twin levels of sophistication or maturity (Madni et al., 2019).

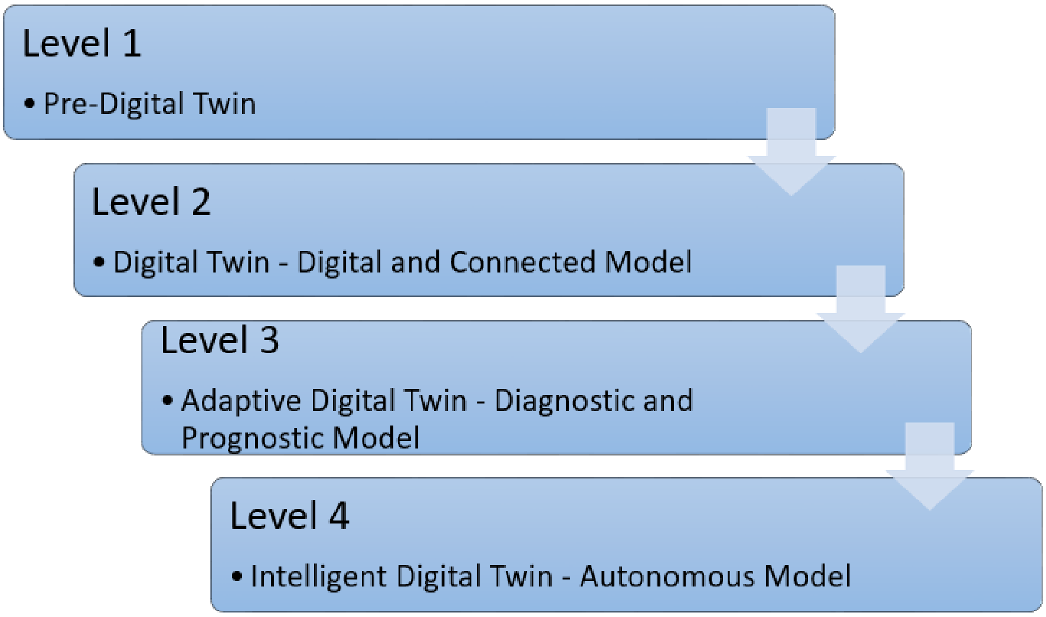

Figure 2.1: Levels of Sophistication or Maturity based on (Madni et al., 2019)

The first level known as the 'Pre-Digital Twin' is the level at which a physical system may or may not exist. At this level, a virtual model of an existing system or a system that is to be conceptualized is created (Madni et al., 2019). This is synonymous with virtual prototyping early in a design process. The second level is known as the 'Digital Twin'. At this level, a virtual model is created of a physical system that exists (Madni et al., 2019). This enables the virtual model the ability to incorporate data from the physical system. The third level is known as the 'Adaptive Digital Twin'. At this level, the digital model exists with an adaptive user interface (Madni et al., 2019). Bidirectional flow of information exists between the digital and the physical model. Sensors and IoT devices are used to maintain the connection between the physical and the digital models. The fourth level is known as the 'Intelligent Digital Twin'. At this level, all the capabilities of the previous levels exist with an artificial intelligence and reinforcement learning component (Madni et al., 2019). This ensures that at this level, the digital can monitor and control operations in an unsupervised manner.

A digital twin of a production system provides a detailed digital representation of the various sub-systems that comprise of the overall system. The representation depicts the system from the initial part stages all the way to the final assembly stages. The digital twins in the production sector provide a foundation for the next generation of intelligent/self-learning operation and predictive maintenance (Bao et al., 2019). With the onset of the next generation of technology involving modelling, simulation and optimisation, digital twins not only show the significance of simulation but also that of the continuous bidirectional connection that exists between the physical and digital streams of a production system (Sōderberg et al., 2017).

2.3 Production Systems

Traditional approaches of production systems that are dedicated to manufacturing a specific type of product find it difficult to cope with the changes in the dynamic market of today (Jackson et al., 2016). Changes such as introduction of new product variants, design changes, a production ramp-up, production disturbances, etc. pose a threat to the efficiency of traditional production systems. In order to cope with these changes, industries have turned to automation, new digital tools and connected IT systems (Jackson et al., 2016). This move has made industries move away from traditional fixed production systems to flexible production systems. In the aerospace sector, production volumes are low compared to industries such as the automotive industry and manufacturing processes require a large amount of highly-skilled manual work due to complexity (Jackson et al., 2016). This makes it difficult for the introduction of automation tools. In cases such as this, re-configurable manufacturing systems have been introduced (Koren et al., 2010). These systems possess the ability to cope with product and volume flexibility as well as the complexity in the production system. A key pre-requisite for the successful operation of these reconfigurable systems is a network of inter-connected data systems. These inter-connected systems aid in simulation, monitoring and controlling the variables that influence the operation of the production system (Jackson et al., 2016).

2.3.1 Production System Layout

The layout of a production system can have a significant impact on the productivity of the system (Gyulai et al., 2016). One of the first steps when it comes to establishing a new production system or re-designing an existing system is planning and analysing of production layouts (Watanapa et al., 2011). There have been multiple approaches and methods used to plan and analyse production layouts. Traditional methods involved physically drawing layouts based on variables provided by the different functional departments that comprise of the production system (Iqbal and Hashmi, 2001). The modern techniques involve using computer-aided design (CAD) systems to create and analyse models in order to understand their adoptability. The CAD systems themselves have evolved from 2D to 3D depictions (Iqbal and Hashmi, 2001). This evolution ensured that more variables can be analysed and in turn made for more accurate depictions. The 3D environment depicted by these CAD systems can help provide a different perspective in terms of interactions that take place between entities in the layout. By using 3D models to analyse a production layout, financial investments towards layout changes and proposals can be effectively justified. There are multiple benefits from using 3D models to analyse production layouts such as identifying bottlenecks, material handling flows, product flows and personnel interactions to name a few (Iqbal and Hashmi, 2001).

The design or re-design of a plant layout can be a technique used to improve the level of optimization of one or more of the material flows, logistics of the plant, or utilization of plant resources (Kühn 2006). Simulation models of production layouts are used to identify design problems as well as other potential waste in the layout prior to actual production. Furthermore, after production resumes, the simulation models can be constantly updated for realistic analysis of the system (Kühn 2006).

2.3.2 Production Planning and Control

Every production system can be planned before commencing the actual production work in order to optimize the process and achieve higher productivity throughout. The four steps seen from the Figure 2.2 can be the steps taken to successfully plan and control a production system.

Figure 2.2: Steps Involved in Production Planning and Control

The planning of every production system begins with gathering data regarding all resources available, all the products being manufactured and the processes involved in each. Once this data is collected, it is analyzed so as to obtain an optimal sequence of flow within the production system in order to achieve maximum productivity. Once an optimal routing is completed, the next step of planning a successful production system can be to schedule the processes within the production in order to optimize the production and determine the shortest cycle times for products (Du et al., 2015). Once the production actually starts, timely dispatching and following up with customers can be a very efficient manner of controlling the output from the production. Baldea and Harjunkoski (2014) suggest that integrating the scheduling and controlling of production can help reduce costs as well as optimize future operations.

2.4 Discrete Event Simulations

Discrete Event Simulation (DES) can be used as an effective tool to gather all the available input data and put them into a single format for future analysis and decision making (Golabchi et al., 2016). DES provides accurate results including outputs of the production system such as lead times, buffer capacities and Work-In-Progress, which can be used to optimize the production system. (Lindskog et al., 2012). Applying DES in change projects, such as introduction of a new layout, may also cause a disadvantage in terms of time consumed to collect the data and build the model for evaluation (Skoogh and Johansson 2008). 3D modelling has become more relevant in DES due to ease and preciseness with which the verification and validation can be performed (Rohrer 2000). Visualization of the models can be beneficial when it comes to DES because a clear graphical representation will ensure that the method used to communicate the results is more clear. Furthermore, visualization of models can help achieve credibility when it comes to simulation (Randell 2002). Verification and validation are two critical factors that support the importance of visualization (Rohrer 2000). An accurate visual representation means that comparisons with the real-world system and the verification of the simulation model can be made with ease (Rohrer 2000).

2.5 Point Cloud Data

The invention of 3D scanning technologies has made it a lot easier to depict an accurate visualization of a 3D structure, may it be a building, a machine, or a room inclusive of its inhabitants. Visualization in the form of 3D images can be produced with the help of scanning tools, which are used to capture millions of measurement points and when combined, form a point cloud (Nåfors et al., 2017). Capturing the measurement points involves a 3D scanner placed at different locations within the layout to be scanned which may or may not be pre-defined. The number and position of these locations are based on factors such as the size of the layout, the level of details required for the visualization and other scan settings required to scan the room (Nåfors et al., 2017). The accuracy of the layout to be modelled can be increased by performing the scanning in consultation with the production engineer (Lindskog et al., 2013). The overall image of the production layout can be used to take out parts of the layout such as a single CNC machine or any production machinery and saved as a separate point cloud file (Lindskog et al., 2013). Hybrid simulation models can be created using both point cloud files as well as CAD models by converting into compatible formats (Lindskog et al., 2012). This integration is very helpful while making accurate descriptions of production layouts, since it saves a lot of time and simultaneously provides good results (Lindskog et al., 2012). The use of hybrid models containing point cloud data while performing 3D modelling helps reach a wider audience by making it easier to interpret the information (Wiendahl 2003).

2.6 Research Methodology

This section of the theory describes the methodology followed during the course of the thesis including the procedure used to produce literature review, and further analysis of the literature to form the basis of the thesis.

2.6.1 Literature Review Methodology

The procedure described by Hart (2018) for conducting a literature review is used as the basis for this thesis. According to Hart (2018), performing a literature review is divided into two halves. The first half involves finding the literature that is relevant to the study at hand, while keeping the research questions and objectives of the thesis in mind. The second half involves reviewing the literature found earlier, to determine whether it is the right literature and also find out if it is sufficient for conducting the thesis. A suitable technique for structuring the literature found pertaining to the thesis so that it can be easily understood is by using the grid method, as described by Timmins and Mccabe (2005). Here, all the information collected pertaining to the topics of research are put into tabular formats so that the literature is categorized. Hart (2018) also agrees that putting the literature into categories makes them more organized and helps potential development of connections between different concepts. The process of categorizing the literature further assists in focusing on specific topics or subtopics which may be of higher relevance to the thesis (Hart 2018).

Writing a literature review can be a complex task, which can be made easier by using a strategic approach to identify relevant literature (Rowley and Slack 2004). Rowley and Slack (2004) describe the importance of having a solid literature review through the following points:

1) Identifying a new research topic of research gap, for future work.

2) Identifying the most relevant literature available in the field of research that is in focus. This can be followed by summarizing the research in a structured manner for future reference.

3) Building a solid understanding of the basic concepts surrounding the field of research in focus.

4) Proposing potential research methodologies that can be useful for future use in similar contexts.

5) Evaluating the results from the research, which can be followed by interpretation and explanation of the results achieved.

2.6.2 Case Study Methodology

Denscombe (1998) defines a case as something that *illuminates* the general by looking at the *particular*. Traditionally, a case is defined by its need for having a 'self-contained' entity and having 'distinct boundaries' (Denscombe 1998). A case study allows the researcher to experiment with different methodologies relevant to the topic and determine the best possible adaptation of a methodology or a combination of several methodologies (Denscombe 1998). This can help produce the optimal situation for the particular case study with respect to its variables and specific challenges.

According to Denscombe (1998), the advantages of using a case study approach to researches are as follows:

[1] Possibility of an in-depth study as a result of a detailed investigation on the topic of research, which is complemented by the researcher's focus in achieving the best results for that particular case.

[2] Higher focus given to relationships and processes as the researcher is usually more interested in understanding *why* things happen when compared to *what* happens.

[3] Taking a holistic approach to solving the problems, which can help the researcher understand *how* the different parts are connected to one another.

[4] Research is performed based on a naturally existing setting unlike a theoretical experiment wherein certain variables can be controlled to measure the impact of other variables.

According to Yin (2003), case studies are best suited to researches that require answers to the questions *how* and *why*. The purpose of a case study is to use the real-world scenario to arrive into theoretical propositions and ideologies. This means that case studies can be used to generalize the theories and not consider the determined results from the case study as absolute (Denscombe 1998).

2.7 Data Collection

This section of the theory presents the procedure used for collection of data followed by validation of the data and interpretation of the data. This section helps focus on achieving the objectives with the right usage of data.

Data Collection is an integral part of research studies. This enables the ability to answer research questions with credibility. The process of data collection can help gain a better understanding of the subject of research focused (Halcomb 2016). There are predominantly two sources when it comes to data collection, primary and secondary. Primary sources are classified as interviews and questionnaires, where there is direct contact. Secondary sources are classified as information obtained from books, journals and the internet.

According to Bryman and Bell (2011), the collection of data using interviews can be done either quantitatively or qualitatively. The most common form of interviewing being the quantitative interviews, which are generally structured and have little option of deviating from the set approach during the interview. In other words, quantitative interviews are more of pre-determined questionnaires to be answered by the interviewee (Bryman and Bell 2011). The process of interviewing can be done either in a structured, semi-structured or unstructured manner. During structured interviews, the questions are usually decided prior to the interview and there is little difference between the way how each interview is conducted. This method limits the freedom of answering for the interviewee but can be time-saving as the data collected is easier to process or categorize (Bryman and Bell 2011).

Unstructured interviews often have the interviewer less prepared and open for a healthy discussion relevant to the topic of the conversation. An advantage of unstructured interviews is that they can provide a great detail of information potentially useful for the interviewer but can be difficult to format the information for future use (Bryman and Bell 2011). A midway between structured and unstructured interviews is the semi-structured interview, where qualitative form of interviewing is performed but in a structured manner. This technique requires a certain level of preparation by the interviewer prior to the interview, with questions to initiate discussions regarding specific topics. An advantage of this technique of interviewing is that the interview can take different routes along the way depending on the answers provided by the interviewee. This possibility for openness in the conversation while maintaining the essence of the topic relevant makes it a powerful method of conducting interviews (Bryman and Bell 2011).

2.7.1 Data Analysis and Interpretation

Data can be available in abundance. This does not mean all the data is relevant in terms of the project at hand. Analysis of data can differentiate the relevant data from the non-relevant data and provides a better understanding of the collected data. The process of analyzing data ensures that the collected data is of good quality and provides more detailed information about the relevance of the data through description, explanation and interpretation (Denscombe 1998).

Interpretation of data is a process which converts the data into a suitable format so that the information obtained can be useful for the specific project at hand. This process of interpreting the data is done only after the level of accuracy required from the data quality is decided thoroughly. This is to ensure that the right amount of data is available before narrowing it down into a suitable format. Interpretation of data can also help in presenting the information in a more readable format, to make the concepts easier to understand by providing details such as time and reason for collection of data (Denscombe 1998).

Once all the relevant data is assembled, the information is seen from an overall perspective to summarize findings regarding potential patterns or similarities present within the data. These observations form the basis of what type of data is essential for the project work and to what extent (Denscombe 1998). The final step is to make certain decisions regarding the data, such as why this data helps answer the questions, or what type of additional data is required to successfully defend these deductions.

3

Methodology

In this chapter, the methodology and approach used to conduct the thesis is described. The chapter also focuses on the procedure used for collecting the data for the thesis and evaluate the better methods for doing the same.

3.1 Approach

The methodology chosen for the thesis project is shown in the Figure 3.1. The initial portion of the thesis involved construction of a framework for forming a base for the literature study and identifying the objectives of the thesis. The next phase of the methodology involved structuring of the literature review and summarizing its findings to lay a foundation for developing a suitable methodology to create digital twins. The fourth phase consisted of developing a methodology for creating a digital twin of the production system. The fifth phase was applying the methodology to help create a digital twin at the case company. The final phase involved analysis and discussion of the methodology proposed to create the digital twin and its evaluation within the case company.

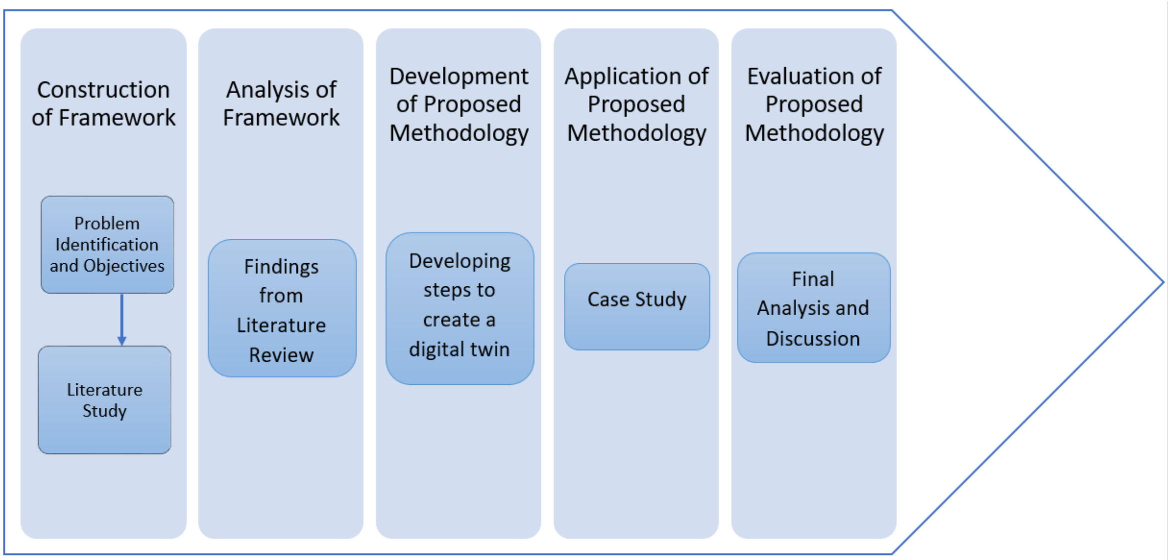

Figure 3.1: The methodology established for the thesis

3.2 Construction of framework

This section of methodology presents a foundation of the thesis by answering the first research question: *"What are the steps to be achieved in order to establish a digital twin?"*

3.2.1 Problem Identification and Formulation

The first step for any project is formulating a solid problem. The type of method used to run the project, the extent of research required for the project and what constitutes a satisfactory result at the end can all be connected with the problem identified in the beginning stages of the project (Shoket 2014).

Literature can be found regarding the concept of digital twins and their creation in a production environment. However, there is no single methodology available that has been tested in a practical situation for the creation of digital twins. The purpose of the thesis was to find the recent literature in terms of digital twins and their creation and adapt their findings to formulate a suitable methodology for creating the digital twin of a production system. Utilizing new literature in the field of using modern technology to facilitate digital twin creation, along with the help of discrete event simulation was sought after in this thesis. The problem identified was to increase the level of digitalization within the industry using the help of discrete event simulation by building a model of the production system.

3.2.2 Literature Study

Literature studies form a foundation to research projects, theses and dissertations (Salkind 2010). According to Gall et al. (1996), the purpose of having a solid literature review for a research project is to find new lines of enquiry, gain knowledge regarding methodological approaches and recognizing potentials for future researches. On the other hand, Hart (1998) recognizes other relevant aspects to having a good literature review such as identifying what is yet to be done in the field of research, improving vocabulary revolving around the topic of research and looking at different perspectives. The topics of research covered in the literature study for this thesis are primarily digitalization, digital twins and maturity levels of digital twins, followed by discrete event simulations. Other topics of research focused in the thesis are production systems, production layouts, production planning and point cloud data.

Rowley and Slack (2004) mention that building a concept map can help identify all relevant areas of focus and the relationships in between each focus area. A concept map can be a used to help the researcher understand the topics of research better (Rowley and Slack 2004). The concept map shown in Figure 3.2 was used to relate the different areas of research in focus as well as help identify literature in a more structured manner during the course of the thesis.

The peer reviewed articles used to formulate the literature study were found on

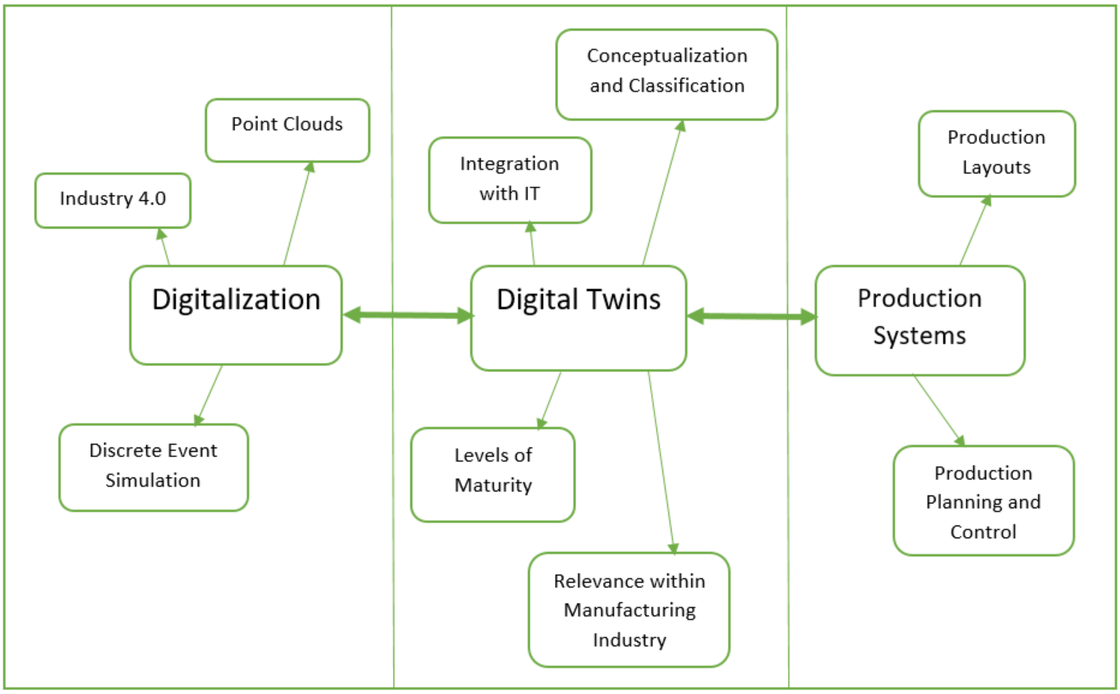

Figure 3.2: Concept Mapping used for Building Literature Framework

the database known as Scopus. As the focus of the thesis revolves around digital twins, the first stage of the literature review involved establishing a fundamental understanding of the concept. In this stage, focus was given to sources that described digital twins on a foundational level and studied the concept from a broader perspective. The subsequent stage of the literature review focused on identifying articles that connect digital twins to discrete event simulation. The literature study helped identify the different themes that are associated with digital twins and discrete event simulation thereby reinforcing the ability to answer the research questions of this thesis.

Peer reviewed articles at different stages were identified using the process of keyword searches on the Scopus database. Multiple keywords were used together in order to identify sources which elaborated on their connection. In order to identify the relevance of a peer reviewed article in terms of this thesis, the abstract and conclusion were studied carefully. Articles that were deemed relevant were then studied more closely. In order to find other sources for this study, the references of articles that were deemed relevant were scanned thoroughly. This method was employed to enlist many literature articles and research papers which either have a strong connection with one of the topics in focus or have some important information regarding the inter-connections between these areas of focus.

3.3 Analysis of Framework

This section represents the procedure used in categorizing all the relevant literature into tabular formats for easier reception of information. Once this categorization is completed, the findings of different literature are analyzed and compared. These findings of the literature were structured and interpreted in a tabular perspective to make the analysis part of the methodology easier. Further, this analysis of the framework was also assisted by the concept map drawn to retrieve better literature for the research, as shown in Figure 3.2. From the concept map and findings of the literature review, the problems within this research area was identified through analysis of framework. The analysis here refers to studying the different literature and summarizing their findings, which was followed by a comparison of different literature findings with respect to the same topics of research that are in focus.

The results of this analysis is used to provide a framework for devising a suitable methodology for the creation of digital twins thereby answering the first research question: *"What are the steps to be achieved in order to establish a digital twin?"* The analysis of this literature review acts as a base for developing a proposed methodology for conducting the thesis work.

3.4 Development of Project Methodology

This section of the methodology was used to develop a new method for creating digital twins of a production system. The development of the new method was specifically aimed at manufacturing industries with high level of manual labour within their production. This section of the thesis methodology helps answer the first research question: *"What are the steps to be achieved in order to establish a digital twin?"* and the second research question: *"How can Discrete Event Simulation support the process of establishing digital twins?"*

The challenges faced in a highly labour intensive production system are used to propose the new method for creating the digital twin. The proposed steps for creating a digital twin are mainly based on the findings from the literature review section of the thesis. These findings were then divided into certain literature themes and categorized based on the literature papers and articles that were relevant to these individual themes. The categorization of literature into themes brought more light onto the research areas in detail and made the findings more authentic.

The categorization of literature was performed in two stages. The first stage was revolving around the concept of digital twins and how other research topics surrounding them are inter-linked to one another. The second stage of categorization was performed to focus on digital twins in detail. The analysis of findings from this literature review helped develop the steps that can be taken to establish digital twins in production system. These steps proposed to create digital twins were an adaption of existing methods for digital twin creation in the form of levels of maturity, also known as sophistication levels of maturity.

3.5 Application of Proposed Methodology

According to Rowley (2002) and Sarah et. al. (2011), researches surrounding *how?* and *why?* questions can be better answered with the help of a case study in researches. According to Sarah et. al. (2011), the use of a case study can also help in new research fields, as they can provide certain inferences in theory development through existing research gaps. The use of a case study in this thesis can help uncover certain variables in the real-world and adapt accordingly the proposed steps to create digital twins within the real-world scenario. By using a case study for this research, the practicality of creating a digital twin of a production system can be understood, more specifically a production system with high levels of manual labour.

3.5.1 The case company

This section of the thesis methodology was used to establish the steps for creating a digital twin within a highly labour intensive production system at the case company, SAAB AB. The production systems relevant to this thesis work are the A350 production system and the honeycomb structure production system. These production systems at SAAB served as a good platform to test the adapted methodology for creating digital twins. Some of the unique attributes associated with these two production systems are as follows:

1) Both the production systems were highly process oriented.

2) The production volume was low, with the products having very high cycle times for production.

3) The process involved in manufacturing these products were highly manual and required high skill levels. This required some essential training before allowing the operators to work within these production systems. The high level of manual labour was due to the complexity of products being manufactured.

4) There was a very low level of tolerance for errors and quality of products was given utmost priority as they were later used in the aerospace industry sector.

5) The manufacturing execution systems used within these production systems are exposed to an abundance of data but lack the interface to collate the data and use it in order to monitor, maintain and continuously improve the system as a whole.

These factors relating to the case company and the production systems considered for application of the proposed methodology for creating digital twins provided a practical touch to the methodology and some tweaking of the methodology to adapt to the real-world situation. The process of creating digital twin for the production system at the case company is a long term vision. However, in order to fit the time-frame of 20 weeks given for the thesis, the focus was on creating a digital model of the production system as a step towards creating the digital twin of the production system.

3.6 Evaluation of Proposed Methodology

The findings from the case study were analysed to help answer the second research question: *"How can Discrete Event Simulation support the process of establishing digital twins?"* The evaluation of the proposed steps to create a digital twin of the production system at the case company was performed using this section of the thesis methodology. The methodology used to evaluate this practicality of the proposed steps for the creation of digital twins was through the use of observations during each stage of the thesis regarding both the methodology followed as well as the practical issues involved in applying this methodology to a real case situation. These observations were documented regularly and later analysed for getting further input regarding the adapted methodology. This analysis can be found in Chapter 6 of the thesis report.

The next phase of the thesis involved a discussion regarding the thesis methodology followed throughout the course of this thesis and whether or not it was a successful attempt in terms of achieving the thesis objectives as well as answering the research questions. Another important aspect discussed was the significance of using discrete event simulation in the case study, to build digital models of the production systems and their products. The problems arising in the real-world scenario despite following a structured methodology were also discussed in this section of the thesis. Finally, some sustainability aspects were also discussed with regards to the thesis, which was followed by potential future research aspects. These discussions can be read in detail in Chapter 7 of the thesis report. The analysis and discussion sections of the thesis also bring more light onto whether or not the literature findings and developed methodology for creating digital twins were reliable and trustworthy with respect to a research, and also with respect to applying them in a practical situation within the manufacturing industry.

4

Development of Project Methodology

This chapter introduces the learnings of the literature study and the different themes explored. This chapter provides a foundation for the proposed methodology that is built in the coming chapters.

4.1 Literature Review

The literature review conducted established a theoretical foundation for the process of creating a digital twin. The literature review explored different themes that were found to be relevant for this thesis work and the digital twin concept. The literature review focused on 24 peer-reviewed articles which were split into 6 broad themes, as can be seen in Figure 4.1. The categorisation of these themes was done in two stages. The first stage of categorisation involved the digital twins and its links to other important themes in industry.

Literature topics considered relevant for the thesis
T1: Digital Twins
T2: Input Data Management
T3: Digitalization in the manufacturing industry
T4: Industry 4.0
T5: Production Systems and planning
T6: Discrete Event Simulation

The two ideas that formed the basis of the research questions and drove this thesis were - establishing digital twins and the role discrete event simulation can play in establishing the digital twins. In the first stage of the literature review, the methodology focused on understanding the relevance of digital twins in the manufacturing industry. Multiple reviewed sources were used in order to establish a clear link between the concept of digital twins and how they are perceived in the manufacturing industry. A set of six themes were determined based on the different directions that peer review authors, of this literature study, followed in order to express the idea of digital twins. Multiple sources were used to explore each theme and establish authenticity.

Table 4.1: Literature topics reviewed during the course of the thesis

Author(s)	T1	T2	T3	T4	T5	T6
Bao et al. (2018)	X		X			
Bengtsson et al. (2009)		X				
Enke et al. (2018)			X	X		
Erol et al. (2016)				X		
Golbachi et al (2016)					X	X
Grajo (1995)					X	
Grieves and Vickers (2016)	X					
Gyulai et al. (2016)					X	X
Jackson et al. (2016)	X					X
Kagerman et al. (2013)			X	X		
Koren and Shpitalni (2010)			X			
Kritzinger et al. (2018)	X					
Kühn (2006)			X	X		
Lasi et al. (2014)			X	X		
Madni et al. (2019)	X					
Randell (2002)						X
Rodič (2017)			X	X		
Rohrer (2000)						X
Rojko (2017)				X		
Rosen et al. (2015)	X					
Schleich et al. (2017)	X					X
Sōderberg et al. (2017)	X					
Tao et al. (2019)	X					
Wagner et al. (2019)	X					X
TOTAL	**10**	**1**	**7**	**7**	**3**	**7**

With the focus of this thesis work revolving around digital twins, it was important to understand the fundamentals of the concept of digital twins, from existing and established research work. Ten peer reviewed sources were used in order to establish this understanding. Grieves and Vickers' (2016) research describes the origins of the digital twin idea as well as the importance of data and information. Madni et al. (2019) explored a different route which described digital twins in terms of its levels of maturity and Bao et al. (2018) focused on digital twins in terms of the manufacturing context. The importance of digital twins in the context of industry 4.0 and digitalization of the manufacturing industry was explored by Enke et al. (2018) and Kagerman et al. (2013). These different approaches and perspectives used by various authors provided a strong foundation for this thesis work.

The second categorisation of the literature study, as can be seen in Figure 4.2, delves deeper in to the concept of digital twins. This categorisation focuses on establishing a foundation of digital twins and its important facets. Based on the reviewed sources that focused on digital twins, 5 themes were identified which described the different facets of the concept of digital twins. The themes identified flow into each other which strengthened the foundation of this thesis work. Rosen et al. (2015) describes the digital twin concept in terms of its importance in the entire lifecycle of a product. Madni et al (2019) and Kritzinger et al. (2018) describe the classification of digital twin in terms of two different contexts but yet draws similarities. These reviewed sources were instrumental in developing a step-by-step method for creating digital twins. It was beneficial to understand the challenges faced with respect to the establishing digital twins and more specifically in the manufacturing industry as described by Schleich et al. (2017) and Wagner et al. (2019). The specific themes are as follows:

Literature topics within the field of digital twins
T1: Conceptualization of digital twins
T2: Classifications of digital twins
T3: Integration of digital twins with Information Technology
T4: Relevance of digital twins in manufacturing
T5: Challenges faced while establishing digital twins

Table 4.2: Literature topics reviewed specifically within digital twins

Author(s)	Digital Twins				
	T1	T2	T3	T4	T5
Bao et al. (2018)	X			X	
Grieves and Vickers (2016)	X		X		X
Jackson et al. (2016)			X		X
Kritzinger et al. (2018)	X	X			
Madni et al. (2019)	X	X	X		
Rosen et al. (2015)	X			X	
Schleich et al. (2017)			X	X	X
Sōderberg et al. (2017)	X	X			
Tao et al. (2019)		X	X	X	
Wagner et al. (2019)				X	X
Total	**6**	**4**	**5**	**5**	**4**

As the role of DES in establishing digital twins is the second research question, it was important to get an understanding of DES and its different characteristics. This helped establish how DES can be influence the process of creating a digital twin. Jackson et al. (2016) describes how DES can be used in the manufacturing industry and draws connections to digital twin systems. Schleich et al. (2017) describes the importance of virtual models in establishing digital twins. These peer reviewed sources served as a guide for this thesis work.

4.2 Findings of Literature Review

The results of this literature review showcased the relationship between digital twins and different themes that are relevant in the manufacturing industry today. The themes explored under the framework of digital twins can be found in Figure 4.2. This formed a foundation for the work done in this thesis work which aimed at exploring two research questions:

1) What are the steps to be achieved in order to establish a digital twin?
2) How can DES support the process of establishing digital twins?

Answering these questions begin with understanding the concept and the idea of a digital twin. Grieves and Vickers (2016) describes the digital twin from its origins in 2002 and how the concept has evolved through different definitions. Madni et al. (2019) elaborates the digital twins at a modular level and moves to the next stage of classifying the concept. The different stages of the digital twins are described through the levels of maturity or sophistication. This provides a foundation for the first research question and denotes, on a broad level, the various different stages in the evolution of a digital twin. Bao et al. (2018) and Rosen et al. (2015) explore the relevance and the impact of digital twins in the manufacturing industry. According to Rosen et al. (2015), digital twins in the manufacturing industry can open up opportunities to perform diagnosis, real-time planning and ability to deal with disturbances as well as a way to introduce a completely autonomous production system. This idea of ensuring an autonomous system draws parallels to Madni et al. (2019) referring to the levels of sophistication of digital twins where the final level is one which is autonomous.

The process of establishing a digital twin can be supported with the use of simulation according to Madni et al. (2019) and Wagner et al. (2019). Simulation is found to be a tool which is used to establish and evolve the process of creating a digital twin. Another finding from literature review is the importance of integrating Information Technology systems and their role in establishing and developing a digital twin. According to Grieves and Vickers (2016), digital twins require large amounts of data and communication technology. This is further supported by Madni et al. (2019) in the digital twin levels of sophistication which requires information technology systems to be inter-connected in order to maintain a continuous exchange/flow of data between the real system and the digital model of the digital twin.

The literature review also reflected on the challenges encountered in the process of establishing digital twins. According to Grieves and Vickers (2016), there are significant obstacles in the path of establishing digital twins. One such obstacle being the lack of connectivity between two departments, such as design and engineering for example, in an organization. This creates gaps between the information and the systems that govern these different departments. Another obstacle is the collection of data from the physical world. This can be seen as the connectivity between the physical and the digital system. This is echoed by Schleich et al. (2017) and Wagner et al. (2019) who state the existence of challenges in terms of collecting and gathering data from the physical system.

4.3 Proposed Methodology

The findings of the literature study provided a foundation for the work conducted in the thesis. The digital twin levels of sophistication acting as a reference prompted the identifying of the current state of production system at the case company. The literature themes specific to digital twins helped propose a methodology for creating digital twins of a production system and Chapter 5 presents this adapted methodology in detail.

5

Proposed Methodology for Creating Digital Twins

This chapter describes the findings from the literature study and aligns the findings in terms of the proposed methodology for this thesis. This chapter addresses the steps to be followed in order to establish digital twins as well as the role that DES has in this process.

The working of the production system can be essential to understand and determine what is required in the process of implementing a digital twin. The functionalities and the purpose of the software systems that govern the production systems can also provide critical information that influence the process of a digital twin creation. Identifying the current state of the production systems is one of the first steps in this process. This is made possible with respect to the maturity levels for digital twins. These maturity levels are based on the levels of sophistication of any given system, starting from a system that does not have a platform for the implementation of digital twins to a system that is completely controlled by a digital twin.

5.1 Levels of Maturity in Digital Twins

The extensive literature study resulted in a significant finding which shaped the progress of the work in this thesis. The digital twin concept was found to be defined through different perspectives by various authors depending on the questions that shaped the respective research focus. Madni. et al (2019), Kritzinger et al. (2018), Söderberg et al. (2017) and Tao et al. (2019) studied digital twins through different perspectives. These sources presented the evolution of digital twins in terms of maturity levels or levels of sophistication as well as through different phases of a product throughout its lifecycle. These different perspectives possess similarities in terms of evolution of the digital twin from its conceptual phase to a more advanced phase which is essentially self-supporting in nature. A common framework can be derived from these different perspectives. This framework can describe the different levels through which a digital twin evolves in terms of its capabilities and functionalities. The levels of the framework as can be seen in Figure 5.1.

- Level 1: Pre-Digital Twin
- Level 2: Connected Digital Twin

- Level 3: Diagnostic and Prognostic Digital Twin
- Level 4: Intelligent Digital Twin

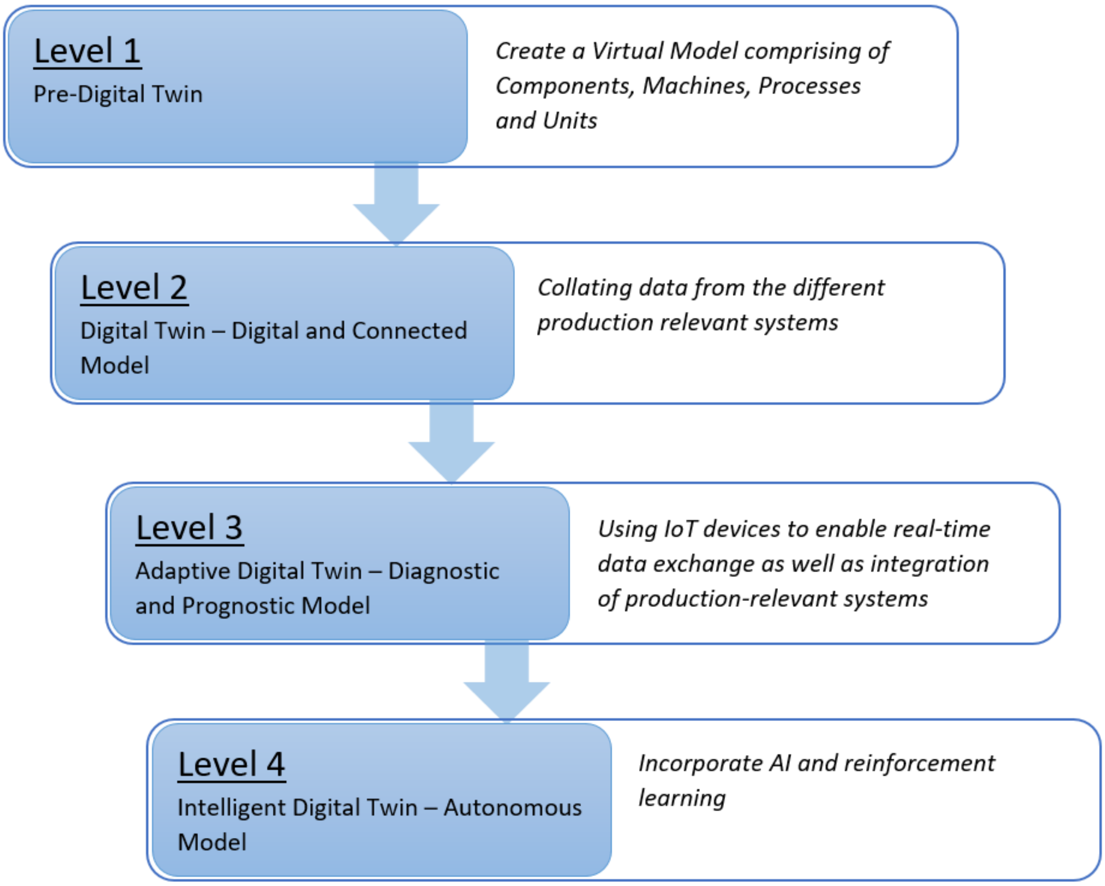

Figure 5.1: Maturity Levels for Digital Twins

In order to establish a digital twin, one of the foremost steps is to understand the current state of a physical system that is the target of digitalization. The current state of a physical system represented in terms of the levels of maturity provides a foundation for this process. This can, in turn, dictate the direction of the next subsequent step. The current state of the system can be determined by identifying the components of the system and their digital identities. It is also essential to understand the connectivity of the physical system with production-relevant systems such as the MES, ERP, etc.

5.1.1 Level 1: Pre-Digital Twin

The Pre-Digital Twin at level 1 of the maturity index is the level associated with a system where digital models are in place. In this framework, this is the first level addressed in the process of establishing a digital twin. According to Kritzinger et al. (2019), the key area of focus at this level is the creation of digital models. These digital models are replicas of the different components of a physical system. The physical system that is replicated at this level can be a system that is already in existence or a physical system that is in the early design stages. Madni et al. (2019) describes this level as being comparable to the concept of virtual prototyping. The digital models at this level can be simple models with the focus of replicating the key features and functionalities of the physical system. These digital models replicate each component of the physical system which includes both, the products and the resources. More specifically, digital models of the parts and assemblies that come together to form the final product, the machinery and equipment used in processing the product and the final product itself. In order to move to the next level of the maturity index, significant changes need to be made which forms the foundation for each subsequent level.

5.1.2 Level 2: Connected Digital Twin

Once a pre-digital twin is established, a foundation for the creating digital twins is established. Madni et al. (2019) suggest that the next step in terms of the levels of maturity focuses on establishing a connected model. This level is known as the connected digital twin which comprises of a digital and connected model. At this level, the digital model possesses the ability to collect and process data from different sources of data. The data can be from production-relevant systems or data acquisition devices such as physical sensors that monitor the physical systems. But, the data collected at this level is not continuously fed into the model through a real-time connection. The data is supplied to the digital model through batch-updates. According to Kritzinger et al. (2019), at this level, a change in the physical system leads to a change in the digital system because of the variation of the data parameters. But if there is a change in the digital system, is cannot affect the state of the physical system (Kritzinger et al. 2019).

At this level, the digital twin possesses the capability to support decision-making making process in terms of possible design changes of the physical system, identify optimal maintenance schedules as well as an analysis of the overall physical system. Production data for a specific range in time can be analysed through the digital model at this level. This data is fed into the model in batches. The analysis of production and the system is determined by the way the model behaves after feeding of the data. The type of data collected can range from process parameters of manufacturing processes to quality control data which can play an important role in determining production state of the system within a specific range of time. Data in terms of redesign of the production layout as well as production takt times can help identify potential improvements in the physical system.

Tóth et al. (2018) suggest that a digital model that is connect to the real system can be used to determine errors within production. Using digital models to identify such errors is quicker and it is essential to use the quickest way possible for determining production errors, in order to rectify them at the earliest (Tóth et al. 2018). Using the virtual counterpart to implement changes can increase quality of production planning and reduce the time required to plan the production (Lindskog et al. 2016). Essentially, the connected digital twin provides the ability to analyse potential investments, using the data from the batch updates, in the digital model before implementation in the physical system. This connected digital model provides a foundation for the next level of maturity.

5.1.3 Level 3: Adaptive Digital Twin

The next step in the maturity of digital twins is a diagnostic and prognostic model. Once the digital model possesses the ability to process data sets, the digital twin has evolved to a connected model. At this level, there exists a continuous connection between the physical system and the digital model (Madni et al. 2019, Kritzinger et al. 2019) . This connection is a bi-directional connection which enables the flow of information. The flow of information can be in terms of data acquisition systems supplying data to the digital model or the digital model sending out information in order to control the physical system. This level has the ability to monitor and control the the physical system through the digital model (Madni et al. 2019). The digital twin is connected to all the production-relevant systems through IoT devices such as sensors.

The adaptive digital twin has the ability to diagnose the state of the physical system based on the continuous real-time information exchange with the physical system. Besides this functionality, the adaptive digital twin also possess the ability to act as a prognostic model (Rosen et al. 2015). Tao et al. and Söderberg et al. (2017) suggest that, based on the different parameters input into the model, it can predict the performance of the physical system depending on how the change in parameters affect the system behaviour. It possesses the ability to predict optimal parameters in order to reach a specific target state of the physical system. Parameters such as changes in productivity, resource utilization and layout logistics can be predicted using this digital twin. The adaptive digital twin provides a foundation for the next level of maturity.

5.1.4 Level 4: Intelligent Digital Twin

The final level in the digital twins levels of maturity is known as the intelligent digital twin. Kritzinger et al. (2019) suggest that at this level, the digital model and physical system continues to maintain a connection that enables bidirectional exchange of information. This characteristic that differentiates this level with the previous level of maturity is that artificial intelligence and reinforcement learning are incorporate into the digital twin. The reinforcement learning continuously learns the patterns of data from the physical system thereby making this an autonomous model. The intelligent digital twin possesses the ability schedule its own maintenance as well as adjust and cope with any unexpected changes to production parameters. The benefit of this level of digital twin is that it requires no supervision due to its self-analysing nature.

5.2 Discrete Event Simulation within Digital Twins

This section of the chapter describes in detail how discrete event simulation can be used as a tool in reaching Level 1 of the Digital Twin as shown in Figure 5.1. The use of discrete event simulation for this purpose majorly comprises of its ability to create digital models of objects (in this case, models of the production systems and their components).

The very essence of a digital twin is the ability to produce a virtual equivalent of the real-world system. The rapid growth of technologies has led to high possibility of collecting data from the real-world through advancements such as data mining, deep learning and reverse engineering (Schleich et al. 2017). This can lead to quicker and reliable data collection in larger amounts (Schleich et al. 2017). By using this data collected from the real-world entity as input to the simulation models, accurate and realistic predictions can be made, which can further assist in planning day-to-day operations (Rosen et al. 2015). This method of forecasting based on simulation models and real-world data can enable establishing a digital model of the production system, which is a fundamental phase in the creation of digital twins (Rosen et al. 2015). Schleich et al. (2017) says that an essential factor governing modern manufacturing industries is their ability to predict the consequences of decisions made in relation with production processes and their products. A virtual model of the production system can provide the industry this ability of predicting the effect of their decisions.

Technological advancements within the concept of 'Industrie 4.0' like higher computing power, real-time exchange of data and IoT devices can provide new prospects in the field of data collection. The IoT devices such as sensors can help easier acquisition of data for better overall results from the simulation model (Schleich et al. 2017, Söderberg et al. 2017 and Söderberg et al. 2018). Schleich et al. (2017) suggest that there is a need for having at least an abstract model of the real-world system which comprises of all aspects of the physical counterpart including the entire product life-cycle. This model could fulfill the need for having a digital model in the creation of digital twins, which is the essential part connecting the virtual and physical counterparts.

Grieves and Vickers (2016) mention that the concept of digital twins can be used to design and test the virtual counterpart to predict the manufacturability of the designs as well as forecast their potential failures before it is actually manufactured in the physical system. In other words, a digital twin can carry out a role similar to that of simulation, in the sense that it can be used for future analysis and decision-making (Golabchi et al., 2016). Hence, a digital twin requires an accurate simulation model of the physical system in order to operate with its full potential. Simulation modelling can help predict the outcome and optimize the production system for future use. Building a digital twin can connect these abilities of simulations with real-time data (Botkina et al. 2018). In practical situations, building a simulation model can be a good first step towards creating a digital twin of the production system.

6

Evaluation of Proposed Methodology

This chapter represents the adaptation of the proposed method for creating digital twins to the case company, SAAB AB. The evaluation of the proposed methodology to create digital twins after considering the limitations of the real-world production and time restrictions are described in detail in this chapter.

6.1 Current Level of Maturity at SAAB AB

In order to understand the process of creating a digital twin for the production system, it was essential to understand the production system as a whole and the associated production-relevant software systems. With respect to this production system, there were primarily 4 IT systems that governed production were as follows:

1) Enterprise Resource Planning (ERP) system
2) Manufacturing Execution System (MES)
3) Statistical Process Control (SPC) data
4) Downtime Maintenance System (RS Production)

Interviews were conducted with different specialists in order to gain an understanding of the different IT systems in place. The connectivity between these systems and the compatibility of the data processed by each of these systems were important factors when creating digital twins (Madni et al., 2019). Although there was a connection between the ERP system and the MES system, it was strictly in terms creating production orders and to keep a track of their status. The maintenance system was used only at the CNC workstation in order to measure the amount of downtime and its productivity. According to the digital twins levels of sophistication/maturity, the first level is a system that has digital models of each component of the production system followed by a second level which ensured connectivity between the systems (Madni et al., 2019). This did not exist for the two production systems in focus which ensured that this system was not at level 1.

With respect to the case company in this thesis work, the maturity levels of digital twins is at level 0. This was determined based on the information collected about the A350 production system and the honeycomb production system. The lack of connectivity between the different production relevant systems and manufacturing execution systems, followed by the lack of a digital representation of the components of the production systems are two major reasons for the current state being at level 0.

The next step involved in establishing a digital twin involves identifying ways towards attaining the first level of maturity. One major pre-requisite for achieving the first level of maturity is obtaining a digital model of the real production system. The two production systems pertaining to the thesis were the A350 production and the Honeycomb production system. With respect to the A350 production system and honeycomb production system, digital models of the products do exist. But, models of the different workstations such as the manual workstations, the measuring machines that controls quality and the CNC machines do not exist and therefore need to be created. This would also involve creating a digital database of the manufacturing processes and their process parameters such as assembly operations, milling operations, measuring operations, etc. The production system used for this phase of the thesis work is the honeycomb production system. This production system was chosen due to the fact that data was more readily available.

6.2 Simulation model using DES

The goal for achieving the next maturity level for the honeycomb production system is level 1. In order to achieve this level, digital models of the various components of the production system need to be established. Based on the available data such as product variants, product flows and production times a model of the production layout is created with the help of simulation modelling. The approach used in this model building process begins with identifying a production sequence for the unique products flowing through the system. Due to the high number of variants, prerequisites in terms of sub-assembly and part precedence, changes to layout in terms of new stations/machines and bottlenecks in the system, a production sequence was established before the model building process. The next step involved creating the simulation model of the production system with the help of Discrete Event Simulation.

With regards to the production system at the case company, the simulation model needed a re-sequencing of the product flows to improve efficiency in production and stabilize the production schedule. The improved sequence of product flow would also help make the simulation model more accurate to the actual production.

6.2.1 Sequencing of Product Flow

The data collected from production personnel was broken down in order to create a production sequence. The information available regarding each of the machines and processes within the production layout were broken down into individual data sets. This was done by taking individual process times of each station and each product type, and assigning them with a priority level which determined how and when they have to be manufactured in order to achieve the highest efficiency.

Sequencing of the production flow was performed using Microsoft Excel. This process involved cutting down individual process times and re-assigning different time slots for their production. The sequencing was done in two parts - Sequence 1 and Sequence 2, each can be seen in the Figure 6.1.

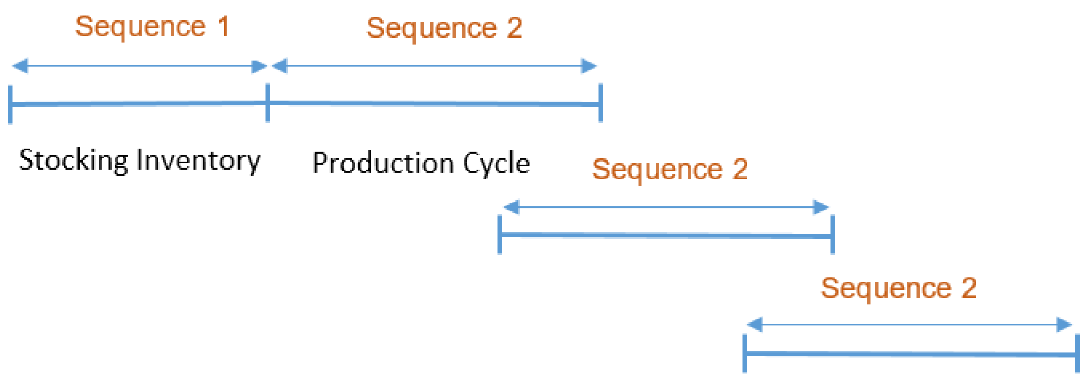

Figure 6.1: Sequencing of Product Flow Within the Production System

Two sequences as can be seen from the Figure 6.1, the first sequence is eight days in length and is used in order to stock up the buffer for Work-In-Progress with sub-assemblies. This sequence is very essential for meeting the overall production demand, and maintaining a buffer stock. Sequence 2 begins at the end of sequence 1. A more detailed explanation of how the re-sequencing of product flow was performed within the case company can be read in the Appendix 1 section at the end of this report.

The sequencing of product flow was re-structured in order to optimize the production and increase overall efficiency in order to achieve maximum productivity. Once the production sequence for one aircraft was scheduled, it was used as input to the simulation model.

6.2.2 Building the Model

For the process of building the simulation model, there was certain data available through the ERP system. This data included the volume and variety of different product variants being manufactured within the system. Other available data included the type of processes conducted in each station, amount of time spent by each product at each station, types of jigs/tools used in the production for each product type. The type of unavailable data included the number of production personnel required to perform these operations within the layout on a day-to-day basis, the level of skills required to perform individual operations in different stations, frequency of machine breakdowns, CAD data regarding the jigs/tools used for each product type or the CAD data regarding the individual product variants manufactured.

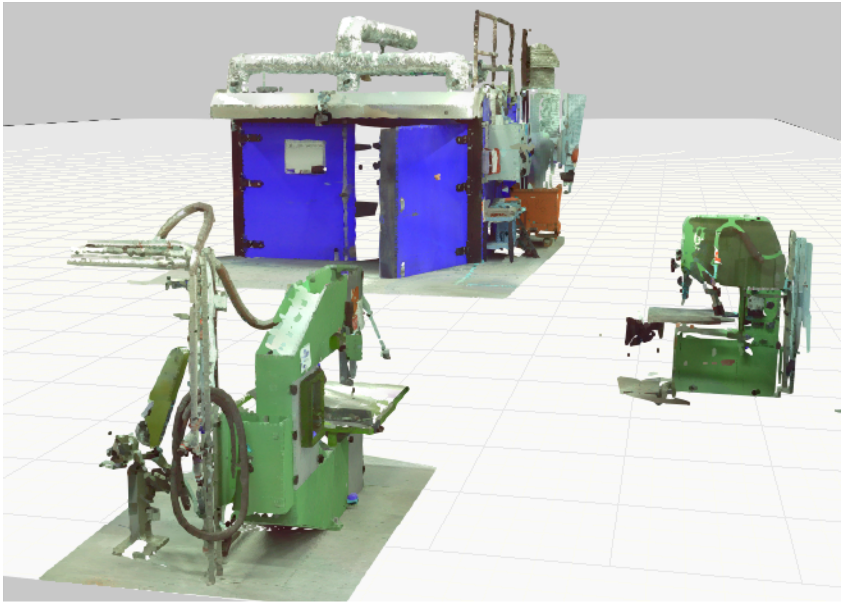

Figure 6.2: Sample Point Cloud images of Band-Saw machines and Curing Oven

From the available data, only necessary data which directly affect the performance and visual clarity of the model was used. Portions of the point cloud data available denoted the machinery used in the production. Figure 6.2 represents the point cloud images of the band-saw machines and curing oven imported into Visual Components. The available data in the form of CAD models and 3D point clouds were converted into suitable formats in order to incorporate them into Visual Components. The 2D CAD model of the production layout was compatible with the software and hence imported directly into it. The actual building of the model began after all the available and relevant data was successfully compiled into the software. Figure 6.3 represents the CAD model of the new CNC machine installed in the production system to increase productivity.

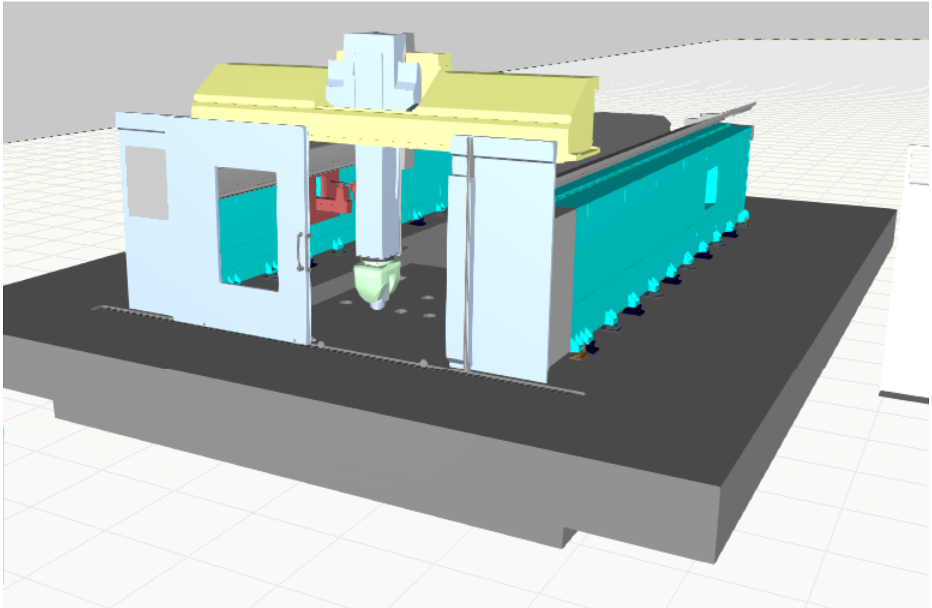

Figure 6.3: 3D CAD model of CNC machine

The procedure used to build the simulation model can be seen in Figure 6.4.

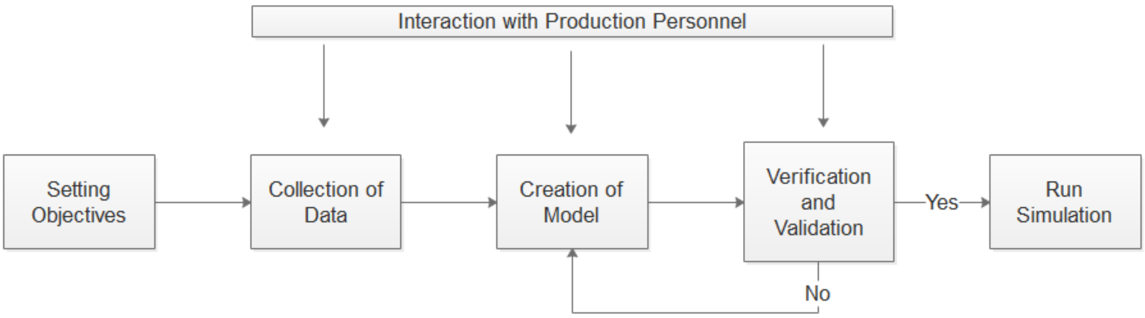

Figure 6.4: Model Building Process

The first stage involved setting clear objectives to be fulfilled using the simulation. The objectives were a means to understand why the simulation model was necessary. The next stage involved the collection and compilation of data that would be used as input for the model. The spreadsheets from the ERP system provided the necessary information for this step. The third and perhaps the most time consuming step for model building was to use Python API, the programming language used in Visual Components, to create the different stations within the layout. This was followed by creating the actual products that flow throughout the model and the automated vehicles used to transport these products in between the different stations as and when required. The storage units for the raw materials, Work-In-Progress parts, finished products were also built in suitable locations. This stage involved a process of continuous verification and validation with the production engineer and other decision makers of the project regarding the credibility and accuracy of the model being built when compared to the actual production.

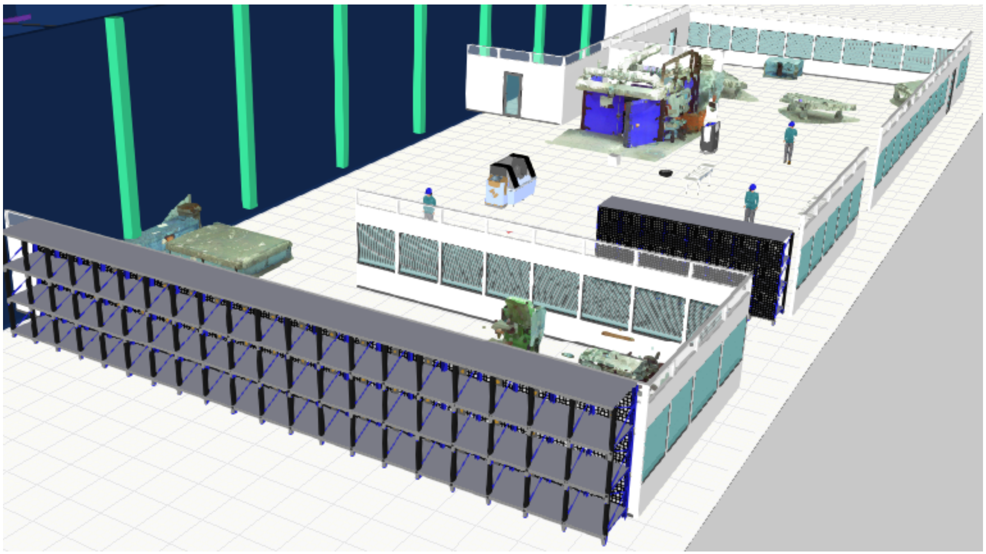

Figure 6.5: Simulation model of the Production System as seen in Visual Components

Figure 6.5 and Figure 6.6 describe images of the simulation model as seen from the software. Another means of validation of the model was to check for the visual accuracy of the animation in the model when compared to the actual production. This step was repetitive until the decision makers reached a level of satisfaction in terms of the simulation model. The final step was running the simulation model and extracting the results produced. These results were then used to check the capability of the production system to meet the future demands and recognize the bottlenecks of the system, followed by analysis of potential improvements suggested within the production to increase the productivity and meet the demand fluctuations.

6.2.3 Running the Model

The simulation model was used for two occasions: one for the production of one entire fin sub-part; another for following the production schedule of Day 1 of the production of both Sequence 1 and Sequence 2. The simulation model was built by creating the jigs of each sub-part of the aircraft as automated vehicles that move in between process stations. Each processing station of the layout such as the cutting stations (where the band-saw machines are located), curing oven, cleaning station (where bonding also takes place) and CNC machine are all created as works processes. Storage location for the products and raw materials are also created in the form of works processes. All human resources are created by directly taking from the library in Visual Components. Other common objects such as walls, doors and storage shelves are also taken from the Visual Components library. The code used to create the automated vehicles and process stations can be viewed in the Appendix below.

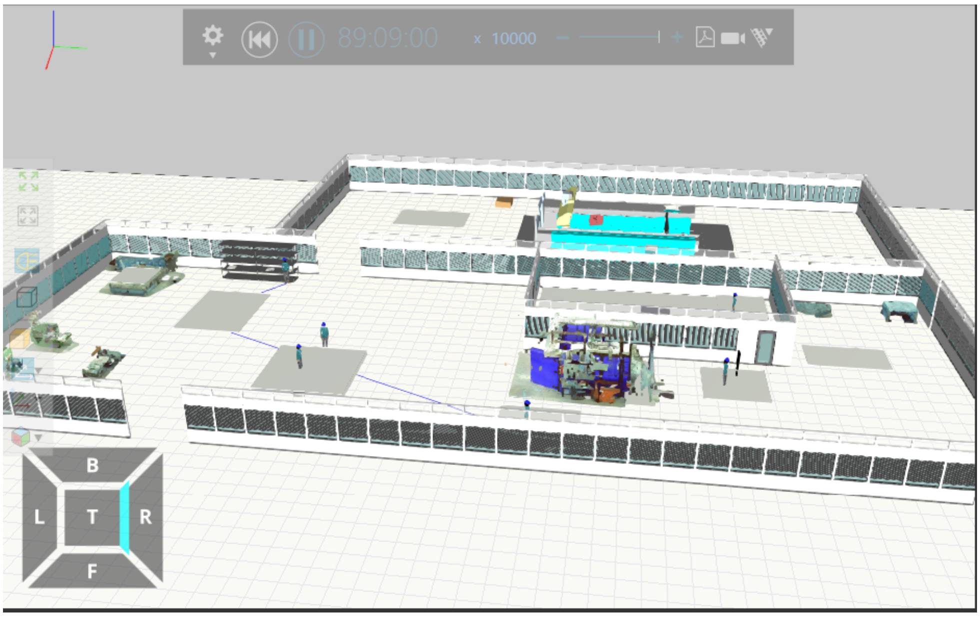

Figure 6.6: Side View of the Final Simulation model as seen in Visual Components

From the first production schedule, the bottleneck of the production system was found to be the CNC machine. The weekly schedule was altered by adding extra shifts on all five work days as well as a weekend shift to keep the CNC machine running. These changes were added into the sequence and the subsequent bottleneck was found to be the band-saw machine. A proposed change to install a new band-saw machine that could cut bigger pieces of raw material cores was analyzed, in order to cope with the bottleneck. This change resulted in optimizing the production but required additional manpower to run the band-saw machines. Another important change made to the production system was addition of extra workforce, followed by re-assigning the tasks within the production. One production operator was responsible for each of the band-saw machines, one operator was in-charge of the inspection tasks for all products, while the last two operators were in-charge of handling all other processes within the production such as assembly, bonding and pre-fitting. After several iterations, the bottlenecks were still found to be the CNC machine and the band-saw machines. However, the production capacity was increased to manufacture the desired production volumes as per the market demands.

6.3 Evaluation and Analysis

To produce a simulation model with higher accuracy, the model building process was performed with continuous interaction with the production personnel as shown in Figure 6.4. The reason behind this was to update the model based on their feedback so as to make it as close to the real-world scenario as possible. Coming to the analysis of the methodology used to create Level 1 of Digital Twin for the production system, it was recognized that there were little evidence of digital models for the production system as well as its individual components. Hence, simulation modelling was used as a tool to combine the available different variations of virtual representations of the production system and its components, and also to build a similar format of digital models for other components that do not have a virtual representation yet.

The methodology proposed in Chapter 5 for establishing Level 1 of Digital Twins is incorporated for this case study. The digital models of the production system and its components, machines and products built were shared with the production personnel and their feedback was used to make the models more accurate. This procedure followed during the case study can act as a reliability test for the proposed methodology in Chapter 5, especially for manufacturing industries within the aerospace sector and more specifically production systems involving high levels of manual labour, low volume and high complexity of processes. Further evaluation of the proposed methodology with respect to the case study in detail can be read in Chapter 7.

7
Discussion

This chapter discusses the methodology used for the thesis, the challenges faced during the thesis, how the proposed method for creating digital twins is suitable for the case company and evaluation of the proposed method. This chapter also describes other aspects such as sustainability and future research in the field of digital twins.

7.1 Thesis Methodology

The methodology used for the thesis was an adaptation of the levels of maturity based on findings of the literature found on research areas involving digital twin and its creation within the industry. These step-wise increments for achieving the highest level of digital twin of a production system was chosen because a clear foundation for each of the levels can be defined. Since the chosen adaptation of the method is for production systems with high manual labour, this method is not advised to be used directly for other production systems where mass production and automation are predominant. That being said, this procedure for creating digital twins can be adapted for a similar production system with high levels of manual labour by studying its current state and determining the current level of maturity of that production system.

Regarding the data management in the thesis, the procedure used to collect the data primarily being semi-structured interviews and focus-grouped sessions. These techniques of data collection made the validation process easier and significantly more trustworthy. The collection of qualitative data from these semi-structured interviews and focus-group sessions when combined with collection of quantitative data from the ERP and MES systems provided a solid platform for conducting the thesis in the desired methodology.

7.1.1 Case Company

The use of a highly labour intensive production system from the real-world as a case study helped in solidifying the developed methodology for creating digital twins. The case study provided authenticity in the form of real-world limitations, which re-routed the thesis towards using simulation modelling to establish a higher level of digital twin of the production system. Using a case study also gave an idea of the time-frame required to establish a complete digital twin of the highest level of maturity, which can be seen as a long-term vision rather than a quick introduction of new technology.

The thesis methodology was adapted to meet the requirements pertaining to the case company, which involved high levels of manual work. In case the industry chosen to implement this methodology was within the automotive sector rather than the aerospace sector, the methodology would have to be altered to meet this difference. For example, most industries within the automotive sector have higher levels of automation to cope with the very high demanding market scenario. In such cases, the current level of digitalization within the industry can be considerably higher. Therefore, establishing digital twins in such an industry can focus more into combining the different software systems as well as using the data collected to improve the overall efficiency in production.

Irrespective of the industry, the first step towards establishing digital twins, as per the proposed methodology in this thesis, is to identify the current level of digital twins within the industry. Depending on the industry chosen, the current level of digital twins can be used as a base to create higher levels of maturity. An important step in establishing the desired level of maturity is collecting all the data pertaining to the industry and recognizing what prerequisites of digital twins have already been implemented. This will help build a better picture of what needs to be done to achieve the desired level of maturity of digital twins.

7.2 Literature Study

The goal of the literature study in this thesis work is to establish a theoretical framework for the concept of a digital twin. Under this goal, the two research questions focused on the steps to be followed in order to establish a digital twin and how DES can be used to support this digital twin implementation. Peer reviewed sources were used to establish this theoretical framework. The sources collected during this review were segregated into different themes. The themes that were identified in a broad manner lay in between digital twins and DES. Themes such as digitalization and Industry 4.0 are themes that are associated with both digital twins and DES. It was also essential to establish a theoretical framework for research methodology in order to guide as well as validate the methodology followed in this thesis.

Addressing the research questions begin with understanding the the digital twin concept on a fundamental level. This was done with the help of multiple peer reviewed resources that studied digital twins from different perspectives that revolved around different research goals. Once the reviewed sources were collected, the sources were segregated based on their underlying themes on a deeper level and specific in terms of the digital twins. The themes in focus here studied the conceptualization of the digital twin idea through to the different classifications of the digital twins. The classifications helped in identifying the different levels that a digital twin achieves in its evolution from creation to an ideal state. During the evolution of digital twins through its different levels of maturity, integration and connectivity with other components of a system was found to be a significant learning. This expanded the literature study to include resources with research that looked at the importance of integration with different systems in a manufacturing set up.

7.3 Maturity Levels for Digital Twins

The research questions that were in focus for this thesis work involved establishing a step-by-step procedure to create a digital twin and using DES as tool to support this process. This step-by-step procedure was established through an extensive literature study in the form of the different levels of maturity for digital twins. Once this procedure was developed, it was found the production systems at SAAB that were in focus for this thesis work were at level 0. Bridging the gap between each level involves significant changes which are done in different forms.

Progressing through to each level creates a new base for an organization's digital transformation. The first step which is to reach level 1 is a significant step in an organization's digitalization. An organization at level 0 does not possess digital models of all of the production system components. Organizations that work mostly with 2D drawings of products fall under this category. With respect to SAAB, there are 3D models of the parts that are manufactured in the production system but no models of the other components of the system such as tools, equipment and the shop floor. Creating digital models of the components of production systems can provide benefits such as increasing operational efficiency and also aid in creating flexible work-space. This is rather a big step for an organization that is at level 0.

Moving from level 1 to level 2 involves establishing an inter-connected network of systems with the aim of connecting all components of a production system. This yields significant benefits as it provides that ability to monitor production through digital means as well as create a connection between the physical system and the digital models. This in essence is the idea behind the concept of a digital twin. The prominent characteristic of level 3 in the maturity levels of digital twins is the bi-directional connection that is established between the physical system and the digital model. This connectivity ensures a real-time exchange of information. External factors that affect the physical system can be monitored as it is reflected immediately on the digital model. In addition to this, any changes to the physical system can be performed through the digital model. These two capabilities signify the primary benefits of the digital twin concept.

The final level which is an autonomous model is characterised by artificial intelligence and reinforcement learning. The gap between level 3 and level 4 is characterised by the incorporation of artificial intelligence which ensures that the production system in essence is self-controlled and can perform self-analysis. An organization at this level possesses multiple benefits in terms of overall costs and efficiency. Significant cost reductions can be made in terms of labour costs and efficient maintenance scheduling. Efficiency in terms of productivities can be high. The ability to effectively reconfigure the production system signifies the flexibility that is beneficial in a dynamic market.

This thesis work suggested that the first step, in order to establish digital twins for the production systems at SAAB, was to achieve level 1 in the maturity levels for digital twins. With respect to the digital transformation journey at SAAB, moving from each level further reinforces their capabilities. A digital transformation journey provides flexibility in terms of adding new technological developments that are made in the future.

7.4 Significance of Simulation Model

The case study involved only two production systems at the case company, which might restrict the impact of its findings. However, the two production systems were behind in terms of digitalization and stood at level 0 of maturity. This section of the chapter focuses on the reason behind following the procedure of building the simulation model in order to benefit the case company, thereby bringing them closer to achieving the first level of maturity of digital twins.

7.4.1 Re-sequencing of Product Flow

While going through the process of creating the simulation model, an equally important step of planning the production sequence for the model was done in parallel. The production sequencing ensured that the model building process was on track with the actual production process. This process involved understanding different elements of the production system. As the number of variants that would flow through this system was high, it was critical to understand the different sub-groups of the products. As the parts produced in this system were for the final assembly of the jet, each sub-group of the products would join the final assembly at different stages. This would mean that a particular sub-group of products would have to flow through this system before others. The next factor that was crucial in this sequencing was the availability of labour. Each operator in the system had different skill levels. There were specific operators assigned to specific workstations or tasks. The availability of these operators at different times dictated the flow of the products as well.

Initially, in terms of the workstations there were two bottlenecks in this system - the CNC machine and the band-saw cutting station. During the layout change, an additional band-saw cutting machine was added to the station which ensured that CNC was the single primary bottleneck in production. The sequencing was done in two phases. The first sequence would contain parts that were essential for other larger products. The first sequence aimed at creating inventory. The second sequence was constructed with the preference to the larger products that would used the products made in the first sequence. When this was established the first sequence was added over the second sequence to ensure that production would flow simultaneously with the re-stocking.

7.4.2 Building the Simulation Model

During the model building process, the conversion of point cloud data into compatible formats for the virtual model not only assisted in creating visually accurate depiction of the layout and its components, but also saved a significant amount of time for model creation. The process of cutting specific pieces of the point cloud data took between 2 minutes to about 20 minutes, depending on the size of the point cloud data. Files containing large number of points took more time. This was because each time a point was selected for the cut or the orientation (along or about an axis) was shifted, the whole point cloud image refreshed. The jigs were an important part of the production since each product type was required to be mounted on a unique jig before entering the first workstation. Modelling of individual jigs and product types took a significant amount of the modelling time due to unavailability of actual CAD data regarding the jigs and fixtures. Once completed, each product type was routed to a specific set of processes as per the available information. The use of the point cloud data provided for a more accurate visual representation in terms of mirroring the real production system.

The production layout in this project involves high levels of manual labour and a high variety of products flowing through it. There are several risks involved in creating a simulation model of such a production layout. Some of them include unavailability of relevant data, collection of unwanted data, access to qualified personnel for validation of the model, procurement of data in specific formats, to name a few (Lindskog et al. 2016). These risks are often magnified due to the presence of certain factors present in the production system such as a change in scope. A clear mapping of information that would be required for the simulation was prepared before the model building process. This ensured that these risks were accounted for, should they exist. In cases where data was provided in different formats, a separate procedure was carried out in order to standardize the formats such as was done for the point cloud data. The point cloud data that was available was to be converted into a specific format in order to be included in the model building process.

7.4.3 Analysis of the Simulation Model

The simulation model was used in this project as a tool for manipulating the production system in order to understand the level of its capabilities. The model was first studied to assess its ability to meet the requirements that are borne out of the production ramp-up that is being planned. Beyond this, assessing the possibilities of re-routing the sequence of the production process proved to be of interest. The re-routing of production flow opened up possibilities to accommodate demands from other departments. This simulation model can act as a starting point for future changes to be made in the production, saving both time and money by first implementing the changes into the simulation model for validation. The simulation model was planned in order to represent the actual production layout in a virtual format in 3-D. This digital representation of the physical model using discrete event simulation can be a step towards creating a digital twin of the production system.

7.5 Sustainability Aspects

The purpose of the thesis is to identify steps for creating digital twins of the production system. One of the advantages of achieving the first level of maturity of digital twin within the production system is that the digital model present can be used to analyse potential changes to the production before actually implementing them in the real-world. This application of digital models can display the economic aspect of sustainability, since it saves the industry a lot of cost by evaluating the potential changes and predicts their effect on the production. Implementation of digital twins within the production system can increase the overall efficiency of the production thereby taking into consideration the environmental aspect of sustainability.

The sequencing of product flow, with respect to this thesis work, in the production system improved the overall efficiency and provided a basis for future scheduling of the production in order to cut costs. The simulation model following the sequencing of product flow also complemented in assisting the case company in economic and environmental terms.

7.6 Future Research

The future researches should consider the other pre-requisites involved in achieving the higher levels of maturity for digital twins such as installing IoT devices to enable simultaneous data collection and connecting the real-world production system to its digital replica to feed continuous data for maintenance predictions. There must be a more detailed analysis for adapting the levels of maturity for digital twin creation in production systems where the production quantities are low and lead times are very long. This would provide a better understanding of this method of creating digital twins and improve its applicability within real-world production scenarios. With regards to future researches specific to digitalization and digital twins, deeper understanding of these topics should be uncovered leading to a better version of the method for establishing digital twins, and thereby improving its standardization overall.

8
Conclusion

In order to cope with this dynamic market it is essential for organizations to move forward in the digital transformation spectrum. This thesis provides a methodology to establish a digital twin in a step-by-step process with each step being the foundation for the subsequent step. The methodology was developed based on the findings from the literature review and analysis. The proposed methodology was an adaptation of several previous researches in the field of digital twins, but more closely modified to suit the needs of a highly labour intensive production system.

The proposed methodology for creating digital twins is described in the form of levels known as the digital twin levels of maturity or sophistication. The process of creating a digital twin begins with analysing the current state of the production system in focus and to ascertain its level of maturity. An important aspect while establishing a digital twin involved creating a simulation model of the production system with the help of DES. The simulation model made using DES provides an overall picture of the production which can help analyse its drawbacks as well as advantages of the current production planning techniques. These applications of DES can be used to achieve the first level of maturity in creating a digital twin.

The next step after creating a simulation model is to integrate all the systems that govern the production system. Following the integration of all the systems, the next step would be to continuously update the simulation model with real-time data. The digital twin along with the simulation model can be used to monitor real-time production and simulate production scenarios. The final level of maturity is achieved with incorporating AI into the system to allow self-analysis, thereby creating an autonomous model. This level of digital twin can be used to pursue improvement through reinforcement learning. Building on each level of maturity will lead to industries expanding on the digitalization spectrum.

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A

Appendix 1

This chapter describes in detail how the sequencing of the product flow throughout the production system was performed.

A.1 Sequencing the Product Flow

The honeycomb structure production system contains both manual and automated operations. This system can be classified as a highly labour-intensive and high product variant system. The production of these honeycomb structures is a complex task due to the high quality standards needed as well as due to the complex material properties of the raw material cores used. This production system manufactures up to 128 unique products, which are required for one Gripen fighter jet. The overall production is complex and difficult to stabilize due the various process specifications and process times. The current production capacity cannot meet the required market demands that are expected to rise considerably in the foreseeable future. This means that the lead-time per aircraft should be improved to cope with this increase in demand. As a part of a production ramp-up plan, this production system has undergone layout changes in terms of restructuring of workstations and addition of new workstations/machines.

The IDEF diagram in Figure A.1 displays how an optimal sequence in production was determined for the honeycomb structure production layout.

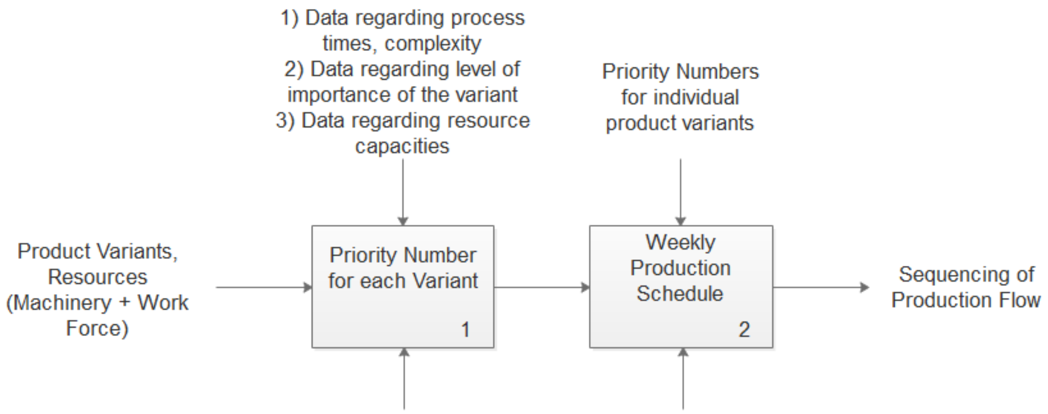

Figure A.1: Scheduling the sequence

As seen from the IDEF diagram, the data regarding individual process times, complexity and the level of importance given to the sub-part of the final product (the aircraft) were determined from discussions with the production engineer and data retrieved from the ERP system. Apart from this, all the information regarding each resource (both machinery and work force) within the production were determined based on observations and discussions with the operators on the shop floor. Based on this data, each product variant was assigned a priority number. These priority numbers determined when the products entered into the weekly production schedule. The process was repeated in a trial-and-error form, until the required product lead-time was achieved. To explain this, let us consider the example of production of one of the sub-parts of the aircraft, the fin. The fin is made up of 14 parts, cut individually from the raw material cores.

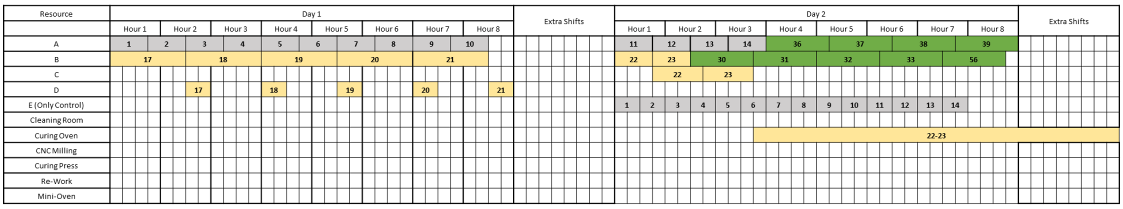

Figure A.2: Sequence 1 - Fin

The grey blocks numbered from 1 to 14 are the raw material cores cut by Resource A for the production of a fin. Each core takes 45 minutes to be marked and cut out from the raw material. These parts are then inspected by Resource E, who takes about 30 minutes per inspection. These are then stored in a Work-In-Progress storage unit until the next stage is resumed.

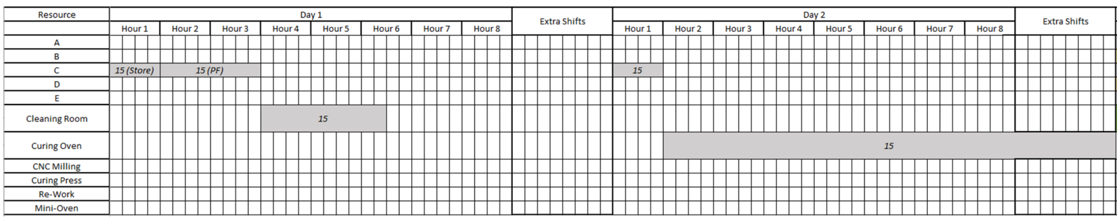

Figure A.3: Sequence 2 - Fin

The number 15 depicts a fin sub-assembly, which is assembled from the previously cut 14 parts. The fin goes through several processes before the final assembly and inspection. After this process is repeated for each of the high number of product variants and their unique manufacturing procedures, the final production schedule will include all the variants, each of whom have been given different colour codes to differentiate. A sample of the production schedule can be seen in Figure A.4.

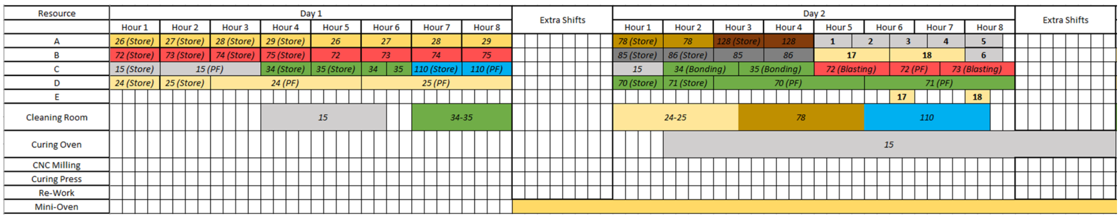

Figure A.4: Final Production Schedule - Sample

The sequencing was performed such that the priority to manufacture was given to the fin sub-part, followed by the canard wings of the aircraft. The third most priority was given to the inner wall cores of the aircraft.