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Digital twin for dynamic coordination of systems in complex and variable environments

A case study at KLM Engineering & Maintenance Component Services

Delft University of Technology

TU Delft

KLM Engineering & Maintenance

Digital twin for dynamic coordination of systems in complex and variable environments

A case study at KLM Engineering & Maintenance Component Services

by

J.B. Niers

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Preface

Dear reader,

In this report, you will find my graduation project to complete the Master's degree in Mechanical Engineering at Delft University of Technology. During this assignment, I had the opportunity to execute a case study within KLM Engineering & Maintenance. In this research, I aimed to develop a digital twin that supports process operators in coordinating a system in a variable and complex environment.

The past few months have been quite a journey. It was quite a challenge to find a suitable project in a company that is constantly in transition. Therefore, I would like to thank my supervisor Ronald Brouwer for giving me the opportunity to explore the interesting world of this aircraft MRO, and supporting me throughout the entire project with his expertise and view. Thanks also to Sascha Romeijn, for his support, feedback and extensive knowledge of all systems and processes within Component Services. But above all, thanks to the entire team for the pleasant time, which made me enjoy working with you.

Of course, I would also like to express my gratitude to my daily supervisor, Asst. Prof. Alessia Napoleone. Her enthusiasm and valuable insights helped me keep progressing throughout the process, even at the moments when I struggled to find the right research direction. Moreover, she helped balance the theoretical and practical value of this research. I also appreciate the visit to KLM. In addition, I would like to thank Prof. Dr. R.R. Negenborn for his valuable and critical feedback during the progress meetings.

Finally, I would like to thank my girlfriend, friends, family, and roommates for their support and interest throughout the project.

I hope you will enjoy reading this thesis!

J.B. Niers
Delft, February 2024

Abstract

This research explores the value of applying a digital twin in systems facing challenges related to variability and complexity, aiming to develop and validate a digital twin concept that supports process operators in dynamically coordinating these systems. The research is a theory-oriented case study within the Component Services (CS) department of KLM Engineering & Maintenance (KLM E&M). KLM E&M is a Maintenance, Repair, and Overhaul (MRO) company that operates as a subsidiary of Koninklijke Luchtvaart Maatschappij / Royal Dutch Airlines (KLM) and is responsible for the technical condition of the aircraft fleet. The scope of the research is CS, a department focused on the availability, repair and logistics of aircraft components. The availability of aircraft components is directly influenced by the time between an operable (Serviceable (SE)) component is delivered to a customer and the returned inoperable (Unserviceable (US)) is repaired and placed in stock. Therefore, CS is constantly looking to make the supply chain of aircraft components more efficient and reliable. Part of this supply chain is the Logistic Handling Area (LHA), where incoming goods from different external parties are handled, inspected and distributed to other internal or external parties. The case study of this research is focused on this area, as this area is confronted with lower performance than desired, leading to challenges in the availability of aircraft components. While the company has identified various reasons, the main research problem is linked to the system's variability and its ability to adapt effectively. Consequently, this research aims to explore the role of a digital twin in supporting process operators to dynamically coordinate systems within a complex and variable environment. The research is executed according to the DMADV (define, measure, analyse, design and verify) methodology.

Besides the problem definition, the *define* phase also includes a literature review. The literature review revealed that the supply chain in the MRO industry is indeed characterised by variability. This variability arises from the wide variety of goods within an aircraft, together with the fluctuations in demand. This results in variability in input into the individual supply chain process steps, and the required processing time per component. To avoid buffering of time, inventory or capacity, effective and adequate managing available resources is required. Within the literature review, the possible value of digital twin applications is researched. A potential research gap is found related to the short-term dynamic coordination of systems in complex and variable environments by using a digital twin. In the *measure* and *analyse* phase, the current state of the LHA is assessed, giving insight into the issues the system encounters. Through observations of processes and analyses of inflow, together with performance evaluations based on Key Performance Indicators (KPIs), it can be concluded that variability in daily inflow and processing times significantly impact operations. The complexity and dependency of the processes and the absence of integral coordination among departments further strengthen operational challenges. The disturbed operation results in a lower performance represented in a large number of goods waiting (Work In Progress (WIP)) and a significant total handling time within the LHA (Turnaround Time (TAT)). This lower performance cannot be assigned to specific tasks, as there are many bottlenecks within the process.

The objective during the *design* phase was to bring the challenges identified in the literature review and the analysis of the current state together with the potential benefits of a digital twin. By taking advantage of its descriptive and predictive capabilities, digital twins may prove beneficial in improving operational coordination. Considering the existing processes within the LHA system, a comprehensive layout is developed. This layout is intended to support process operators to dynamically assess system performance across the past, present, and future. To achieve this, the inputs, constraints, and resources are identified. The data of these elements serves as input for the digital replication, which, when combined with the proposed layout, generates outputs and a certain performance. The performance assessment, aligned with the KPIs, need to support process operators in making deliberate decisions during the operation. The developed design is transformed into a verified and validated digital model by Discrete Event Simulation (DES). This simulation enabled the possibility of assessing the value of the digital twin.

The last phase, the *verifying* phase includes a value assessment. This assessment first proved the impact of variability on the output of the system. Both variability in daily inflow and processing time results in uncertainty and fluctuations in outflow, leading to difficulties in the other steps of the supply chain. This impact is strengthened if the backlog of goods waiting is decreasing. The developed digital twin concept has to deal with this variability. The value is distinguished into three parts: (1) real-time monitoring of KPIs; (2) dynamic testing of need-based resource allocation; and, (3) integral operational target setting. The first value offers the possibility to quickly evaluate the performance of the system by calculating KPIs, which is valuable in a complex process with many dependencies. Additionally, dynamic testing with a digital twin is crucial for stably reaching KPI objectives, especially in processes where these objectives may fluctuate over time. The last value refers to the integral coordination that is important to get the desired output. This prevents backlog shifting within the system. However, the value related to variability arises from the three individual values executed in a continuous loop. By continuously monitoring the input and output of individual tasks and the entire system, the possible effects of variability can be identified and the operator can adequately react. If a mismatch between input and output in individual tasks is observed, a new resource allocation can be assessed by the developed digital twin, taking into account all dependencies and constraints in a complex system. This prediction of future performance by using KPIs can be translated into operational targets for the individual departments. After the implementation of a new resource allocation, the decisions and targets can be evaluated by monitoring the system. To conclude, the developed digital twin can support process operators to dynamically coordinate a system to create a predictable and stable outflow, which is helpful in a system that faces complexity and variability.

List of abbreviations

AFKLM Air France Koninklijke Luchtvaart Maatschappij

AFI Air France Industries

AHA Automated Handling Area

CLSC Closed-Loop Supply Chain

CS Component Services

DES Discrete Event Simulation

FIFO First In First Out

IIG Inspection Incoming Goods

KPI Key Performance Indicator

KLM Koninklijke Luchtvaart Maatschappij / Royal Dutch Airlines

KLM E&M KLM Engineering & Maintenance

LHA Logistic Handling Area

LSP Logistic Service Provider

MHA Manual Handling Area

MRO Maintenance, Repair, and Overhaul

OAM Original Aircraft Manufacturer

OEM Original Equipment Manufacturer

OTP On Time Performance

SE Serviceable

TOC Theory of Constraints

TU Delft Delft University of Technology

TAT Turnaround Time

US Unserviceable

WIP Work In Progress

WMS Warehouse Management System

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DEFINE

1 Introduction

In this chapter, the introduction of this research is described. First, the research context (1.1) and research field (1.2) are presented. Then, the research problem from KLM and scientific perspective are addressed (1.3), together with the research scope (1.4). These elements are translated into the research objective with deliverables (1.5) and the research (sub)questions (1.6). This chapter ends with the methodology and structure of the report (1.7).

1.1. Research context

The aeronautical industry places the highest importance on safety, which is achieved through the implementation of reliable practices throughout aircraft development, operation, and maintenance. MRO activities within this industry play a crucial role in ensuring this safety. These activities encompass a wide range of tasks that aim to mitigate the effects of ageing and wear on aircraft structures, components, and engines during their operational lifespan. Maintenance activities can be broadly categorised into three types: preventive, predictive, and corrective maintenance. Preventive maintenance is performed at predetermined intervals, often based on the number of flight hours and cycles (completed take-off and landing sequence). On the other hand, corrective maintenance is carried out in response to unforeseen failures in the aircraft. Predictive maintenance, when implemented as a proactive strategy, serves as a valuable tool for anticipating and predicting potential failures. By effectively managing maintenance tasks, it significantly contributes to minimizing aircraft downtime and positively impacting overall safety levels [1]. While aircraft development is primarily executed by Original Aircraft Manufacturers (OAMs) like Airbus, Boeing, and Embraer, these companies are relatively underrepresented in the MRO market. This market gap is filled by external MRO companies, often affiliated with airlines, which receive support from OAMs, Original Equipment Manufacturers (OEMs) and system suppliers [2]. Considering the predicted substantial growth of the airline industry over this decade, the global aircraft fleet size is expected to experience significant expansion. Between 2020 and 2030, it is estimated that the in-service fleet size will increase by 3.4%, surpassing 40,000 aircraft worldwide [3]. This growth in fleet size will lead to a higher demand for service at MRO companies. However, intense global competition significantly influences the business environment of MRO companies. Additionally, more robust aircraft systems and improved materials and designs result in less required maintenance per aircraft [4]. This competition and quality improvement force MRO companies to find solutions to remain profitable.

One of the aviation MRO companies that acknowledges these challenges is KLM Engineering & Maintenance (KLM E&M). Operating as a subsidiary of Air France Koninklijke Luchtvaart Maatschappij (AFKLM), KLM E&M primarily focuses on maintaining the fleet of Koninklijke Luchtvaart Maatschappij / Royal Dutch Airlines (KLM) and conducting engine and component maintenance and overhauls for various other airlines. KLM E&M actively collaborates with their partner company, Air France Industries (AFI), sharing their expertise and task portfolio. Within the different departments of KLM E&M, employees are constantly looking for business improvements. The departments will be explained in section 1.2.

1.2. Research field

This research is conducted at the Delft University of Technology (TU Delft) as the final assignment for the MSc Mechanical Engineering with a specialisation in Multi-Machine Engineering. The research is based on a case study at KLM E&M in collaboration with the Data, Transformation & Continuous Improvement team. Within the KLM E&M company, there are three main departments, as visualised in Figure 1.1: Airframe, Component Services (CS) and Engine Services. This research is focused on the CS department, as highlighted in blue. CS is responsible for the availability, maintenance and logistics of aircraft components, both for KLM's fleet, as well as for more than 50 other customers worldwide. The main location of CS is located at Schiphol-East, part of Amsterdam Airport Schiphol, where the other facilities of KLM E&M are also based. The research is related to the processes of the Logistics and Supply Chain Operations departments.

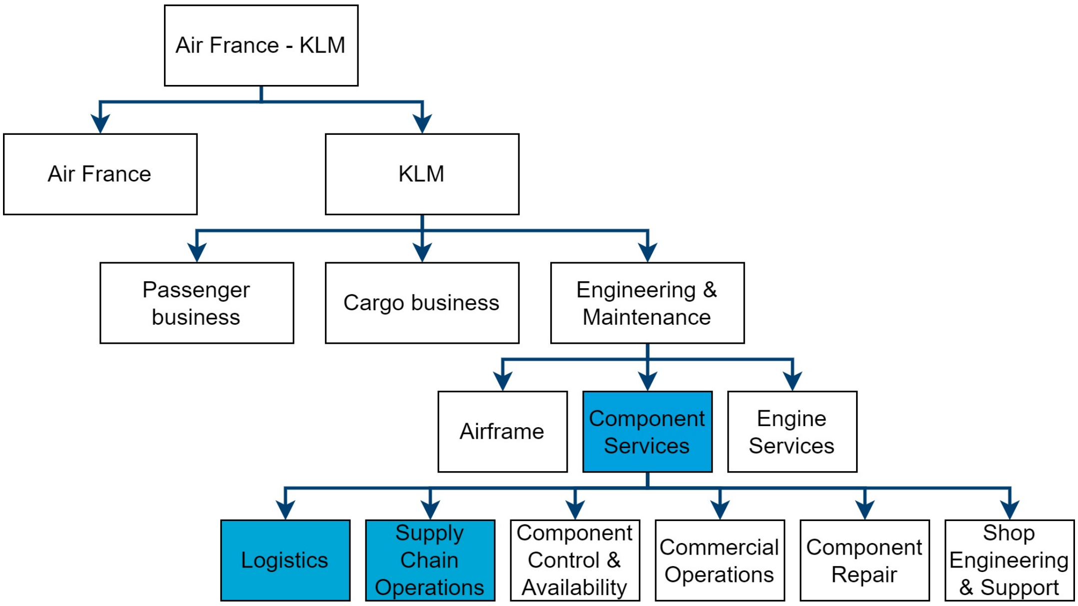


Figure 1.1: Simplified overview of the Air France - KLM organisation

1.3. Research problem

This section is divided into two aspects to define the research problem. First, in subsection 1.3.1, the reason for the research will be addressed, approaching it from a KLM E&M perspective. Subsequently, in subsection 1.3.2, the problem definition will be described, taking into account a scientific perspective.

1.3.1. Reason for the research

Airline operators must maintain a constant focus on maximizing the utilisation of available resources, particularly their fleet of aircraft. This highlights the importance of safe and reliable maintenance, while also striving for minimal downtime. This puts pressure on the performance of MRO companies, also faced by KLM E&M. To minimize downtime due to repair, various components (assembly of parts) within an aircraft can be replaced with a functional, Serviceable (SE), alternative whenever they become inoperative, Unserviceable (US). Because of the high value of these components, many of them will be repaired after removal, to ensure their suitability for installation in another aircraft. This results in a Closed-Loop Supply Chain (CLSC), as this is a combination of the regular forward supply chain of delivering components, and the reverse supply chain of repairing components. However, having an individual stock of components can be costly, particularly for small aircraft operators. Therefore, CS offers a solution by facilitating the availability of components through a shared pool utilised by fifty airlines. CS is also responsible for the logistics, and repair work scope.
The main objective of CS is to guarantee this availability of components, and additionally minimise the repair, logistic and stock costs. The availability of components and the stock costs are influenced by the time between the delivery of a SE component until the returned US component is repaired and

placed in stock again. This period is defined as the Turnaround Time (TAT) of a component. A lower TAT will require fewer components of a specific type to guarantee the same availability. Also, higher employee productivity has a direct influence on operational costs, such as repair and logistic costs. Therefore, CS is constantly looking to optimise its processes and eliminate waste.

In 2022, a project called CS2.0 was finished. In this project, the logistic centre of KLM E&M is moved to the building of the CS department and the newly built logistic supply chain is partly automated. In this new logistic centre, the inbound, handling, temporary storage and outbound of goods for CS will be facilitated. This area is called the **Logistic Handling Area (LHA)**. An impression is shown in Figure 1.2. The goal of the CS2.0 project was to improve the internal supply chain, make the data more reliable and lower the TAT of goods. However, the supply chain in the logistic centre still has a lower performance than expected, and the desired handling of incoming goods within two days is often not reached.

Figure 1.2: Impression of the Logistic Handling Area (LHA)

Within the company, different reasons for the lower performance of the LHA are stated:

- The automated system is not completely adapted to the incoming goods, as the system is still in development.
- It is unpredictable which goods will arrive in the LHA.
- A lot of skilled people have left the company in the past years.
- Different departments at CS are understaffed.
- The processes are too complicated and inflexible.
- Goods are not offered and requested correctly by the external parties.

Within CS there are already initiatives to improve the performance of the LHA. However, these projects are mainly concentrated on short-term improvements, as the logistic operation will continue. This results in less focus on long-term improvement strategies. In addition, CS is in the transition towards some new IT systems, which has an impact on these improvement trajectories.

1.3.2. Problem definition

In the previous section, various reasons for the lagging performance of the Logistic Handling Area (LHA) from a KLM E&M perspective are described. Looking from a scientific view, these issues can be summarized in two main problems: *variability* and *adaptability*.

- **Variability -** In the LHA, a wide of variety of goods is handled. The variety of goods primarily arises from the wide range of parts built into an aircraft. A significant portion of these goods will be handled within the LHA. Due to each of these goods having unique characteristics, such as varying sizes, weights, technical complexity, and the potential presence of dangerous goods, a lot of variability in the operation arises. The variability is further enhanced by varying numbers of goods flowing into the LHA daily and the presence of the CLSC, where both Serviceable (SE) and Unserviceable (US) goods are handled within the same system.
- **Adaptability -** This variability can lead to operational problems, as coordinating the operation is challenging in a constantly changing environment. To handle this, adequate operational decisions have to be made, so that a predictable and stable performance can be guaranteed. However, the current operation is not able to adapt quickly to changes, as there is no insight into the operation of the LHA and the effects of operational decisions. Furthermore, strict aeronautical regulations lead to rigid designed processes and skill requirements for employees.

The main problem arises from the interaction between variability and adaptability. The existing process coordination is not prepared to handle this variability, leading to operational instability. Consequently, there is a need to determine a method that can effectively support coordination in this dynamic and variable environment.

1.4. Research scope

This research is based on a case study within KLM E&M. Therefore, the physical area within the CS department must first be determined (1.4.1). Then, the design and control level at which the research will focus, will be formulated (1.4.2).

1.4.1. Physical scope

As described in section 1.3, the desired performance of the process of handling goods within the Logistic Handling Area (LHA) is often not reached. Therefore, the scope of this research will focus on the LHA, highlighted in blue in Figure 1.3. This LHA consists of an Automated Handling Area (AHA) and Manual Handling Area (MHA) and is influenced by both Serviceable (SE) and Unserviceable (US) goods from different external parties. These parties include customers, external repair vendors, part traders and OEMs. As can be seen in the figure, the actual storage process in the warehouse will be excluded from the research. All related administrative tasks that will be executed in the back office are included in the scope.

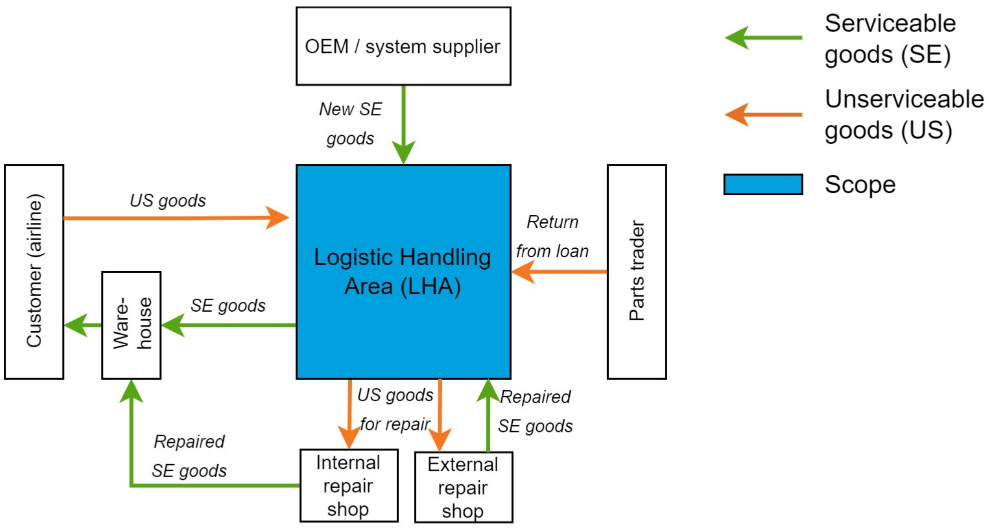


Figure 1.3: Physical scope of this research

1.4.2. Design level scope

As the physical scope is defined, the scope of the design and control level can be determined. For this definition, the three levels described by Rouwenhorst et al. [5] are used:

- *Level 1 - Long-term strategic level:* The decisions at the strategic level influence the long-term benefits of a system. This includes the process flow and the correct type of technical system.
- *Level 2 - Medium-term tactical level:* These lower impact decisions are based on the strategic decisions of level 1. The decisions are related to the characteristics of equipment, the system layout and the organisational design.
- *Level 3 - Short-term operational level:* The operation is influenced by the choices made at levels 1 and 2. The interfaces of different subsystems are managed at higher levels, so it is possible to analyse operational design strategies individually. The short-term operational decisions are mainly related to the coordination of people and equipment.

Following these design-level definitions, the research will mainly focus on short-term operational decisions, see Figure 1.4. The focus on coordination of the LHA system related to daily goods input and resource allocation is something that can be managed at the operational level. Nevertheless, the outcome of the research can also give insights into the consequences of process adjustments, a domain more closely linked to strategic and tactical decision-making.

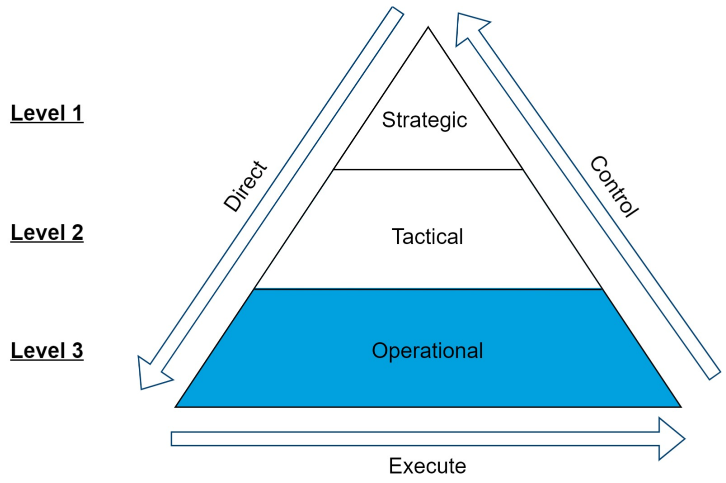


Figure 1.4: Control level scope of this research (based on [6])

1.5. Research objective

Considering the specified research problem and scope, the research objective can be formulated, along with the proposed method to achieve this objective. The objective is defined as:

> **Research objective**
>
> Develop and validate a digital twin concept that supports process operators in dynamically coordinating a system in a complex and variable environment.

While there are many methods to support operational coordination, this research is already scoped to the development of a digital twin. As the research is executed in collaboration with KLM E&M, the LHA of Component Services (CS) is used as a case study. The primary goal is to create a concept for using a digital twin in the daily operation.

1.5.1. Research deliverables

To reach the defined research objective, a list of deliverables is created. This list includes background research, insight into the state of the current process, a proposal for the design of the digital twin concept and an assessment of the value.

- Conducting a literature review about the use of digital twins (in scheduling and coordination).
- Analysing the current state of the MRO supply chain and the LHA.
- Defining operational KPIs of the LHA system.
- Creating a design for developing a digital twin representation of the LHA according to defined requirements.
- Identifying the operational parameters that have to be included in the digital twin and its current value.
- Creating a verified simulation of the digital twin concept that can demonstrate the value.
- Assessing the value a digital twin brings related to supporting coordination (in the LHA).

1.6. Research question

Given the research objective outlined in section 1.5, the research question is formulated as:

Research question

How can a digital twin support process operators to dynamically coordinate systems in a complex and variable environment?

This research question can be divided into sub-questions, to provide a systematic answer to the research question.

- SQ1: What are the characteristics of the supply chain in the aircraft MRO industry?
- SQ2: What are the objectives of using a digital twin (in scheduling and coordination)?
- SQ3: What are the Key Performance Indicators (KPIs) for assessing performance in an MRO supply chain?
- SQ4: How does the Logistic Handling Area (LHA) currently operate and perform?
- SQ5: What are the main issues of the current operation of the LHA?
- SQ6: What layout and parameters characterise an accurate digital representation of the LHA?
- SQ7: How can the digital twin concept be simulated to demonstrate the concept?
- SQ8: Is the developed design and simulation an accurate representation of the LHA?
- SQ9: What is the added value of the digital twin on the operation of the LHA?

1.7. Research methodology and structure

This research is conducted as a case study within a company. In the book of Dul and Hak [7], information is provided for executing such types of research. Within the research, the authors distinguish a difference between theory-oriented and practice-oriented research.

- **Theory-oriented research -** A theory-oriented research has as objective to contribute to the development of theory. However, as a lot of theory can be applied in practice, this theory may also be useful for practical applications.
- **Practice-oriented research -** The practice-oriented research has as its only objective to contribute to the knowledge of one or more practitioners, for example by the development of a product.

This research is primarily focused on the contribution to the theory, so a theory-oriented research will be executed. The objective of the research is not related to creating a digital twin model that can be applied directly, but to develop a method that can support operational coordination. However, by using the case as a storyline for the research, the value of this research to the theory can be better explained. Furthermore, using a case study helps create new and creative insights and contributes to a broader context than this company or sector.

Next to the focus of this research, the methodology has to be defined. For this research, the DMADV (define, measure, analyse, design, verify) methodology is used [8]. This methodology is often used in cases where a completely new way of working or a new product is introduced. It is based on the DMAIC (define, measure, analyse, improve, control) methodology from Lean Six Sigma, which is focused on the continuous improvement of existing processes. As this research does not focus on process improvement, but on the design of a new method to support the coordination of processes, DMADV is a more suitable methodology for this research.
An overview of the structure, related to the DMADV approach and the (sub-)questions is visualized in Figure 1.5. This introductory chapter (1) provides an overview of the problem, including its background,

and scope. It also outlines the research objectives and presents the (sub-)questions that will be addressed. To explore the MRO supply chain and digital twin theory, a literature review is conducted in chapter 2. This review examines previous studies and identifies any existing gaps in the literature related to the research objective. These two chapters include the *define* phase, whereafter the direction of this research has to be clear. Then the *measure* and *analyse* phase starts. This involves executing measurements and analysing the current system (3). This section defines the current state of the Logistic Handling Area, taking into account the findings from the literature review. As soon as the problems that the process is facing are clear, the *design* phase can start. Based on the literature review and the current state of the LHA, the report describes the development of a design for the digital twin in chapter 4. After the design phase, a simulation model is created (5). The simulation model is then verified and validated (6) to ensure its accuracy and reliability. Next, the *verify* phase starts, to check whether the developed design contributes to the solution of the defined problem. For this phase, the concept is demonstrated and discussed in chapter 7. Finally, the report ends with the conclusion of the findings in chapter 8, followed by a description of the limitations and recommendations in chapter 9.

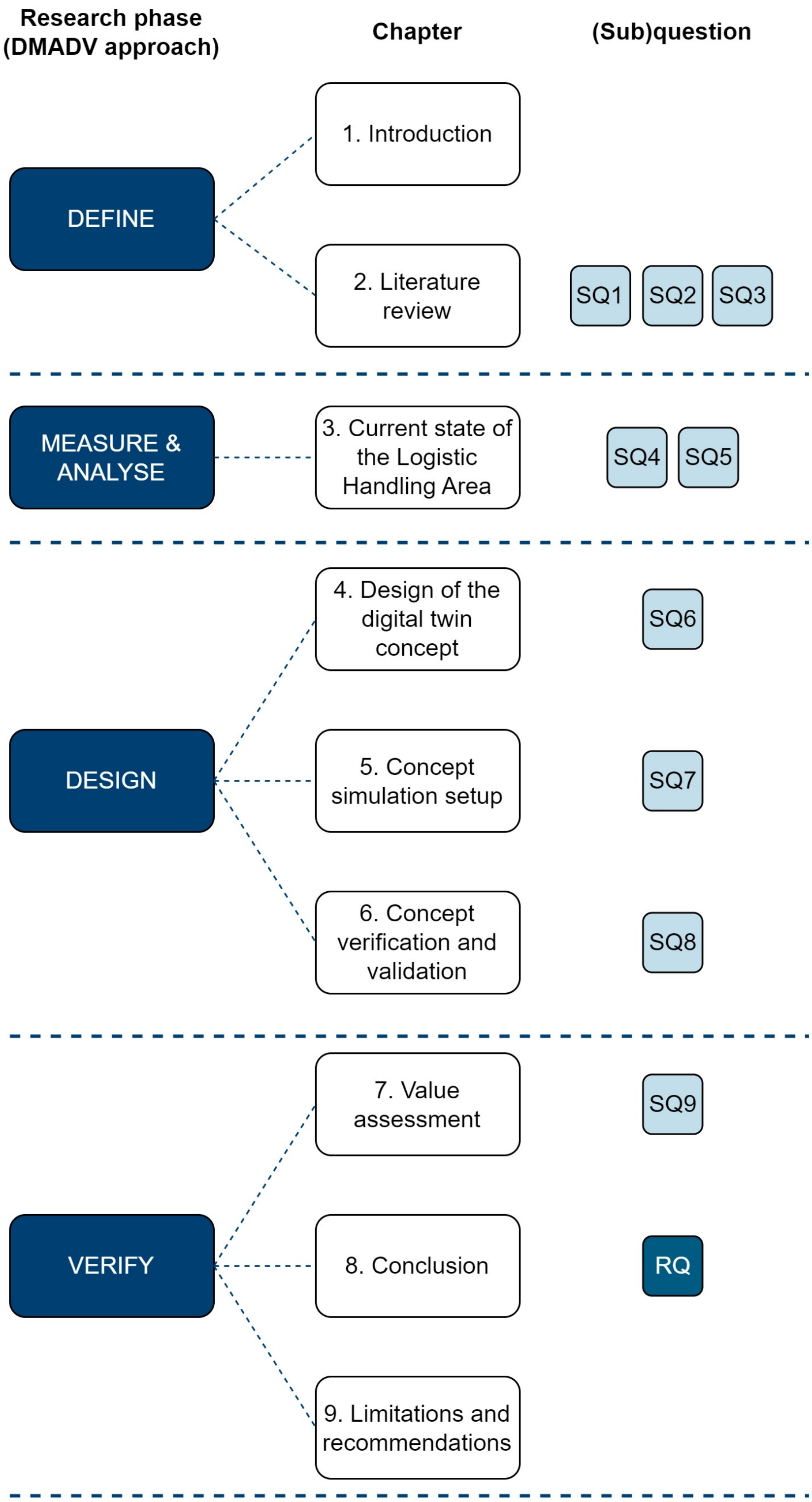


Figure 1.5: Research methodology and structure

2

Literature review

In this chapter, a literature review is presented to give insight into existing knowledge about this research subject and to identify the gap in existing literature. To find relevant research studies about MRO supply chains and digital twins, the search methodology is described in Table 2.1. Here, the main concept groups are shown, which are necessary to answer the first sub-questions. These concept groups are split into keywords to find relevant articles. The research is not limited to a specific publication date, as older articles are sometimes still relevant for this topic.

Concept groups	MRO; Digital Twin; Variability; Planning; Coordination; Performance
Keywords	MRO; Maintenance, Repair and Overhaul; Aircraft MRO; Supply Chain Variability Digital twin; DT; Digital shadow Planning; Scheduling Coordination; Control Performance; Key Performance Indicator; KPI
Truncation	(MRO) AND/OR (Variability) AND/OR (Digital Twin) AND/OR (Planning) AND/OR (Coordination) AND/OR (Performance)
Databases	Google Scholar, Emerald, Science Direct, TU Delft Library, IEEE

Table 2.1: Concept and keywords for literature review

This chapter aims to answer the following subquestions:

Subquestions covered in this chapter

- SQ1: What are the characteristics of the supply chain in the aircraft MRO industry?
- SQ2: What are the objectives of using a digital twin (in scheduling and coordination)?
- SQ3: What are the Key Performance Indicators (KPIs) for assessing performance in an MRO supply chain?

In this chapter, the literature about MRO supply chain is described in section 2.1, followed by research on the impact of variability in section 2.2. Next, digital twins (for scheduling and coordination) are explored in section 2.3, and performance indicators and tools for process analysis are described in section 2.4. The chapter concludes with a summary of the literature's key points and research gap in section 2.5.

2.1. MRO supply chain

This section describes the MRO supply chain to identify characteristics that could impact the operational performance of the research subject, the LHA. In the past, much research has already been conducted on the supply chain of (aircraft) MRO companies, also at KLM E&M. In general, a supply chain is defined as a '*network of organisations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer*' [9]. The activities of the MRO supply chain are mainly related to the repair and logistics of products. However, MRO supply chains differ from regular supply chain models, where 'consumable' products usually flow in one direction towards the customer. In the case of MRO supply chains, there is a balanced exchange of products from the customer towards the supplier, while repaired items follow the traditional downstream flow. This combination of forward and reverse logistics creates a Closed-Loop Supply Chain (CLSC), that enables the flow of 'rotable' items, as is also visualised in Figure 2.1 [10]. This exchange of items is executed to maximise the uptime of the aircraft [11]. The introduction of reverse logistics is mainly driven by environmental, legal, social and economic factors [12]. Focusing on the aircraft MRO industry, the decision to repair a component instead of replacing is mainly driven by economic factors. As the aircraft components are very expensive to purchase, it is economically beneficial to restore them to an airworthy condition.

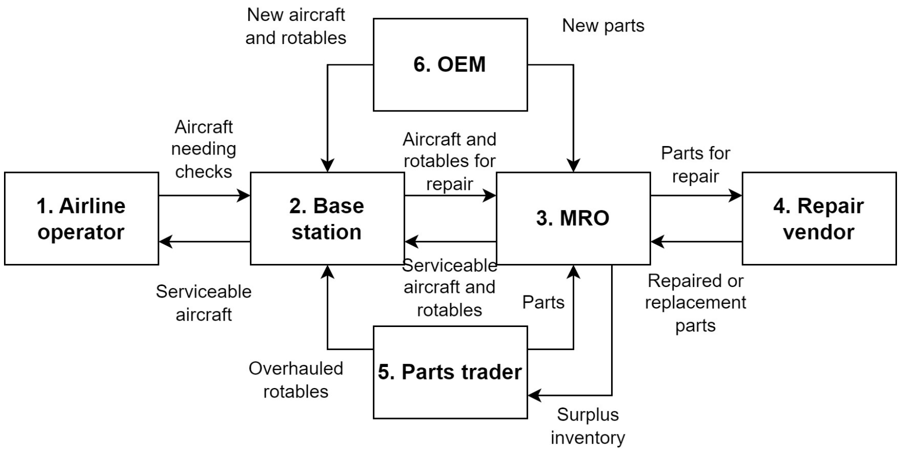


Figure 2.1: Aircraft MRO supply chain [10]

In the aircraft MRO business, the complex and capital aircraft components return for service after they become inoperable or after a pre-defined period of operation. However, after removing the component, quick repairing is a key objective for an MRO service provider. Furthermore, high reliability and compliance with the delivery date are essential. To achieve an efficient operation of the supply chain, together with a high schedule adherence, reliable planning of the supply chain capacity is required. Given that component demand is mainly influenced by the damage patterns in the components, the MRO industry has challenges with fluctuating demands for these components. Consequently, this variability in demand results in significant challenges for capacity planning [13]. These challenges are further enhanced by the uncertain timing and quality of returned products, and variable processing times [14]. The impact of variability on processes is further described in section 2.2.

Within the literature, different approaches for improving the (closed-loop) supply chain are used. In the article of Tzafestas and Kapsiotis [15], three different methods are addressed, that could be relevant for this research:

1. **Manufacturing optimisation:** The first strategy focuses solely on improving the efficiency of production within the supply chain.
2. **Multi-level coordinated optimization:** An alternative approach involves optimizing the entire supply chain by collaborating with all stakeholders and activities. In this method, suppliers and subcontractors not only provide services or goods, but also actively participate in the decision-making process of the whole chain.
3. **Decentralised optimization:** The third approach, decentralised optimization, aims to improve the performance of each involved stakeholder and activity independently, resulting in an overall improvement of the supply chain's performance.

2.2. Variability

Variability plays a significant role in the supply chain of MRO service providers. To understand the effects of this variability on the performance of the supply chain, further research is helpful. In the book 'Factory Physics', Hopp and Spearman [16] have dived into the background and consequences of variability. While their primary focus is on production systems, many of their insights are also applicable to logistics systems.
Variability exists in all kinds of systems, but it can have a significant impact on performance. Therefore it is required to measure, understand, and manage this variability. In their work, the authors define variability as "*the quality of nonuniformity within a class of entities.*" Variability can apply to many system aspects, such as supply and demand rates, physical dimensions, and setup and process times. There is a difference between controllable and random variation. *Controllable variation* is the consequence of decisions, while *random variation* is the result of events beyond immediate control. Both types of variations can have a negative influence on the performance, but the random variation logically is harder to control. The causes for variability can be broadly classified into two main categories: internal and external. *Internal* factors encompass elements such as equipment downtime, production rate fluctuations caused by operators, and the need for rework. On the other hand, *external* factors encompass irregular supply and demand patterns, varying product requirements, and changes in customer orders.

Related to this variability, Hopp and Spearman [16] defined two laws:

- **Variability law:** *Increasing variability always negatively influences the performance of a production system.*
  The Variability Law states that higher variability harms performance and reducing variability is key to improve performance. Increasing variability impacts inventory, capacity, and time efficiency. These impacts can be viewed as buffers that control the system, with worse performance requiring more buffering. This leads to the following law:
- **Buffering law -** *Variability in a production system requires a buffer.* This buffer has three dimensions:
  1. Inventory
  2. Capacity
  3. Time

  These three dimensions are related, as also can be seen in Figure 2.2. If a company is not able to reduce this variability, it will impact the performance on one or more of these dimensions. For example, this can result in a higher backlog of work, overcapacity of employees and equipment, higher lead times and poor customer service. As stated, variability requires some buffer, but the effects can be mitigated by having flexibility. In contrast to fixed buffers, flexible buffers have multiple applications. For example, multi-skilled people can better adapt to this variability.

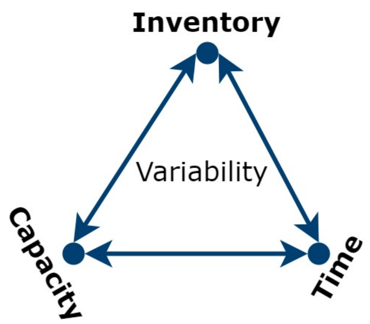


Figure 2.2: Variability trade-off

As described by the authors, eliminating all three types of buffers is challenging when the system experiences variability. Therefore, the primary focus should be on effectively managing and mitigating this variability, by focusing on the 'best buffer'. The choice of buffering strategy should be related to the specific business strategy and environment. For instance, when dealing with cheaper products like pencils, having an inventory may be more practical than investing significantly in increasing production capacity to accommodate this variability. For other types, such as emergency services, it is more likely to focus on higher capacity, as demand is unpredictable, and the service cannot be stored in inventory. Therefore, every business must make a crucial decision regarding the trade-off of buffers that best suits its needs.

2.3. Digital Twin

As described in the previous section, controlling an MRO supply chain could be challenging due to the variability it faces. As digital twins help create insight into physical systems, the potential value of digital twins is researched in this section. First, a general overview of digital twins is described (2.3.1), whereafter is focused on digital twin application in scheduling and coordination (2.3.2).

2.3.1. General

In the literature, many definitions for a digital twin are mentioned. In general, a digital twin is an intelligent virtual replica of a physical system [17], that can provide companies feedback about their system [18]. The aim is to assess the system's effectiveness or performance in specific scenarios to improve this. The concept of a digital twin model has the capability of showing historical insights, improving current operations, and even forecasting future performance across the assessed systems [19]. Differing from the execution of experiments on the actual physical system, a digital twin offers the ability to assess the impact of potential changes in a safe way [17]. According to Moshood et al. [20], the advantages can be categorized into four groups: (1) analytical value, (2) descriptive value, (3) predictive value, and (4) diagnostic value. The *analytical value* relates to the access to data that is normally difficult to compute. The *descriptive value* involves the capability to monitor a physical system without the necessity of direct observation. The third aspect, *predictive value*, concerns predicting the impact of changes on a physical system. Lastly, the *diagnostic value* is associated with the ability to identify potential underlying reasons behind the present performance of a system. The challenges related to digital twin implementation primarily revolve around creating an accurate representation of the physical system, ensuring the availability of necessary data, and sustaining data quality [20].

A digital twin consists of three main elements: a real space containing a physical system, a virtual space containing a virtual system and the two-way link between them (data and information process). This is visualized in Figure 2.3.

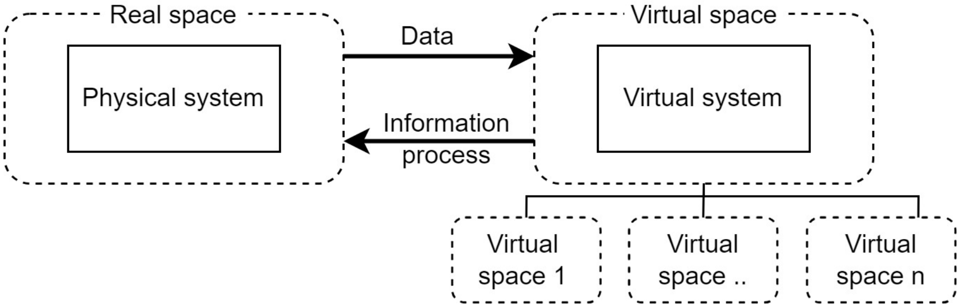


Figure 2.3: General model of a digital twin (based on [17])

According to Kritzinger et al. [21], there are different levels of digital twin integration:

1. At the lowest level, there is no automatic exchange of data between the physical system and the virtual system. This level is known as a digital model.
2. At the second level, data flows only from the physical system to the virtual system, enabling automatic updates to the digital representation. This results in a digital shadow.
3. The highest level of a digital twin involves not only the representation of the physical system in the virtual space, but also considers the influence of the virtual system on the real-life application.

Achieving this level requires a two-way connection, allowing data or information to flow from the virtual system to the physical system and vice versa.

In the research of Uhlenkamp et al. [22], a digital twin application framework is designed, which is shown in 2.2. This framework helps to understand the different goals of a digital twin and the associated focus points, characteristics and requirements.

Dimensions	**Values**			
Goals	Information acquisition	Information analysis	Decision and action selection	Action implementation
User focus	Single		Multiple	
Life cycle focus	One phase		Multiple phases	
System focus	Component	Subsystem	System	System of systems
Data sources	Measurements	Virtual data		Knowledge
Data integration level	Manual	Semi-automated		Fully automated
Authenticity	Low			High

Table 2.2: Digital twin application dimensions [22]

- **Goal -** Starting at the first goal, *information acquisition*, the digital twin is only used to monitor the physical system via different data sources such as sensors. The second phase, known as *information analysis*, encompasses the digital twin capability to receive incoming data and systematically process it, to receive additional insights for decision-making. The goal of *decision and action selection* is related to automatically selecting the best decision or action from multiple options, without manual involvement. The highest goal is the direct involvement of the digital twin in *action implementation*. Here, the digital twin will be used to make changes to the physical system, with different degrees of automation.

- **User focus -** *Single* user-focused digital twins mainly focus on the requirement of one single stakeholder, while *multiple* user-focused digital twins will manage the requirements of multiple stakeholders. This decision is mainly related to the application field and goal of the digital twin.

- **Life cycle focus:** This dimension is related to the life cycle phase to which the digital twin is related. Some digital twins are related to *one* phase, such as development or improvement, while other digital twins are useful in *multiple* phases.

- **System focus -** This dimension is related to the level of detail in the digital twin's representation of its physical counterpart. This includes four levels of detail: *components*, *subsystems*, *systems* and *system-of-systems*.

- **Data sources -** The fifth dimension is focused on the data sources that will feed into the digital twin. *Measurements* serve as the immediate output from the physical system, and this data can be integrated into the digital twin. This integration provides valuable insights into the characteristics and behaviour of the physical counterpart. Another data source is the *virtual data*, which, for example, includes information from forecasting and optimization tools. The third data source, *knowledge*, is related to external data inputs that improve the system's intelligence. Incorporating such knowledge can be beneficial, leading to more accurate system recommendations.

- **Data integration level -** The data integration level is related to the data exchange between the digital twin and the physical system. In the case of a *manual* integration, the data flows manually between the digital twin and system in both directions. A *semi-automated* integration enables automatic data flow from the system towards the digital twin. The *fully automated* integration also enables automatic data delivery from the digital twin to the physical system.

- **Authenticity -** This dimension is related to the level of similarity between the digital twin and the real-life system.

Digital twins are also applied in logistic supply chains. Marmolejo-Saucedo [19] defines a supply chain digital twin as '*a detailed simulation model of an actual supply chain which predicts the behaviour and dynamics of a supply chain to make mid-term/short-term decisions.*' Next to improved decision-making, adopters of digital twins also see advantages in optimization of day-to-day processes, which can enable new business possibilities [20]. An example of utilizing digital twins in the logistics sector can be observed within the construction industry. Here, digital twins are used to improve the allocation of resources, such as equipment and employees. It also helps to detect possible bottlenecks in this resource planning process [18]. The use of a digital twin in relation to coordination and scheduling is further researched in subsection 2.3.2.

2.3.2. Scheduling and coordination

In the study conducted by Agostino et al. [23], various digital twin applications are explored. However, the researchers highlight a research gap in using simulation and optimization models to enable data-driven decision-making for aligning operational aspects with management and control of processes. One of these operational aspects is production planning and scheduling, as companies try to deliver their products on time, with the right quality and with sustainable resource consumption [24]. Production planning and scheduling are mainly utilised in multi-product production facilities. Planning primarily focuses on longer time horizons to align expected demand with the overall resource capacity, while scheduling becomes essential for shorter timeframes, where allocated resources are matched with the actual demand [25]. Koulouris, Misailidis, and Petrides [25] address that timely coupling of this capacity and demand is necessary for optimal production, where a digital twin of the process should be available. In this planning and scheduling task, the authors highlight different challenges that have similarities with the challenges faced by the aircraft MRO industry, mainly related to variability. Aspects such as seasonal demand, variability in product mix and short cycle time lead to a dynamic and unpredictable production environment. This requires a flexible and fast adaptation of production plans [25].

In the literature, different approaches for digital twins for planning and scheduling are proposed. Agostino et al. [23] focused on the development of a digital twin for planning and control of a production system by including an optimisation model. The proposed method is shown Figure 2.4.

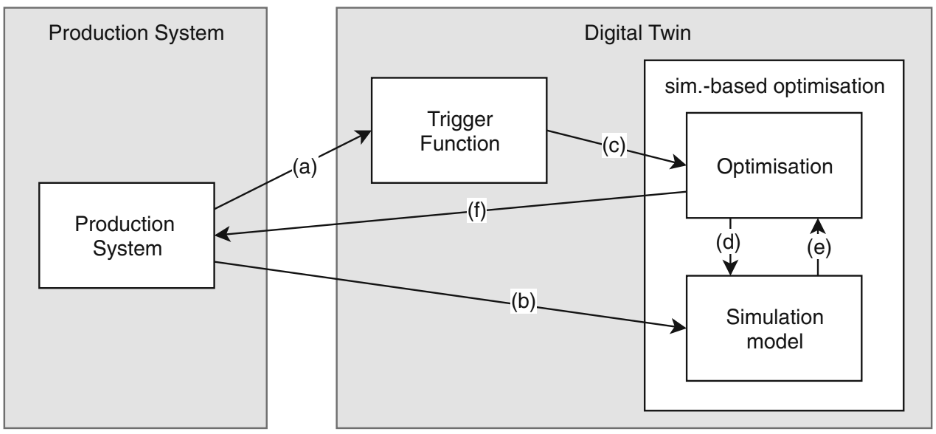


Figure 2.4: Digital twin approach for planning and control [23]

The approach comprises both a physical system (in this instance, a production system) and a digital counterpart (the digital twin), as also shown in Figure 2.3. Notably, their model also incorporates a trigger function and an optimisation model. The system's state is transmitted via flow (a) to the trigger function and via flow (b) to the simulation model. The trigger function continuously monitors potential changes in the system state, such as changes due to machine failures or reduced manpower availability. When a change is detected, a trigger signal is sent to the optimisation model. Consequently, the optimisation model is activated to improve resource utilization, such as manpower or machinery. The output data is forwarded to the virtual model through flow (d), where KPIs are computed. This information is then forwarded to the optimisation model (e) to determine the most beneficial option. The optimisation parameters are sent to the physical system for implementation via path (f).

However, Koulouris, Misailidis, and Petrides [25] address some criticism of including an optimisation model in a digital twin. optimisation models are often tailored to a specific production environment, which limits the reuse of the solution in other applications. Also, it could be hard for users to understand the decision-making process of such models. Furthermore, creating an accurate representation could be difficult, due to the many variables. The authors therefore propose a recipe-based representation for their food production process. To define such a model, the authors defined system and recipe-specific parameters. On a system level, the production model should include all available resources and their constraints. For recipe-specific elements, the processing steps, processing times and necessary resources are included. Biesinger et al. [26] further support this approach, with three key requirements for creating a digital twin for planning: (1) the available resources have to be identified, together with the location of the resource in the overall process. (2) information about the cycle and idle times of the process, resources and individual process steps have to be determined, and (3) the distribution of variant input has to be known. Based on the information, potential bottlenecks and free capacity can be identified.

2.4. Process analysis

This section is focused on process analysis, as this could help determine the current state of the researched process. In subsection 2.4.1, background research for performance indicators for MRO supply chains will be described, whereafter the process analysis tools will be explained in subsection 2.4.2.

2.4.1. Performance indicators

To measure the state of a system, the system's performance has to be analysed. First, it is helpful to understand the exact definition of performance analysis. Lu and Yang [27] define this as: '*the periodic measurement and comparison of actual levels of achievement with specific objectives, measuring the efficiency and the outcome of the corporation.*' These levels of achievement can be expressed in different performance indicators. For these Key Performance Indicators (KPIs), there are six core principles [28]. The indicator must:

- be measurable in physical and financial units;
- be specific, realistic and representative;
- be performed, defined and quantified consistently;
- be linked to the responsibilities of departments or individuals;
- be transparent, and;
- be aligned with the overall goals of an organization;

As KPIs vary depending on the specific processes involved, there is a wide range of KPIs described in the literature. To narrow the scope, this research is focused on KPIs related to the MRO supply chain and logistic systems. The KPIs that are related to the MRO supply chain are defined in Table 2.3 [29]. In this table, the financial KPIs are not described. However as mentioned earlier, increasing operational performance could also have a positive impact on the financial KPIs.

As this research only focuses on the handling of aircraft components in the reverse supply chain, customer Service Level and Lead Time are less relevant. However, increasing handling performance also positively influences these KPIs. In the scope of this research, the following KPIs are considered relevant: *Time in Handling*, *Workforce Productivity*, *Work In Progress*, *Throughput*, and *On Time Performance*. The use of all these KPIs in the performance analysis will be a subject of discussion with the stakeholders and will be described in subsequent chapters of this research.

KPI	Description	Flow
Service Level	Percentage of the times a component is available at the moment it's required	Forward
Lead Time	Time between customer's request initiation to customer's request fulfillment	Forward
End-to-End TAT	Time between US component removal to SE in stock	Reverse
Time at Customer	Time between component removal and component shipment	Reverse
Time in Transport	Time component is in shipment	Reverse
Time in Handling	Time between a component receipt until ready for the repair shop	Reverse
Buffer time	Time component spends in the buffer	Reverse
Repair time	Time component spends in repair	Reverse
Workforce productivity	The amount of components processed during a work shift per employee	Both
Throughput	The output of components over time	Both
On time performance	The amount of goods or services delivered according to target on time	Both
Work in progress (WIP)	The amount of components in a process step	Both
Standard deviation TAT	Variance of the TAT in standard deviations from the mean	Both

Table 2.3: KPIs for an aircraft MRO Closed Loop Supply Chain [29]

2.4.2. Process analysis tools

In order to analyze and improve the process, it is crucial to identify the process improvement tools that are available. This section provides a description of the background and distinctions of these tools.

Six Sigma

The core principle of Six Sigma is to consistently reduce variation with the aim of eliminating defects in any product or service by using a theoretical approach. Later, Six Sigma took on a broader meaning: '*A business improvement strategy used to improve profitability, to drive out waste, to reduce quality costs and improve the effectiveness and efficiency of all operations processes that meet or even exceed customers' needs and expectations* [30].'

For the application of the Six Sigma theory, often a standardized DMAIC (design, measure, analyse, improve, and control) approach is used. This methodology can be used for the continuous improvement of an existing process with a solid basis. The objective is to achieve stability by minimizing or removing variations that result in increased costs and customer dissatisfaction. The Six Sigma statistical standard indicates a maximum of 3.4 defects per million opportunities. However, process changes could introduce new variability. The Design for Six Sigma DMADV (define, measure, analyse, design, and verify) methodology could handle this variability by focusing on improving quality before processes are introduced [30].

Lean thinking

Lean thinking is based on the principles of the Toyota Production System (TPS), represented by the *muda* philosophy. This philosophy tries to maximize the value of a product by minimizing the waste in the process [31]. Lean principles are focused on creating an optimal process by sorting out Value Added (VA) and Non-Value Added (NVA) activities. The five main steps are defined as:

1. *Value:* Define the value for the customer.
2. *Value stream:* Visualise the value stream of each process and eliminate waste.
3. *Flow:* Create a free flow of the remaining value-adding steps.
4. *Pull:* If applicable, switch from a push to a pull system. The pull system is based on customer demand, while the push system relies on a predetermined schedule.

5. *Perfection:* Focus on a continuous improvement strategy.

In order to reduce waste, it is crucial to first recognize what includes waste. Waste can be defined as any activity within a process that does not add value, or that adds cost or time without contributing any value. There are seven types of waste identified: transport, inventory, motion, waiting, overprocessing, overproduction, defects, and skills gap [32].

Lean Six Sigma
The Six Sigma and Lean methodologies have some connections. In the end, both methodologies strive to improve customer satisfaction by applying their principles. Also, they both use flow-mapping tools to visualize the process, and data analysis is executed for process improvement [33]. But there are also some dissimilarities, mainly related to the focus point. Whereas Six Sigma focuses on reducing variability, Lean focuses on reducing waste. This variability and waste have some overlap, because rework or scrap can also be seen as waste. This waste could result in more variability [34]. Another dissimilarity is related to simplicity. Six Sigma is seen as a more complex and time-consuming tool, due to the analytical approach, while Lean is more understandable and faster, due to the more practical approach. Also, Six Sigma is not focused on system interaction, because processes are improved independently [33].

In conclusion, Lean and Six Sigma are both powerful tools, but combining both makes them even stronger. Therefore Lean Six Sigma is introduced and could be described as a methodology '*that focuses on the elimination of waste and variation, following the DMAIC structure, to achieve customer satisfaction with regards to quality, delivery, and cost [34].*'

Theory of constraints
Next to Lean and Six Sigma, the Theory of Constraints (TOC) is often applied, which was developed by Goldratt [35]. In Goldratt's vision, the improvement of any section of a system starts with defining the system's overall goal. TOC is based on defining and solving the issues related to this goal. By analysing a system, a system constraint could be defined as an action or subsystem that has a significant negative impact on the performance of the system. Every system has at least one constraint, otherwise, the performance could be unlimited [35]. The constraint could be physical, for example, a limited machine capacity, but is more often a constraint related to policy or behaviour [36]. In the list below, the five steps of TOC are described.

1. *Identify the system's constraints:* Determine and give priority to the constraints of the system based on their impact.

2. *Decide how to exploit the system's constraints:* Improve the most impactful constraint by using existing resources within the system.

3. *Make everything else subordinate to the above decision:* Evaluate all other relationships in the system to confirm their alignment with the requirements of the constraint.

4. *Improve the performance of the system's constraints:* If the constraint still exists, reduce the impact of the constraint as much as possible by taking further actions.

5. *If steps 1-4 have improved the constraint, start again at step 1:* Solving one constraint will lead to the rise of another constraint. Hence, it is necessary to begin again with step 1.

Overview tools
To summarize the difference between Lean thinking, Six Sigma, and the Theory of Constraints, Nave [37] created Table 2.4. In the end, all three methods try to optimise the performance of a process, but the focus differs.

Program	Six Sigma	Lean thinking	Theory of constraints
Theory	Reduce variation	Remove waste	Manage constraints
Application guidelines	1. Define 2. Measure 3. Analyze 4. Improve 5. Control	1. Identify value 2. Identify value stream 3. Flow 4. Pull 5. Perfection	1. Identify constraints 2. Exploit constraints 3. Subordinate processes 4. Elevate constraint 5. Repeat cycle
Focus	Problem focused	Flow focused	System constraints
Assumptions	- A problem exists - Figures and numbers are valued - System output improves if variation in all processes is reduced	- Waste removal will improve business performance - Many small improvements are better than systems analysis	- Emphasis on speed and volume - Uses existing systems - Process interdependence
Primary effect	Uniform process output	Reduced flow time	Fast throughput
Secondary effects	- Less waste - Fast throughput - Less inventory - Fluctuation - performance measure for managers - Improved quality	- Less variation - Uniform output - Less inventory - New accounting system - Flow - performance measure for managers - Improved quality	- Less inventory / waste - Throughput cost accounting - Throughput - performance measure for managers - Improved quality
Criticisms	- System interaction not considered - Processes improved independently	- Statistical or system analysis not valued	- Minimal worker input - Data analysis not valued

Table 2.4: Comparison improvement tools [37]

2.5. Conclusion

The first subquestion that was objected to be answered in this literature review, is SQ1. By focusing on the characteristics of an (aircraft) MRO supply chain, the impacts on individual steps in this supply chain can be better defined. The MRO supply chain involves handling and repairing rotable components and balancing the forward and reverse supply chains. From the perspective of a customer of an aircraft MRO company, the choice to repair rather than replace parts is determined by economic factors, primarily the cost of purchasing new parts. In case a component becomes inoperable, the component's owner wants the part returned as quickly as possible. This urgency to restore inoperable components places pressure on aircraft MRO service providers to have stable and predictable service levels. However, the uncertainty in this situation arises from variability in the supply chain, including fluctuating supply and demand for different component types and their associated process times. This variability often results in the introduction of three types of buffers: time, inventory, and capacity buffers. Given the high cost of aircraft components, having inventory buffers throughout the supply chain of an MRO is highly unfavourable. The only circumstance in which inventory buffering becomes beneficial for customer service levels, is when the components are stored in an airworthy condition. Related to inventory buffering is time buffering. As stated in the introduction, a longer TAT of the supply chain directly impacts the customer service level or quantity of required components. Therefore both the inventory and time buffer have to be minimized. So, effective management of resource capacity is crucial to avoid these buffers. However, the high level of variability in the supply chain makes resource management challenging.

Therefore, the possibilities for introducing a digital twin (for scheduling and coordination) are researched (SQ2). In general, digital twins are virtual replicas of physical systems with four overall values: analytical, descriptive, predictive, and diagnostic values. Specifically, digital twins provide clear access to the system's data (analytic value). This enables the monitoring of the system and its processes (descriptive value) and supports task coordination and the prediction of system changes (predictive value). Given the importance of capacity management in reducing time and inventory buffers, the use of digital twins in planning and scheduling could be beneficial. While some research explores the benefits of digital twins in scheduling and coordination, most of it is focused on more stable production environments, that are often characterised by longer time horizons. This presents a challenge in the aircraft MRO supply chain due to daily supply and demand variability and unpredictability. Given the limited research on applying digital twins to short-term scheduling and coordination in a highly dynamic environment, this could be a potential research area. Possible performance indicators (SQ3) for this system may include KPIs related to Time in Handling (TAT), Workforce Productivity, Work In Progress (WIP), Throughput, and On-Time Performance.

II

MEASURE & ANALYSE

3

Current state of the Logistic Handling Area

The development of a digital twin requires the analysis of the system that will be replicated. In this chapter, the current state of the Logistic Handling Area (LHA) is described, as can be seen in Figure 3.1. First, a general overview of the Closed-Loop Supply Chain (CLSC) of Component Services (CS) is explained in section 3.1, after which the system and processes of the LHA are described in section 3.2. Then, the current performance based on KPIs is determined (section 3.3). The chapter ends with the conclusion of the current state (3.4). The chapter aims to answer the following subquestions:

Subquestions covered in this chapter

- SQ4: How does the Logistic Handling Area (LHA) currently operate and perform?
- SQ5: What are the main issues of the current operation of the LHA?

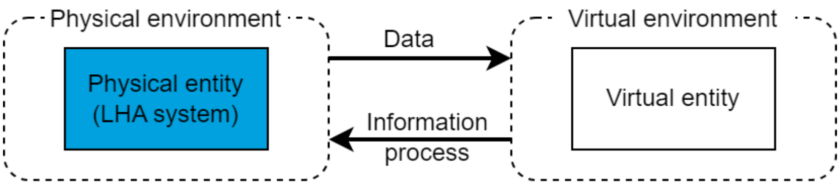


Figure 3.1: Scope of chapter 3 (highlighted in blue)

3.1. Closed Loop Supply Chain

This chapter addresses the supply chain of CS, as this is relevant for further analysis of the LHA. First, the involved categories of goods are explained (subsection 3.1.1), whereafter the related process steps are described in subsection 3.1.2. This section ends with the performance of the CLSC in subsection 3.1.3.

3.1.1. Categories of goods

The supply chain of CS involves a two-way flow, encompassing both a forward and reverse flow. Within this chain, three different categories of goods — rotables, repairables, and consumables — are handled. Further details about the three types of goods are outlined in Table 3.1. In Figure 3.2, the flow of these goods is illustrated among three core locations: (1) the customer, (2) the Logistic Centre of CS, and (3) the repair shop. As can be seen, not all goods flow through the CLSC, as not all goods can be repaired after they become inoperable (US).

Category of good	Description	Supply Chain
Rotable	Category of goods that can be economically restored to a serviceable condition and, in the normal course of operations, can be repeatedly repaired to a fully serviceable condition over a period corresponding to the life of the flight equipment to which it is related.	Forward and reverse
Repairable	Category of goods consisting of replaceable elements, commonly cost-effective to repair, and capable of being restored to full operational status within a timeframe shorter than the lifespan of the associated flight equipment.	Forward and reverse
Consumable	Type of good that is used only once and cannot be repaired.	Forward

Table 3.1: Description of different types of goods

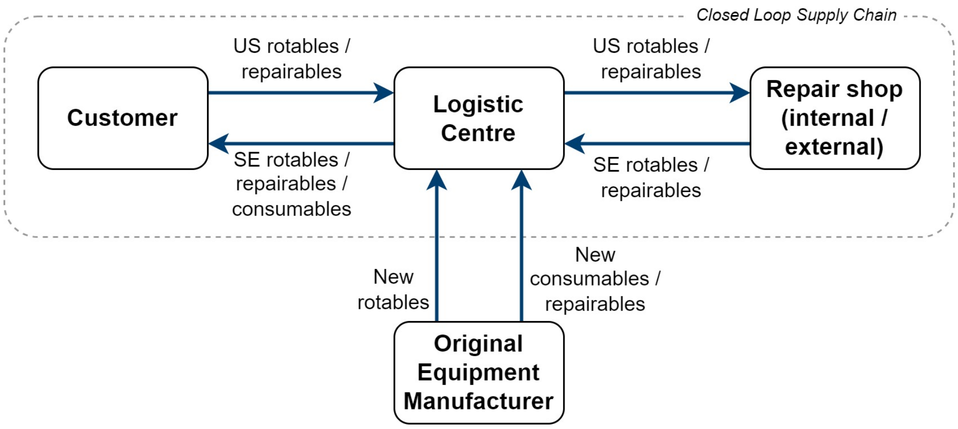


Figure 3.2: Flow of different categories of goods

3.1.2. Process description

This section outlines the process steps that are involved within the supply chain. All categories of goods that are explained in Table 3.1 are included in this process description. Understanding this higher-level supply chain process is required to distinguish the different process flows that will influence the Logistic Handling Area (LHA) system. In Figure 3.3, the supply chain of CS is visualized in both loop and end-to-end configuration. As already explained, the Closed-Loop Supply Chain (CLSC) consists of three core locations: the customers (airlines), the Logistic Centre (with the LHA) and the repair shops (internal or external). The process steps will be explained below:

1. **Serviceable delivery to customer:** The supply chain process within CS starts with a digital request created by the customer. If the requested item is available and falls within the contract, it is retrieved from the warehouse. At the warehouse, essential documentation is attached to the packaging, and the parcel is subsequently transported either to the outbound section or directly to one of the maintenance hangars within KLM Engineering & Maintenance. Within the outbound area, the package remains stored until it is prepared for loading onto a truck. Once taken over by a third-party Logistic Service Provider (LSP), the component is then transported to the specified location of the customer.

2. **Exchange unserviceable to serviceable component:** After delivery of the component to the customer, the serviceable component is temporarily stored until it can be built into the aircraft. During the exchange process, the unserviceable component is replaced with a serviceable one. This marks the transition point from the forward supply chain to the reverse supply chain.

3. **Unserviceable component transport:** Most components are transported to the CS Logistic Centre before being directed to an internal or external repair shop. Sometimes components are sent directly to an external repair shop, but this specific process is outside the scope of this

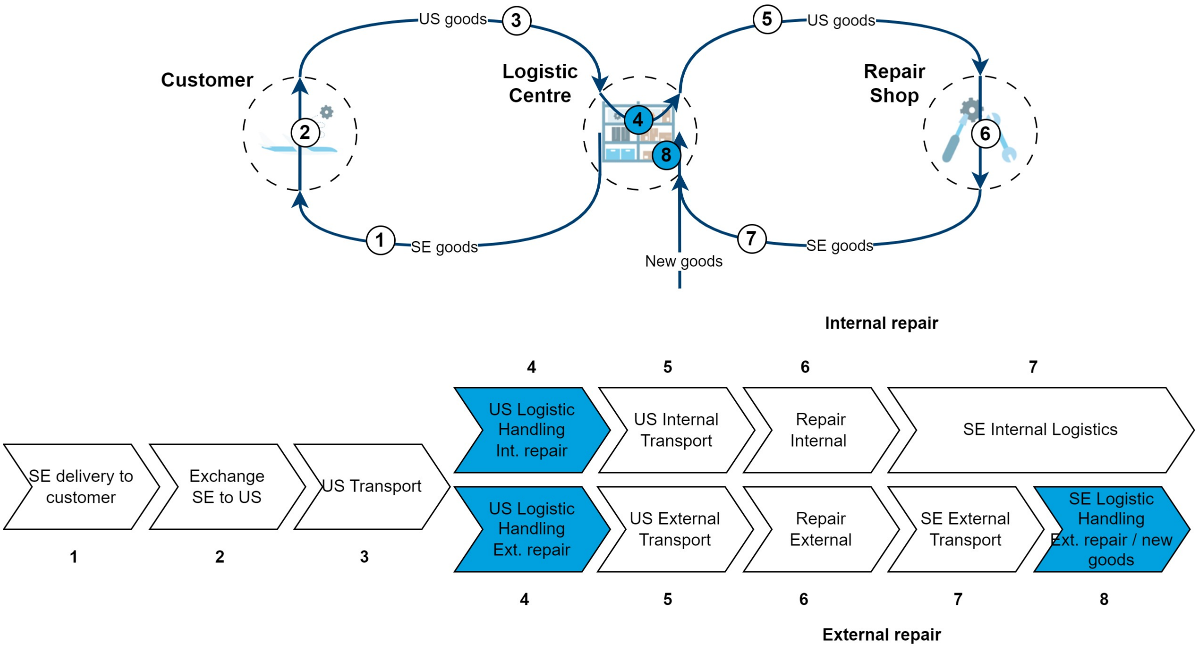


Figure 3.3: Overview of the Component Services Supply chain

research as these goods will not pass the LHA. The transportation is carried out by a third-party LSP.

4. **Logistic handling of unserviceable components:** As soon as the component is transported to the Logistic Centre, a repair order should be created. Upon arrival at the Logistic Centre, the component can either be processed immediately, if the repair order has already been created, or it has to be temporarily stored. If necessary, a visual inspection can also be conducted at this step, along with internal transportation. If the repair tasks are outsourced to an external shop, the component has to be prepared for shipment. Subsequently, the component is held in temporary storage within the outbound area before being shipped.

5. **Unservicable component transport:** The subsequent step of the unserviceable component's journey involves transportation from the Logistic Centre to an internal or external repair facility. This transportation is also managed by a LSP.

6. **Repair process (internal/external)**: This step encompasses the actual repair procedures. Throughout this phase, the unserviceable component undergoes repair in accordance with the established guidelines of the aviation authority. After undergoing the certification process, the component is once again converted to a serviceable state.

7. **Serviceable component transport:** After the repair process, the serviceable component is transported back towards the Logistic Centre. In case of an internal repair process, the component can be directly forwarded to the warehouse. For an externally repaired component, an additional logistic handling step is necessary.

8. **Logistic handling of externally repaired or new serviceable components**: Externally repaired components are once again handled within the LHA. Here, the component is inspected to verify the completion of the repair and certification tasks as required. This inspection is also required when new goods enter the Logistics Centre. Subsequently, the goods are placed into storage within the warehouse. This is the end of the closed-loop supply chain, as the component is again available for delivery to a customer.

3.1.3. Performance

Turnaround Time (TAT) is a commonly used indicator within the aircraft MRO supply chain to assess performance. This indicator is also used within Component Services (CS). In the context of CS, TAT is defined as the time between the delivery of a Serviceable (SE) item to a customer until the returned Unserviceable (US) item is repaired and placed back in stock, as this is the time the item is unavailable for another request. The TAT is visualised in Figure 3.4. Because assessing the performance of individual process steps is also relevant, the total TAT is split into TAT per process step (steps 1 to 8). As the stock level of CS is based on the total TAT of the supply chain, for every step within this chain, a 'design Turnaround Time (TAT)' is defined. The objective is to reach this TAT for all goods within the chain. The design TAT per process step is also visualised in Figure 3.4. As depicted in the figure, the target for the unserviceable logistics process, spanning from the customer to the repair shop, ranges between 3 to 12 days. This range varies depending on the customer's location and the repair facility. For the operation within the Logistic Centre, a designated TAT of 2 days has been specified.

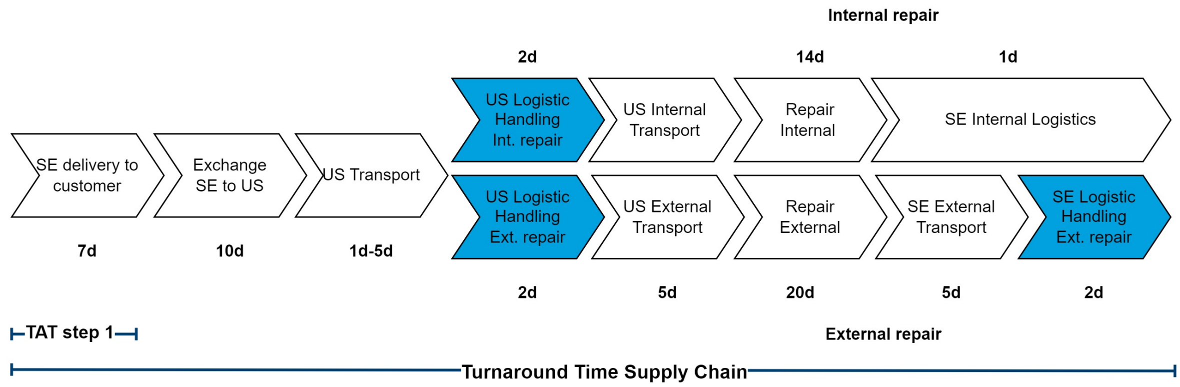


Figure 3.4: Turnaround Time objective of Component Services

Before diving into the LHA process, it is important to confirm that this part of the supply chain is a major bottleneck. Finding and solving the major bottleneck can significantly reduce the overall TAT in the supply chain. In the ideal case, it would be possible to measure the actual TAT of these process steps. However, due to the involvement of multiple IT systems with different timestamps, this is difficult to achieve. As a result, the performance of the supply chain steps is based on Work In Progress (WIP). WIP is the number of goods that are present within a process step. The actual WIP is collected from various IT systems, and the design WIP is calculated based on the design TAT in Figure 3.4, along with average throughput using Equation 3.1. The results are shown in Table 3.2.

$$\text{Design WIP} = \text{Daily throughput} * \text{Design TAT} \tag{3.1}$$

	Nr.	Supply chain step	Actual WIP/designed WIP
Internal/external repair	1	SE delivery to customer	227.5%
	2	Exchange SE to US	unk.
	3	US transport	222.8%
Internal repair	4	**US Logistic Handling**	**136.8%**
	5	US internal transport	n/a
	6	Repair internal	230.3%
	7	SE internal logistics	n/a
External repair	4	**US Logistic Handling**	**1173.8%**
	5	US external transport	
	6	Repair external	204.6%
	7	SE external transport	
	8	**SE logistic handling**	**304.2%**

Table 3.2: Percentage of actual WIP vs. designed WIP (date: 22-07-2023)

As can be seen in Table 3.2, the performance of individual steps cannot always be identified. Therefore, some process steps are combined. However, it is clear that the performance issues are mainly related to the LHA, as the WIP in Logistic Handling of both SE and US goods is significantly higher than designed. Therefore, further research on the performance of the LHA will be helpful.

3.2. Logistic handling

Logistic handling is the process step within the CLSC that is the link between the customer and the repair shop. This step is important, because most goods flow through this step twice, both in SE and US conditions. This logistic handling step is executed within the Logistic Centre of CS, which consists of three core areas: the expedition, the Logistic Handling Area (LHA) and the warehouse. In this research, the focus is on the LHA. The LHA is an essential element of the CLSC. Any disruptions in its operations would reverberate throughout the entire supply chain, also impacting related repair shops and departments. The objective of the LHA system is *to manage incoming goods efficiently, both in US and SE condition, in alignment with the aeronautical regulations*. This system regulates the sorting, handling, inspection, and distribution of incoming goods to relevant departments or storage locations. Additionally, it prepares items designated for external destinations. This LHA system is divided into two subsystems: the Automated Handling Area (AHA) and Manual Handling Area (MHA). As visualised in Figure 3.5, the LHA is affected by different categories of goods and parties. Also, the different contract types and the aeronautical regulations lead to a wide variety of processes. In the design of this system, 36 main categories of handlings are defined, resulting in a total of **115 unique process flows**. A schematic overview of the process layout and choices within the LHA is visualized in Figure B.1 in the Appendix. This section gives a general overview of the handling of US (3.2.1) and SE goods and their main processes (3.2.2).

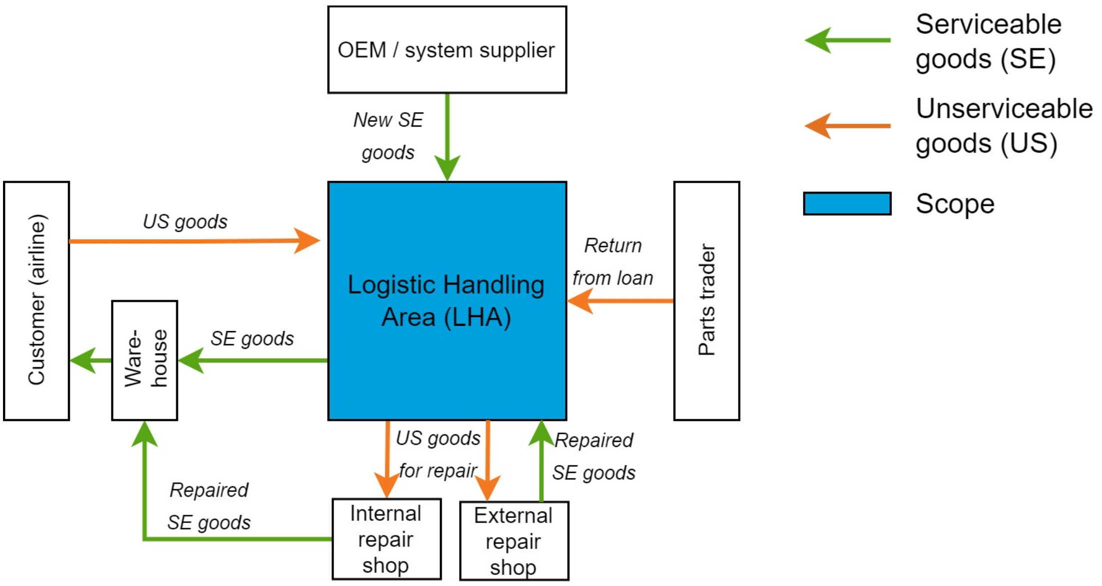


Figure 3.5: Interaction of LHA with other departments

In this LHA, various entities play a role, each accountable for a specific aspect of the operation. The visual representation of relevant departments and their hierarchy is illustrated in Figure 3.6. Notably, two main departments, namely Supply Chain Operations and Logistics, are responsible for the operation within the LHA. Broadly speaking, the distinction between physical and administrative tasks exists between these two departments. Subordinate to these primary departments are multiple process operators, each overseeing separate tasks within the processes. These operators assume responsibility for the day-to-day operations and resource allocation for specific tasks. This group of stakeholders serves as the primary focus of this study, given their direct influence on the operational aspects.

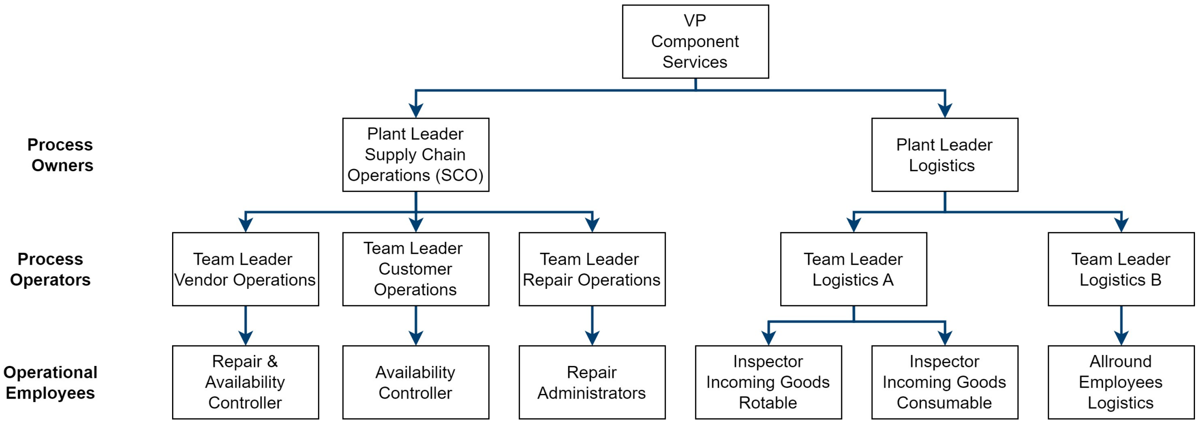


Figure 3.6: Overview of stakeholders

3.2.1. Unserviceable goods

Within the LHA both SE and US goods are handled. This section will provide an in-depth overview of the processes related to the handling of US goods. Within this US flow, there is an exclusive focus on rotable and repairable items, because consumables will not be repaired when they become US. In Figure 3.7, the input and output of the LHA process are visualised. Two external parties deliver goods into the LHA: customers and part traders. After handling in the LHA, the goods have three options: repair at an internal repair shop, repair at an external repair shop or scrapping.

Figure 3.7: Input-output diagram US

Within the unserviceable process, the goods will go through various steps before the goods are ready for repair in an internal or external repair shop. In Figure 3.8, the SWIMLANE of the unserviceable regular process is shown. This process starts with the removal of goods from the customer's aircraft. Once the goods hav been removed, the customer sends a notification to the customer service department of CS. This information must be processed into various IT systems to ensure a smooth workflow in subsequent steps. Following the removal, the customer sends the component to the logistic centre. After delivery by the LSP, the goods are handled in the expedition. There a label will be added which is necessary for further routing in the system. There is a small buffer at this expedition, before the goods will be inserted into the handling system. After measuring, weighing and scanning the package in the AHA or MHA, the system forwards goods that are known in the IT system towards the next step. As this is an administrative task, the goods will be temporarily stored in a buffer. For goods that will be repaired internally, a repair order is not necessary. The goods will leave the LHA system. In the case goods have to be repaired externally, a repair order is necessary. This document is created by the back office, consisting of repair administrators. Also, a proforma invoice and purchase order are created. After releasing the repair order, the external repaired components will be stored in the buffer before the goods are handled at the smart handling station. At this workstation, the necessary documentation is included within the shipping box, thereby readying the unserviceable goods f or shipment. In general, goods are handled according to the First In First Out (FIFO) principle. Only in the case of high-urgency goods, such as for goods of which stock has run out, parts are given a certain priority.

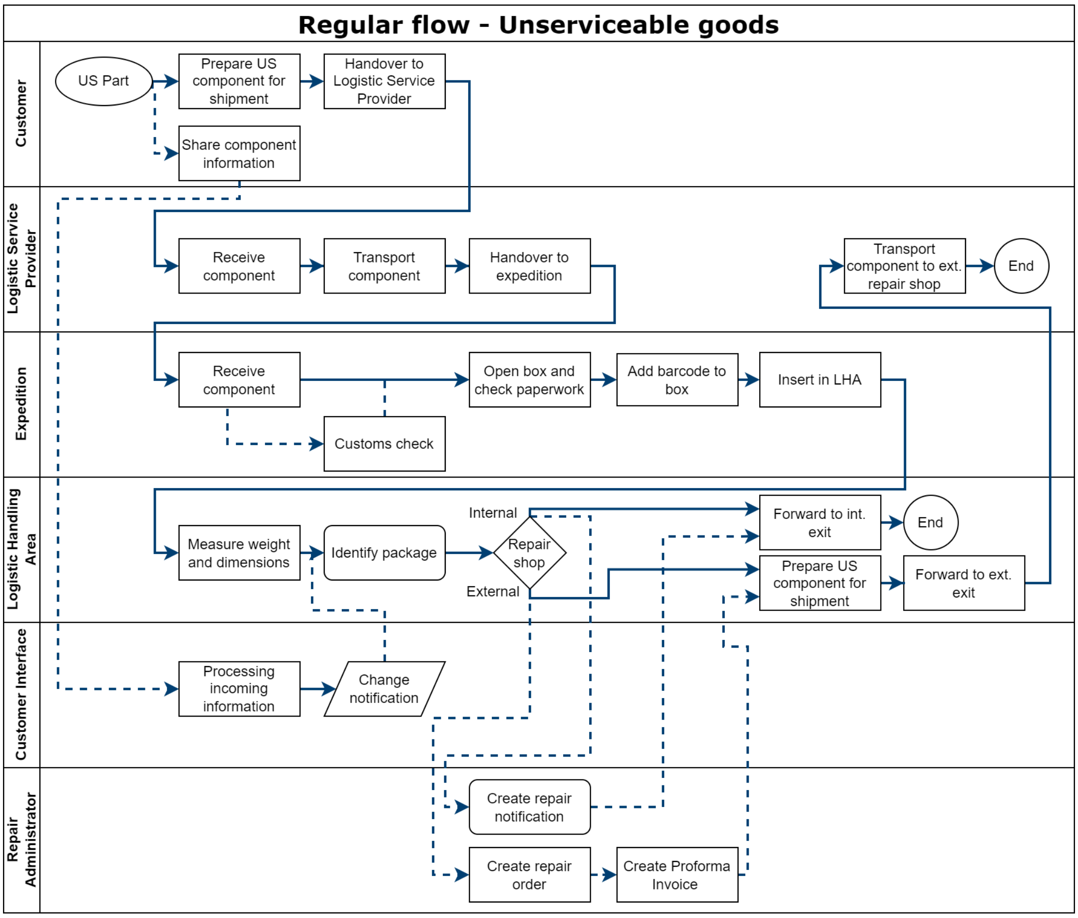


Figure 3.8: SWIMLANE Regular flow unserviceable goods

3.2.2. Serviceable goods

Focusing on processes of serviceable goods, a broader variety of handled components comes into consideration. This includes not only repaired components, but also consumables and new rotables/repairables. Once these new components are received at the Logistic Centre, they will become part of the supply chain of CS. Focusing on the serviceable workflow, the Logistic Handling Area (LHA) handles three types of goods: goods returned from an external repair shop, new rotables and new consumables (Figure 3.9). In general, they follow the same process steps, however, the skill requirements of employees could differ. It also results in varying processing times. After handling, they will be forwarded to the warehouse for storage. Internally repaired goods will be directly forwarded to the warehouse, where the components will be stored.

Figure 3.9: Input-output diagram SE

The detailed process steps are shown in the SWIMLANE on page 29. This process is similar to the unserviceable process described in the previous section. Serviceable goods are received at the expedition area, where they will be stored temporarily. After inserting the goods into the LHA system, the process starts with the identification and measuring step. Items that are identified are then routed to the Inspection Incoming Goods (IIG) workstation. The IIG workstation encompasses two main categories: IIG Rotables and IIG Consumables/Repairables. After the inspection tasks, the serviceable goods are moved forward into the warehouse. Only goods that are intended for direct delivery to external parties need a proforma invoice and undergo preparation at the smart handling station.

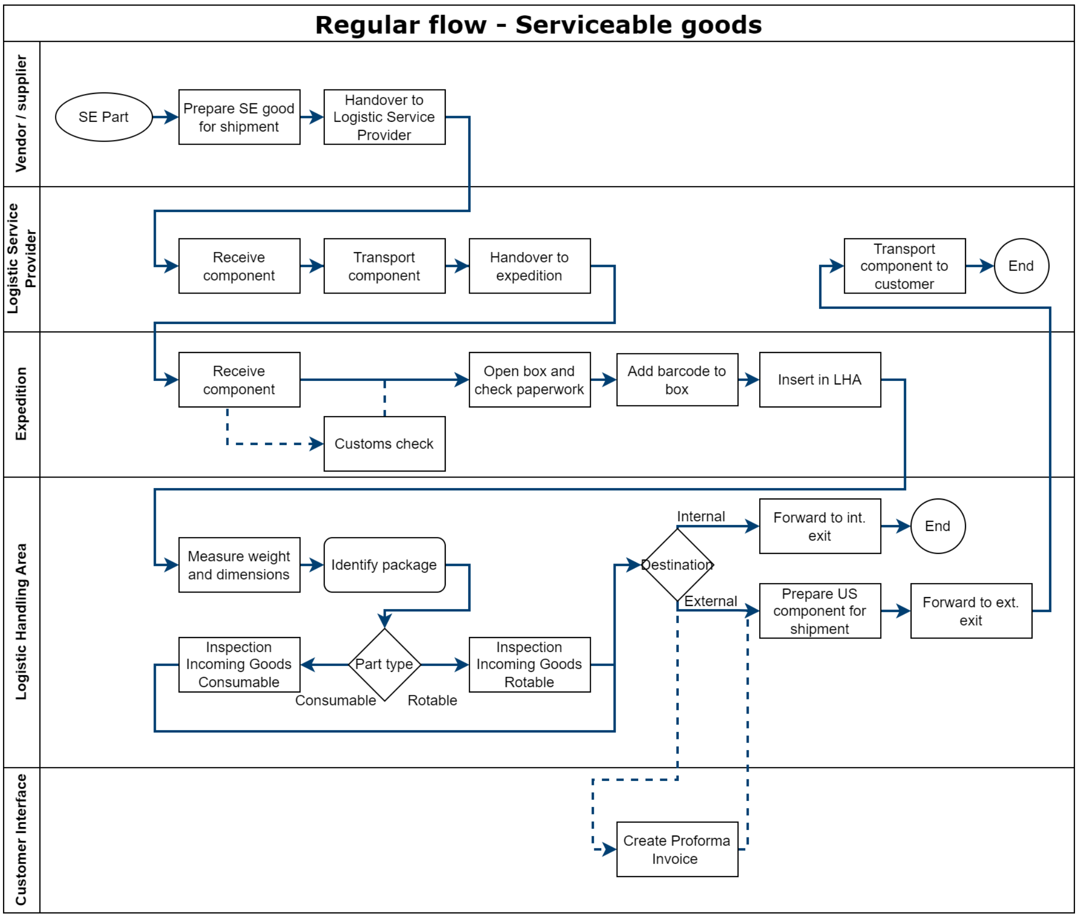


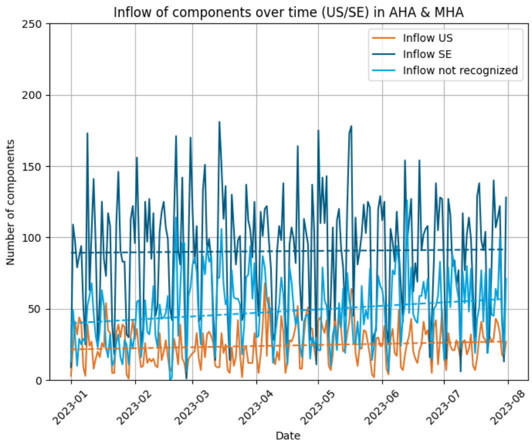
Figure 3.10: SWIMLANE Regular flow serviceable goods

3.3. Performance LHA

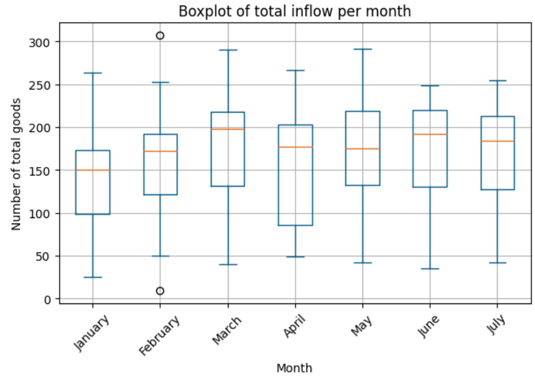
This section describes the performance analysis that is executed on the process within LHA, both on the SE and US process flows. The objective of this analysis is to further identify issues the LHA is facing. The outcomes can also support findings from the literature review. This analysis starts with the inflow analysis (subsection 3.3.1), whereafter the KPIs are defined and evaluated (subsection 3.3.2).

3.3.1. Inflow analysis

To gain insight into the flow of goods into the LHA, an analysis of the incoming goods is conducted. This analysis aims to identify any variations in the inflow to the LHA. Initially, a visualization of the overall inflow over time is presented in Figure 3.11a. The figure illustrates substantial fluctuations in the inflow, encompassing both US and SE goods, while the dotted trend line indicates a relatively consistent average inflow over the researched months. The variability in inflow is further depicted in the boxplot of total monthly inflow, as illustrated in Figure 3.11b. This figure visualises a month-to-month fluctuation in inflow, unrelated to seasonal effects. Moreover, examining individual months reveals day-to-day variations, as evident in Figures 3.12a and 3.12b. Notably, the inflow experiences a significant decrease on weekends compared to weekdays. However, the spreading is on all days significant.

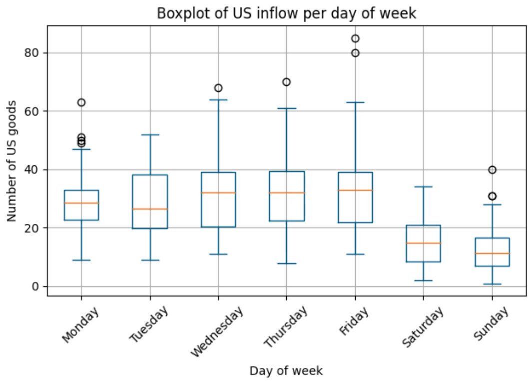


(a) Inflow over time (data January-July 2023)

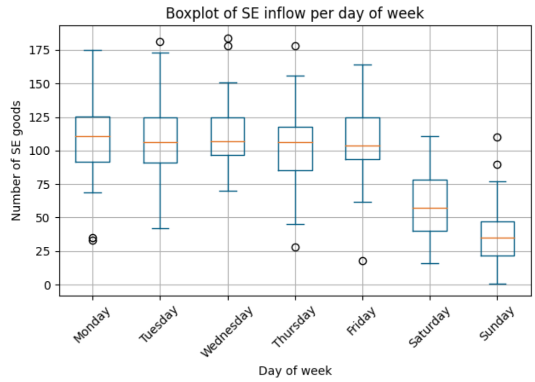


(b) Boxplot of total inflow per month (data January-July 2023)

Figure 3.11: Inflow of all goods over time



(a) Boxplot of US inflow per day of the week (data January-July 2023)



(b) Boxplot of SE inflow per day of the week (data January-July 2023)

Figure 3.12: Boxplots of US and SE goods (scale differs)

The data from the graphs is summarized in Table 3.3. What stands out, the inflow of serviceable goods is significantly higher than the unserviceable inflow. This is partly caused by the fact that relatively many US packages are not recognised at the first attempt. This results in extra work at the NRSI (Not Recognized Shipment Identification) station before they can be processed. Therefore, the number of packages after identification is also shown, where the number of serviceable packages is still higher. As can be seen, an average of 48 packages cannot be recognized directly. After the identification at the NRSI station, 76% of the packages contain unserviceable components, the remaining contain serviceable items.

	Before NRSI station	After NRSI station
Serviceable	90.4	102.0
Unserviceable	24.3	61.1
Not recognized items	48.4	n/a

Table 3.3: Average inflow of serviceable and unserviceable goods

However, not only the separation of serviceable and unserviceable goods is relevant. Also, the category of goods is relevant, as the handling time per type of goods could differ. A further down-drill of this inflow is visualised in Figure 3.13. From this analysis, it can be concluded that the main category of goods is related to US rotables, SE consumables and SE rotables.

To determine if the inflow for all these goods is predictable, the mean, standard deviation, average demand interval (ADI) and coefficient of variation (CV) are calculated by using equations 3.2 and 3.3

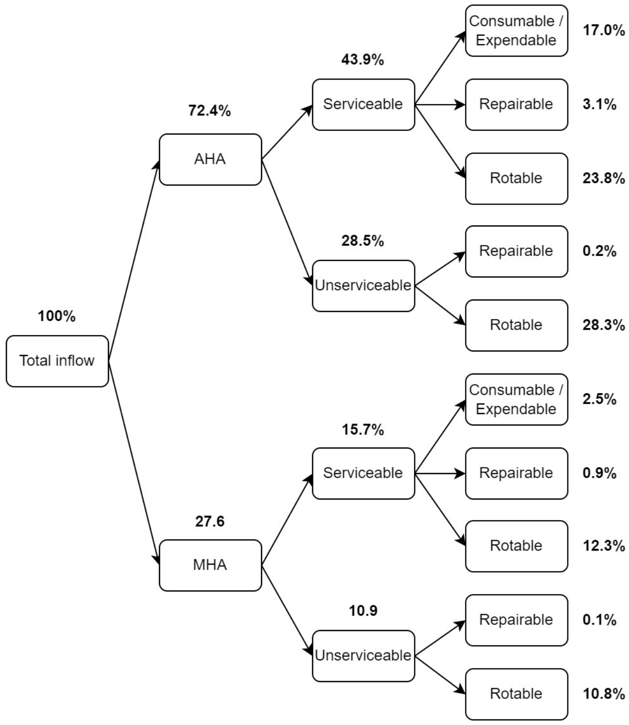


Figure 3.13: Inflow breakdown (data January-July 2023)

and are summarized in Table 3.4. Based on the combination of CV^2 and ADI, the inflow of almost all types of goods is classified as smooth [38].

$$ADI = \frac{\text{number of data points}}{\text{number of non-zero demand}} \tag{3.2}$$

$$CV^2 = \left(\frac{\text{standard deviation demand}}{\text{mean demand}}\right)^2 \tag{3.3}$$

	SE/US	Serviceable			Unserviceable	
	Total	Consumable	Repairable	Rotable	Repairable	Rotable
Mean	160.0	27.4	6.0	55.8	1.4	67.4
St. dev	61.7	16.0	3.9	28.6	0.7	30.2
ADI	1.00	1.02	1.07	1.00	4.07	1.00
CV^2	0.15	0.34	0.42	0.26	0.26	0.20
Classification	Smooth	Smooth	Smooth	Smooth	Intermittent	Smooth

Table 3.4: Inflow per good type

3.3.2. KPI analysis

Following the analysis of the inflow, it is crucial to assess the operational performance of the LHA. This assessment helps to explain the necessity for developing a digital twin for the system and provides valuable insights into potential bottlenecks and other issues. The analysis involves the evaluation of two key performance indicators (KPIs). These KPIs are established based on information gathered from the literature review described in subsection 2.4.1. In alignment with the list and the KPIs employed by KLM E&M, the subsequent KPIs are utilized for the performance analysis.

- **Work In Progress (WIP):** Total number of goods in the LHA system or split per task (#)
- **Turnaround Time (TAT):** Average time a good is within the LHA system (h)

Work In Progress (WIP)
First, the buffer of goods over time is determined. This WIP shows the number of goods waiting to be processed in one of the process steps. If this WIP is higher than the 'design WIP', this can result in lower system performance, such as high TAT. Figures 3.14 and 3.15 show the average number of goods in the LHA per flow type and task respectively. This backlog of goods is further specified per type in Table 3.5, together with the mean and median value.

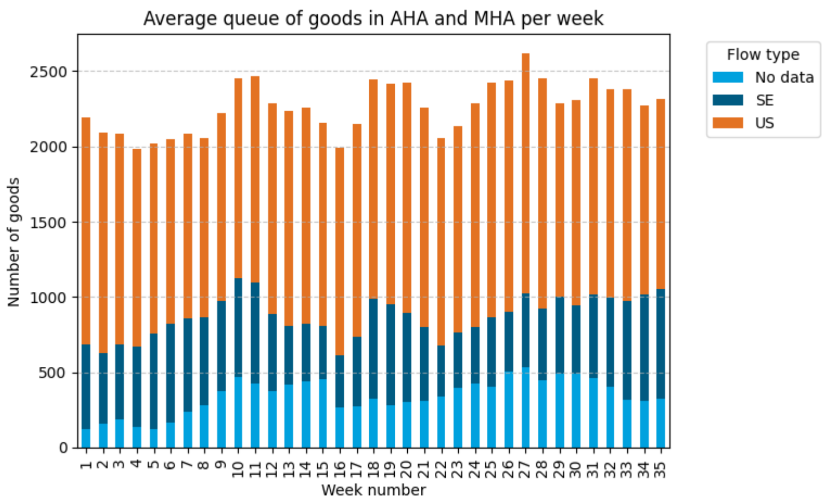


Figure 3.14: Average Work In Progress LHA per week split per flow type (Jan-Aug 2023)

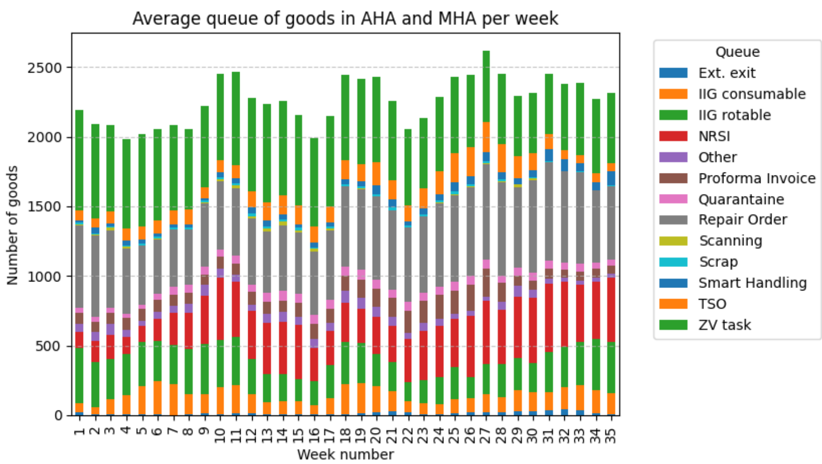


Figure 3.15: Average Work In Progress LHA per week split per task (Jan-Aug 2023)

	SE/US	Serviceable				Unserviceable			No data
	Total	Total	Consumable	Repairable	Rotable	Total	Repairable	Rotable	Total
Mean (#)	2260.2	524.8	138.2	34.7	346.7	1394.5	20.3	1364.7	340.9
Median (#)	2268	515	139	33	345	1397	22	1369	347

Table 3.5: WIP per day per good type (Jan-Aug 2023)

Overall, the WIP is significantly higher than the design WIP based on the design TAT (see also Table 3.2). Especially at the unserviceable flows, the buffer of work is high, while the inflow is lower than the serviceable flow. Further, the amount of serviceable goods is also higher than designed. Zooming in on the individual process steps, there are high buffers at the following tasks: *ZV task*, *Repair order creation*, *IIG rotable* and *NRSI*. What stands out even more is the presence of queues for almost all tasks, with the size of the backlog varying over time.

Turnaround Time (TAT)
The second KPI is Turnaround Time (TAT). A higher WIP than designed could result in a higher Turnaround Time in the LHA system, as goods have to wait longer before they can be handled. The TAT in the context of the LHA is defined as the total time between a package entering and leaving the LHA system. For the CLSC of Component Services (CS), reducing this time is important. In Figure 3.16, the overall TAT performance of the LHA is visualised.

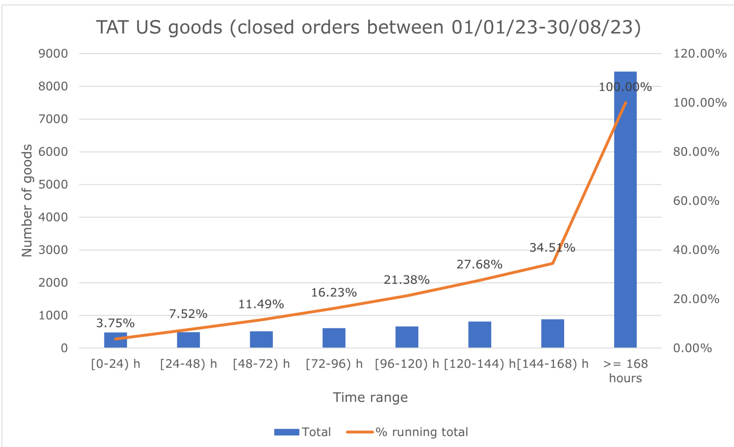
(a) Graph

Flow Type	All
Nr. of goods	36260
Mean TAT	364.4 h
Median TAT	136.0 h
OTP	24.6%

(b) Data

Figure 3.16: TAT and OTP all goods (Jan-Aug 2023)

As can be seen, the TAT is significantly higher than the design of 48 hours. This results in an On Time Performance (OTP) of less than 25%, so less than one-fourth of the goods are handled within the desired time. To further specify the performance of the unserviceable and serviceable flow, the individual TAT performance is visualised in Figures 3.17 and 3.18. From this data, it can be seen that the unserviceable flow has the longest TAT. This is in line with the higher WIP related to this unserviceable process. However, the serviceable flow also has a lower performance.



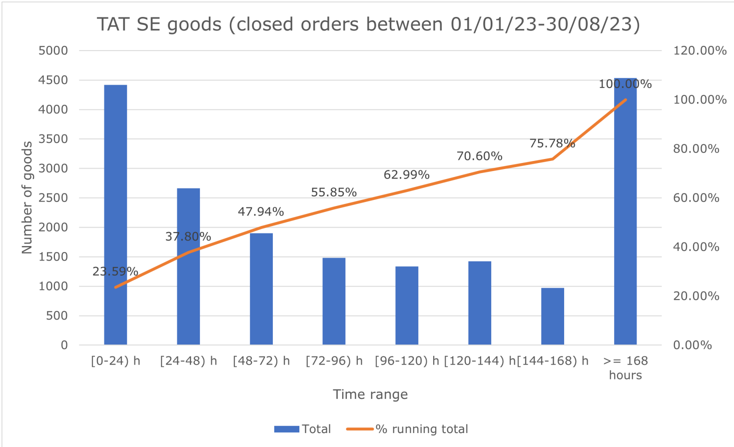
(a) Graph

Flow Type	US
Nr. of goods	12911
Mean TAT	698.9 h
Median TAT	262.0 h
OTP	7.52%

(b) Data

Figure 3.17: TAT and OTP US goods (Jan-Aug 2023)

The volume of goods handled can also be important, apart from the Turnaround Time (TAT). For instance, focusing on the process improvement goods with both a high TAT and frequent handling might be more crucial. Therefore, the percentage of total handled goods is plotted against the average TAT, see Figure 3.19.



(a) Graph

Flow Type	SE
Nr. of goods	18797
Mean TAT	158.6 h
Median TAT	83.0 h
OTP	37.8%

(b) Data

Figure 3.18: TAT and OTP SE goods (Jan-Aug 2023)

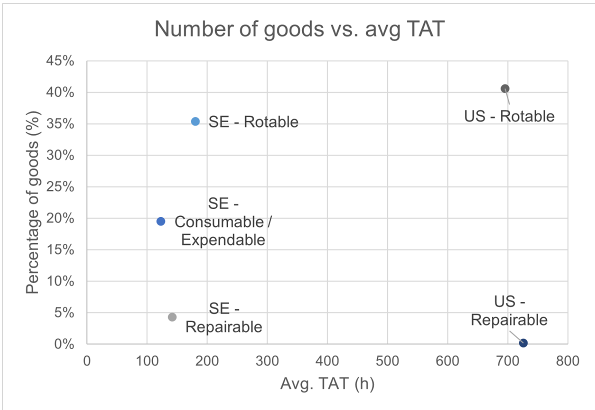


Figure 3.19: TAT vs. number of goods per good type (Jan-Aug 2023)

3.4. Conclusion

This chapter started with an analysis of the overall supply chain. Initial indications of a bottleneck in the LHA system surfaced upon reviewing the WIP throughout the supply chain. Consequently, a deeper analysis of the process and performance of the LHA is executed. Both analyses led to the conclusion (SQ4) that the LHA operation is complicated, and characterized by a variety of processes and tasks with significant interdependencies. The combination of varying daily inflow and individual goods' processing times contributes to performance issues, resulting in an overall LHA performance below the desired level. To summarize, the findings from these analyses indicate the following main issues (SQ5) that the system is currently dealing with:

- **Influence of variety of processes on the LHA:** The operation within the LHA is quite complex, due to the many processes involved. The tasks in these processes will share buffers, but the handling time can differ. This makes it difficult to have a good overview of the current state of the LHA. Therefore, a simplified but comprehensive overview is necessary to coordinate all tasks and process flows involved.

- **Presence of various bottlenecks in the LHA:** Overall, the performance of the LHA expressed in TAT and WIP is lower than desired. This directly impacts the operation of the complete supply chain of CS. After analyzing individual tasks, it is evident that the overall low process performance cannot be assigned to one single task in the process (see Figure 3.15), as there is a backlog of goods across nearly all tasks. While certain tasks have higher backlogs than others, solving these specific issues might not entirely resolve all bottlenecks. Thus, a strategy must be found to improve the overall LHA process.

- **Uncertainty and variability in daily inflow into the LHA:** The inflow in the LHA is affected by input from the previous supply chain step: the expedition inbound of CS. However, as the inflow of the expedition is directly affected by external parties, such as the LSP (transporter), customers and external repair shops, the daily inflow cannot be determined exactly in advance. Based on the inflow analysis, it is visible that the inflow can fluctuate from day to day. Strictly looking at the demand classification, the demand cannot be classified as erratic. However, the combination of a fluctuating inflow, significant processing time for some tasks and the short desired TAT can still lead to a low process performance.

- **No integral coordination of the LHA:** In the current operation, there is a lack of coordination among processes that impact the LHA. Each department is prioritizing its individual goals without considering the broader context. The lack of a comprehensive approach to the handling of goods, results in fluctuations across various process steps, as can be seen in the analysis of WIP. Therefore, it is crucial to create a structured and transparent method to coordinate all operational tasks effectively.

In summary of the points above, the reason for poor performance cannot be assigned to one process step. Rather, it arises from a broader issue related to a lack of comprehensive process understanding due to limited data availability and the complexity of the processes itself. Consequently, adequate coordination of employees across tasks becomes notably challenging. Primarily, achieving real-time, clear insights into the system is important. This involves visualizing the impact of capacity changes on individual tasks and the variability in input per type of good. These insights empower process operators of the departments with the necessary information to make adequate operational decisions. Moreover, it directly clarifies the effect across the entire chain in the LHA. This becomes particularly relevant when the workload decreases, strengthening the effects of fluctuations.

III

DESIGN

4

Design of the Digital Twin concept

In chapter 3, the challenges related to the current operation of the LHA were addressed. In this chapter, the design of the digital twin is proposed, that should support operational coordination and scheduling to mitigate these challenges. This chapter discusses the objective and requirements (section 4.1), and the design of the digital twin and the required parameters (section 4.2), as visualised in Figure 4.1 in blue. Also, the methodology for creating this design is described. This chapter aims to answer the following subquestion:

Subquestion covered in this chapter

- SQ6: What layout and parameters characterise an accurate digital representation of the LHA?

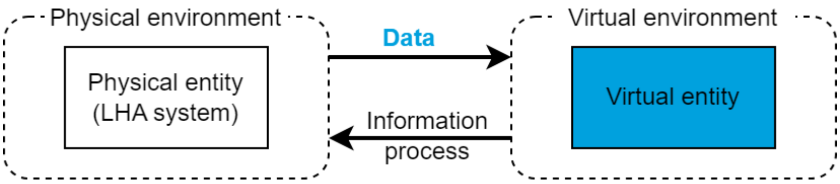


Figure 4.1: Scope of chapter 4 (highlighted in blue)

Before zooming in on the design of a digital twin, it is essential to introduce commonly used definitions found in the literature. The definitions suggested by Jones et al. [39] are used, as their research summarizes definitions from a collection of articles. A summary of these definitions is shown in Table 4.1.

4.1. Objective and requirements

The reason for the development of a digital twin of the LHA arises from the challenges this system faces. Section 3.4 addresses four main challenges: the influence of a variety of processes; the presence of various bottlenecks; uncertainty and variability in daily inflow; and, lack of integral coordination. Directly solving these challenges is preferable, but improvement trajectories at KLM E&M have shown that this is complex, due to the many dependencies, both internal and external. So, the objective for the development of a digital twin is not directly related to solving these challenges, but to mitigate the effects by offering a crucial benefit: *providing real-time insight into the past, current and future state of the LHA*. This objective relates to the values of a digital twin, as described in chapter 2: analytical value, descriptive value, predictive value, and diagnostic value. Especially the descriptive and predictive values could be beneficial to the LHA. The descriptive value involves the capability to monitor the physical LHA system, while the predictive value has the potential to show the impact of changing parameters, such as input and processing time. As the digital twin has to support process

Definition	Description
Physical Entity	The real-world system, in this research the Logistic Handling Area (LHA).
Virtual Entity	The computer-generated representation of the physical entity, in this research the virtual representation of the LHA.
Physical Environment	The measurable environment in which the LHA exists.
Virtual Environment	The replication of the state of the physical environment of the LHA by using simulation.
State	The current value of all parameters of the physical or virtual entity.
Parameters	The types of data, information and processes transferred between LHA and digital model.
Physical Processes	The physical purposes and processes within which the physical entity operates.
Virtual Processes	The computational techniques employed within the virtual world.

Table 4.1: Definitions related to digital twin (based on [39])

operators by coordination of the system, the digital twin has to create an output that is interpretable for these operators. Therefore, the following requirement is essential:

1. **The digital twin must be able to calculate the KPIs of the LHA.**
   The current operational performance of the LHA is evaluated by KPIs, as described in section 3.3. To assist process operators in their coordination tasks, the digital twin must at least generate these KPIs for insight into historical, current, and future states. This functionality supports process operators in making informed decisions.

However, to enable the possibility of calculating the KPIs, the researched system has to be replicated. Since the LHA operates in a complex and variable environment, the further requirements are as follows:

2. **The digital twin should include a comprehensive and structured representation of the processes.**
   Representing the physical system and its processes comprehensively and structurally is crucial for providing clear operational insights to process operators. This requires simplifying the involved processes and selecting essential parameters that will be transferred to the virtual replication. This has to enable dynamic operational decision-making. Additionally, the model must encompass process constraints to ensure accuracy.

3. **Data should be obtained from the physical system or assumptions.**
   A key characteristic of a digital twin is related to automatic data transfer from the physical system towards the virtual replication. Therefore, the model requires data that can be extracted from the physical system in real-time. This enables dynamic monitoring of the system. If direct and real-time extraction is not possible, parameters should be definable based on assumptions.

4. **Environmental characteristics that affect the performance of the LHA should be included.**
   Next to the behaviour within the LHA, also the influence of the environment on the operational performance of LHA has to be included. This is mainly related to variability caused by the MRO supply chain, as defined in section 2.1.

5. **Evaluating the model through simulation should be possible.**
   The last requirement is related to validating and demonstrating the concept of the digital twin model. As simulation could be a useful tool for this, it is necessary that the design can be transformed into it.

4.2. Virtual entity

This section focuses on the design of the virtual entity, that represents the digital replication of the LHA. First, an IDEF (Integration Definition) diagram of the virtual entity is created (Figure 4.2). This diagram visualises the input, output, constraints, resources and performance measurements that are related to the virtual entity. All these influences will be discussed in this chapter, together with the process layout of the virtual entity. For the design, the recipe-based representation of Koulouris, Misailidis, and Petrides [25] is used as a basis. On a system level, the model should include all available resources and constraints. For every unique type of goods that are handled (the recipe), the processing steps, processing times and necessary resources must be defined.

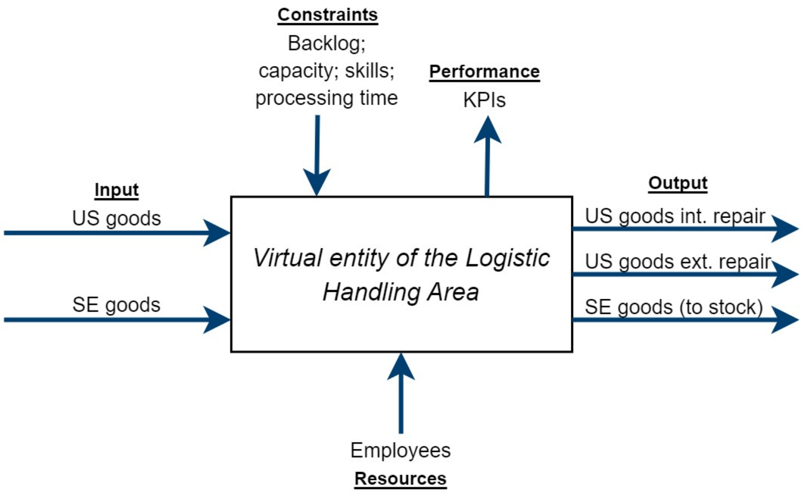


Figure 4.2: IDEF diagram of the virtual entity

4.2.1. Layout

The layout forms the basis of the virtual representation of the LHA. Related to requirement 2 (section 4.1), a comprehensive and structured representation of the processes has to be included. By creating this process representation in a structured way, a simplified version of the current processes is created.

Clustering goods based on process characteristics

In the original process design of the LHA, there are more than 115 unique process flows defined. Visualising all 115 process flows is undesirable as it will be hard to monitor them all. Therefore, a simplified but comprehensive overview of the LHA process is required. To accomplish this in a structured way, the main characteristics of the involved processes are analysed and summarized in four groups: Operation state; category of goods; pool type; and destination.

- **Operation state -** The first characteristic, the operation state, defines if goods are in airworthy condition, or not. Within the supply chain, there are two options: *Serviceable (SE)* and *Unserviceable (US)* condition.
- **Category of goods -** The second characteristic relates to the categories of goods that are handled within the MRO supply chain: *Rotables*, *repairables* and *consumables*. The differences have previously been explained in Table 3.1.
- **Pool type -** The third characteristic, the pool type, defines the ownership of a good. A *KLM pool part* is an item that is part of the KLM Closed-Loop Supply Chain (CLSC), while an *AFI pool part* is part of the Air France Industries (AFI) supply chain. In the case of a *non-pool part*, the handled goods are owned by an external company, but at KLM E&M for repair in one of the internal repair shops. A *loan part* is an item that returns from a loan to another company or part trader, but that has no contract with KLM E&M. A *new part* is an item that enters the LHA because it has been

bought at an Original Equipment Manufacturer (OEM). After handling, a new part will be added to one of the other pool types.

- **Destination -** The last characteristic is based on the destination. Goods required for internal storage, usage or repair are part of the *internal KLM* flow, while goods required for external repair follow the *external KLM* flow.

For these characteristics, the possible combinations are shown in the combination-matrix in Table 4.2, leading to thirteen different types of goods:

1. Not recognized goods
2. Unserviceable rotable loan part for internal KLM
3. Unserviceable rotable loan part for external KLM
4. Unserviceable rotable KLM pool part for internal KLM
5. Unserviceable rotable KLM pool part for external KLM
6. Unserviceable rotable Non-pool part for internal KLM
7. Unserviceable rotable Non-pool part for external KLM
8. Unserviceable rotable AFI pool part for external KLM
9. Serviceable rotable AFI pool part for internal KLM
10. Serviceable rotable new part for internal KLM
11. Serviceable rotable KLM pool part for internal KLM
12. Serviceable consumable/repairable new part for internal KLM
13. Serviceable repairable part for internal KLM

		Serviceable	Unserviceable	Rotable	Repairable	Consumable	KLM pool part	AFI pool part	Non-pool part	Loan part	New part	Internal KLM	External KLM
Operation state	Serviceable			x	x	x	x	x			x	x	x
	Unserviceable			x			x	x	x	x		x	x
Category of goods	Rotable	x	x				x	x	x	x	x	x	x
	Repairable	x									x	x	
	Consumable	x									x	x	
Pool type	KLM pool part	x	x	x								x	x
	AFI pool part	x	x	x								x	x
	Non-pool part		x	x								x	
	Loan part		x	x								x	x
	New part	x		x	x	x						x	
Destination	Internal KLM	x	x	x	x	x	x	x	x	x	x		
	External KLM	x	x	x			x	x		x			

Table 4.2: Combination-matrix of characteristics

For all these thirteen types, the required process steps (tasks) and their sequences are shown in Table B.1 in Appendix B, as also recommended by the recipe-based approach [25]. These process steps are based on the existing processes within the LHA and form the basis for the process layout of the virtual entity.

Process layout
The virtual entity of the digital twin is a combination of the types of goods and process steps defined in Table B.1 in Appendix B. The layout of the virtual entity is shown in Figure 4.3 on page 42 and is visualised as follows: Once goods enter the LHA, the goods are identified by the Warehouse Management System (WMS) SAP P55. More information about the control architecture will be explained in the next section. Based on the characteristics of that item in the IT system, it can be assigned to one of the goods types. This is the start of the process of the good. Based on the subsequent task of all groups, the processes through the system are presented with arrows. Each process step involves a queue of goods and the task itself. This representation makes it immediately clear which groups will share particular tasks and queues. In this visualisation, the distinction between regular and disrupted flow is made. If goods follow the process steps as intentionally designed, this is the regular flow, while undesirable additional tasks fall into the disrupted flow. Visualising the disrupted flow is relevant, as the disrupted flow could impact the performance and resource allocation of the regular flow.

The related tasks are described in Table 4.3. The tasks are executed by different departments as visualised in the hierarchical structure in Figure 3.6. In this process layout, the dependencies between departments are directly visible.

Flow	Task	Notation	Description	Responsible department
Regular	Repair Order creation	T_RepairOrder	Creating a repair order (RO) for parts that will be repaired externally.	Supply Chain Ops
	Proforma invoice creation	T_PI	Creating a proforma invoice (PI) for parts that will be shipped by the forwarder	Supply Chain Ops
	Smart Handling	T_SH	Preparing a package for shipment by adding PI (and repair order)	Logistics
	IIG rotables	T_IIGrot	Inspection of incoming rotables to approve them as airworthy	Logistics
	IIG consumables	T_IIGcon	Inspection of incoming consumables/ repairables to approve them as airworthy	Logistics
	IIG loan/borrow	T_IIGloan	Inspection of incoming rotables loaned to an external company	Logistics
	AFI administration	T_AFIadm	Additional administration of parts that are owned by Airfrance Industries (AFI)	Supply Chain Ops
	Scrap	T_Scrap	Write-off parts that cannot be repaired.	Logistics
Disrupted	Not recognized shipment identification	T_NRSI	Manual identification of parts that are not recognized by the IT system.	Logistics
	ZV status handling	T_ZV	Additional tasks that are required before the component can be handled.	Supply Chain Ops
	Quarantine	T_Quarantine	Parts rejected after inspection requiring further action	Different
	Troubleshooting	T_TSO	Solving problems that cannot be done by regular process operators.	Logistics

Table 4.3: Tasks represented within the design

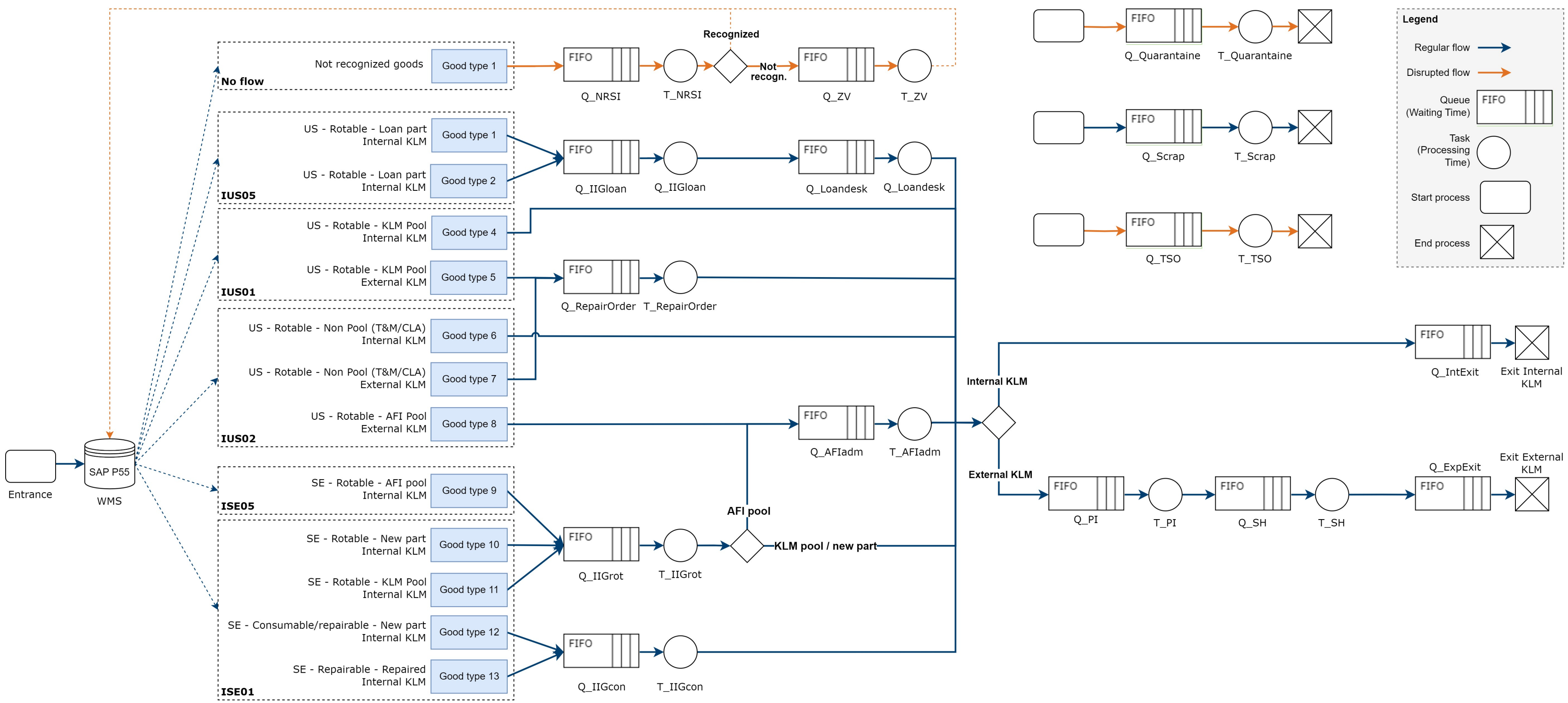


Figure 4.3: Process layout of the virtual entity

4.2.2. Constraints and resources

After the layout of the virtual entity is defined, the parameters that affect the process have to be determined. Based on the IDEF diagram (Figure 4.2), the operation of the LHA is affected by three core elements: input, constraints, and resource allocation. This section discusses parameters related to constraints and resource allocation required to be included in the digital twin model, to represent the physical system. In order to also meet the third requirement (section 4.1), it is required that the data could be obtained from the physical system or assumptions. Understanding the control architecture of the LHA is useful, as it facilitates the identification of necessary IT systems and their data origins. Figure 4.4 provides an overview of this architecture. The control layers are based on the research of Ten Hompel and Schmidt [40]. As can be seen, there is a distinction between the KLM system and the SCHAFER system. SCHAFER is the supplier of the equipment within the LHA. Roughly, three main systems are used: SAP P11, SAP P55 and Crocos. *SAP P11* contains information about all the components within the supply chain, for example, location in the chain, financial transactions and repair details. *SAP P55* is used as a Warehouse Management System for the LHA and the warehouse, containing information about components that are within these locations. If a component is at another location in the supply chain, this will not be visible in the P55. *Crocos* is the IT application that contains the complete history of each rotable component, for example, the history in aircraft and modifications. As can be seen in the control architecture, information from *Crocos* and *SAP P11* will be added to *SAP P55* to make operational decisions within the LHA.

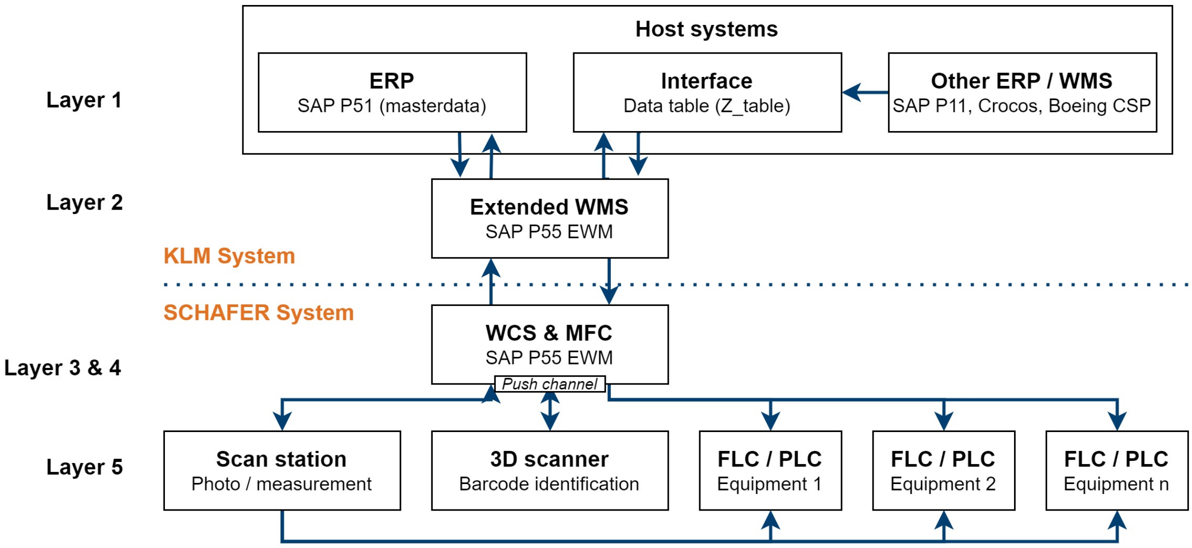


Figure 4.4: Control architecture Logistic Handling Area system (layers based on [40])

The objective of this section is to define parameters that have to be transferred towards the virtual entity to create an accurate representation. Related to constraints and resources in the virtual entity, roughly three elements have to be transferred: resource allocation, backlog of goods and processing time of tasks, as these elements directly impact the performance of the operation.

- **Resource allocation -** Resource allocation involves assigning available employees to specific tasks within the process. As tasks differ in processing times and input, the number of employees needed per task fluctuates. This allocation directly impacts task throughput, which is the volume of goods handled at any given time. In the context of the LHA, these resources primarily encompass assigned employees per task and available workstations. The LHA's equipment is designed to be flexible, allowing tasks to move across various workstations. However, it is crucial to set a limit on the maximum number of workstations. Skill sets also influence task assignments and must be considered a constraint. To create an accurate virtual representation of the LHA, resource allocation needs to be replicated in the virtual entity. This can be achieved manually or in real time based on the number of logged-in employees per task.
- **Backlog of goods -** The operation of the LHA is directly influenced by the number of goods waiting for handling. As goods entering the LHA have to wait until these previously received

goods are handled, an increasing backlog will result in a longer waiting time. While all goods are physically stored in one buffer, they are not all waiting for the same task. Therefore, a distinction has to be made based on the individual tasks shown in the process layout (Figure 4.3). This backlog of goods can be obtained from the Warehouse Management System SAP P55, as this system contains information about goods waiting for handling. However, to allocate specific goods to designated tasks (Table 4.3), data rules must be established (see Table B.3 in Appendix B).

- **Processing time of tasks:** The last element that has to be transferred between the physical and virtual entity is related to processing time. The processing time is defined as the time required to execute a specific task. As it is not possible to define the processing time per unique item, the handling time per type of goods has to be included. Furthermore, productivity can be added as a parameter, as the productivity of executing tasks could differ.

By transferring these elements from the physical to the virtual entity, an accurate and real-time representation of the operational state should be created. However, to forecast the future performance of the LHA, it is crucial to incorporate the process input, a topic that will be discussed in the subsequent section.

4.2.3. Input

The influence of incoming goods on the operations of the LHA is significant. This input is analysed in subsection 3.3.1, revealing significant variability. Meeting requirement 4 (section 4.1), the virtual representation must include this variability in its model, as it is hard to reduce the variability. With a target of processing goods within two days after arrival, forecasting the impact of incoming goods becomes crucial. However, creating an inflow prediction model is not the primary goal of this research. Therefore, the inflow is represented by a variable, incorporating uncertainty to simulate the observed variability. Given the relevance of both quantity and distribution of goods over different types, a distribution factor similar to Figure 3.13 is included. Additionally, besides prediction, the actual daily inflow is essential for assessing performance and can be obtained from *SAP P55*, where all identified packages are logged with timestamps.

Based on the input, constraints and resource allocation, an overview of relevant elements that have to be shared between the physical and virtual entity is shown in Table 4.4. There is a distinction between system and part group level, as some elements are goods type dependent. This is for example helpful in representing the variability in processing times between different types of goods. This is further enhanced by an uncertainty factor of the processing time.

Level	Variables	Parameters	Constants
System	Employees per task (#) Inflow with std. deviation (#)	Employee productivity (%) Uncertainty factor processing time (%)	Skill level per task Number of workstations (#)
Type of good	Backlog per task (#) Inflow distribution factor (%)	Processing time per task (min)	

Table 4.4: Variables, parameters and constants for representation of the physical entity on system and part group level

4.2.4. Output and performance

As visualised in the IDEF diagram (Figure 4.2), the input, constraints, resources and process will lead to a certain output and performance. Related to the main requirement (section 4.1), it is essential that the defined KPIs can be measured in the digital replication. The method of accomplishing this requirement is discussed in this section.

The performance of the process within the LHA will be expressed in Key Performance Indicators (KPIs). A distinction is made between *historical*, *current* and *future* performance. For the evaluation of the current state of the LHA (chapter 3), two KPIs are used: Turnaround Time (TAT) and Work In Progress (WIP). To evaluate the *current performance* accurately, the backlog of goods per task is transitioned

to the virtual replication. This transfer allows for the determination of the current WIP, representing the total number of goods in the system at $t = 0$. Additionally, displaying WIP per task can offer valuable insights, such as possible bottlenecks within the system.
Next to the current performance, visualising the *historical performance* is also relevant. Assessing historical performance involves calculating the *average TAT* by analyzing the average total handling time of goods that have left the LHA over the past time. This data can be obtained from the Warehouse Management System SAP P55.
As it is also helpful that the expected impact of changes in input, constraints and resource allocation can be assessed, the *future performance* also has to be included in the virtual replication. As the combination of input, constraints and resource allocation leads to an expected output over time, the trend of the WIP can be used as a future performance indicator. Adding the prediction of output gives process operators the capability to have proactive coordination, focusing on the best performance.

An overview of the KPIs for assessing historical, current and future performance is visualised in Figure 4.5. Both the historical TAT and the current WIP will be based on the available data from the Warehouse Management System. The future WIP can be determined by a prediction of future input and output. Due to the uncertainty in the process, it is likely that future performance cannot be determined weeks in advance. This is, of course, no issue for historical performance.

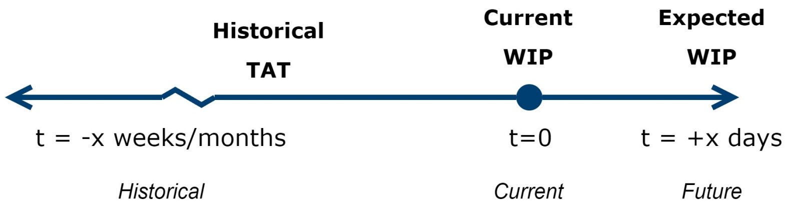


Figure 4.5: KPIs for the digital twin

4.3. Conclusion

The challenges the LHA faces are translated into a design of the digital twin that should *'provide real-time insight into the past, the current and future state of the LHA.'* In order to ensure that this digital representation accurately reflects the physical system and answers SQ6, five key requirements are formulated, with requirement 1 considered as the most important: *The digital twin must be able to calculate the KPIs of the LHA*. To meet this requirement, requirements 2 to 4 have to be met. The second requirement is fulfilled by creating a simplified and comprehensive design of the processes involved, according to a structured methodology. The third requirement, related to data transfer, is reached by transferring three core elements towards the virtual replication: resource allocation, processing times and the backlog of goods. Based on these elements, together with the (expected) input, the behaviour of the LHA should be replicated. To include the behaviour of the environment of the LHA, variability in input and processing times is added (requirement 4). The subsequent chapters will focus on the last requirement, as the design concept has to be evaluated and demonstrated by creating a simulation model.

5

Concept simulation setup

In the previous chapter, a design for a digital twin concept is developed, together with the required parameters and KPIs. However, the value of this design in supporting operational coordination has to be proved. Therefore, this chapter describes the simulation developed to show the concept of applying this digital twin for scheduling and coordination. The following sub-question is attempted to be answered:

Subquestion covered in this chapter

- SQ7: How can the digital twin concept be simulated to demonstrate the concept?

In section 5.1, the used simulation technique is described, whereafter the simulation structure (section 5.2) and input data (section 5.3) are outlined. The conclusion of this chapter is described in section 5.4.

5.1. Discrete-event simulation

Simulations serve as useful tools for testing the impact of changes without disrupting the actual system. They can be broadly categorized into discrete and continuous simulations. Discrete Event Simulation (DES) proves effective for scenarios where variables change at specific, discrete times or steps (events). On the other hand, continuous simulation is better suited for scenarios where variables change continuously over time [41]. When employing DES, each event triggers an immediate change in the system's state. However, it offers limited insight into the system's behaviour between these distinct events [42]. In the context of handling goods within the LHA, what matters are the process steps rather than the intermediary tasks, such as transportation, between these steps. Therefore the application of DES is sufficient.

There is different DES software available. For this research, MATLAB Simulink is used. This software is supported by Delft University of Technology and has the advantage that it can be built very visually. This can help in presenting the concept to stakeholders.

5.2. Simulation structure

In chapter 4, the design of the virtual entity of the Digital Twin is described and visualised. This layout of the virtual entity (see Figure 4.3) is used as the model structure for the simulation. As shown in the IDEF diagram in Figure 5.1, the virtual entity of the LHA is affected by the input of SE and US goods. These goods undergo processing, influenced by factors such as the allocation of employees and constraints imposed by the backlog, resource capacity, and processing time. Consequently, this process delivers a certain output of goods. Next to this output, the performance evaluation occurs through Key Performance Indicators (KPIs).

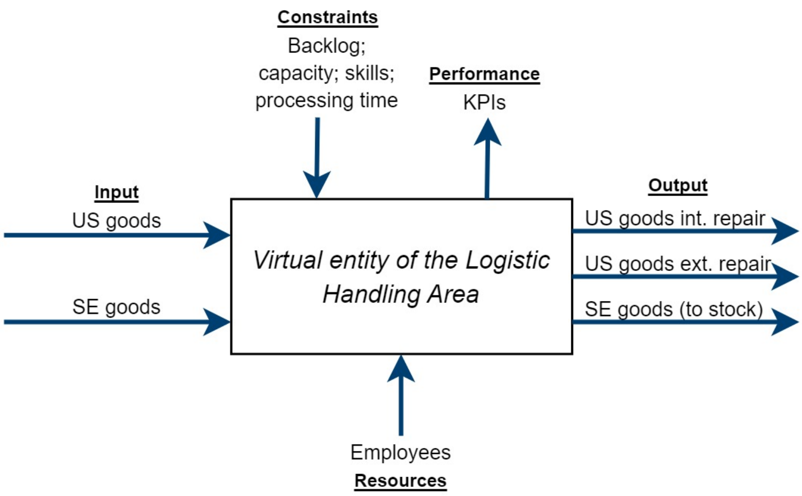


Figure 5.1: IDEF Logistic Handling Area

The goal of this simulation is to simulate the behaviour within the 'box' of the virtual entity in Figure 5.1 based on changing inputs, constraints and resources. The effects will be visualised by measuring the KPIs and expected output of the system.

5.2.1. Building blocks of the MATLAB model

MATLAB Simulink uses block-based modelling, where different blocks represent different system elements. The used blocks for this simulation are described in Table 5.1.

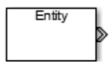
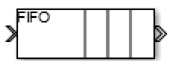
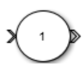
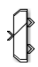
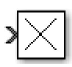
Block name	Represents	Symbol	Description
Entity generator	Inflow of goods		The entity generator is necessary to simulate the inflow of goods into the model. Based on an inter-generation time or an event trigger, the generator creates an entity (in this case goods) that flows into the model. This entity contains attributes: characteristics, such as processing time, that are related to this specific entity and are used by other blocks.
Entity queue	Queue before task		The entity queue acts as a buffer before entities can be served. The entities can be served based on priority or FIFO.
Entity server	Actual task		The entity server represents a capacity-constrained task.
Output switch	Decision		The output switch directs an entity in a direction based on the attribute. Since certain goods share some tasks but require additional tasks, redirecting these goods becomes necessary.
Entity terminator	Outflow of goods		The entity terminator represents the outflow of goods. Once an entity arrives at this block, the simulation considers the entity as completed.

Table 5.1: Used building blocks for the simulation

5.2.2. Simulation logic

In this section, the simulation logic is described to give some insight into the working principle of the simulation. An overview of the created simulation is shown in Figure C.1 in Appendix C.

Model parameters	Entity parameters
Total inflow per run	Percentage of total inflow
Standard deviation inflow per run	Processing time per task
Employee allocation per task	Decisions
Percentage standard deviation processing time	

Table 5.2: Model and entity parameters

Creating goods - First, the entities are generated, representing the inflow of goods into the LHA. This is done by a custom MATLAB code that distributes the defined total inflow per simulation run over the different types (type 1 to 13), based on a defined percentage per type. Then, there are two options for inflow: uniform and normal distribution over time. The effects are visible in Figure 5.2. Then, the different entities are generated by the event trigger. As can be seen in Table 5.2, there is a difference between parameters defined on the model and entity level. Model parameters are applicable for all defined types of goods, while entity parameters are type-specific.

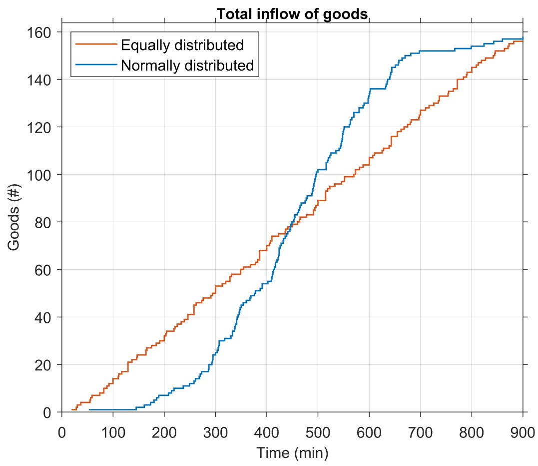


Figure 5.2: Difference between uniformally and normally distributed input

Queuing goods - Every task contains three elements: a backlog generator, an entity queue, and an entity server, see Figure 5.3. The backlog generator creates entities at time zero in the simulation to represent the goods that are waiting for a task (WIP in the current state). These goods flow into the queue. While the LHA contains a physical buffer for storing goods, the queue represents the backlog of goods waiting for specific tasks in this simulation. Each task has a buffer that can be shared by different types of goods. The enitites are served as FIFO. In this simulation is the buffer capacity defined as infinite so that all goods can flow into the queue.

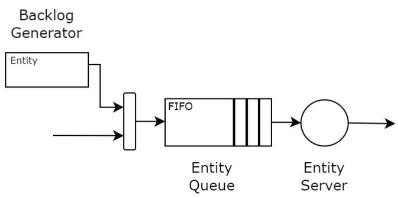


Figure 5.3: Build-up of tasks

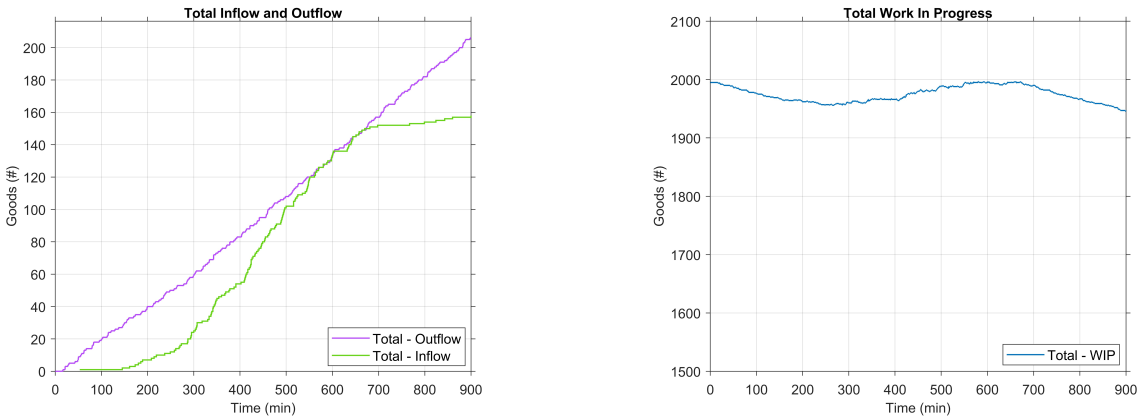
Serving goods - If there is availability for executing a task, the goods flow from the queue towards the entity server. For every task, the allocation of employees can be defined. The time it costs to execute that task, the processing time, is defined per type of goods. This results in a varying processing time. Besides varying processing times for different types of goods, there are also variations within one type. This is simulated by adding an uncertainty factor, so the processing times are not always equal.

Terminating goods - After completing one or more tasks, entities arrive at the entity terminator. Within the simulation, four terminator blocks are defined. The blocks coupled to type 1 goods trigger the generation of types 5 and 11, as these goods flow from the disrupted flow into the regular flow. The other two terminator blocks visualise the two possible destinations after executing the process within the LHA: internal and external KLM. These blocks represent the end of the LHA process.

5.2.3. Performance monitoring

In subsection 4.2.4, an overview of performance assessment within the digital twin is visualised. The performance of the LHA will be evaluated by computing two primary KPIs: Work in Progress (WIP) and Turnaround Time (TAT). These KPIs are also integrated into the simulation for real-time assessment of the LHA process and predictive analysis. The complete list of indicator monitors is listed in Table B.2.

- **Work In Progress:** Monitoring of the WIP is useful for determining the amount of work that has to be done (at a specific task). The WIP gives a first indication of potential bottlenecks in the process. Therefore, both the number of goods that are waiting for a specific task and the total number of goods in the system are monitored over time. The simulation can calculate the WIP over the simulation time, which helps make predictions for *future performance*. The development of the WIP is based on the difference between the inflow (in specific queues) and the outflow. By an inflow > outflow, the WIP increases, while an inflow < outflow results in a lower WIP. Therefore, also the inflow and outflow (per task) can be monitored over time. The link between WIP, inflow and outflow is visualised in Figure 5.4. The WIP at $t = 0$ (5.4b) results from the backlog of goods at the tasks, representing the current state of the LHA. The WIP between $0 < t \leq 480$ is the expected WIP based on the difference between expected inflow and outflow (5.4a).



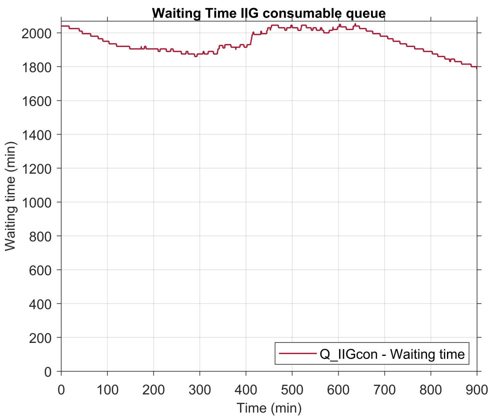
(a) Inflow and outflow over time

(b) Work In Progress over time

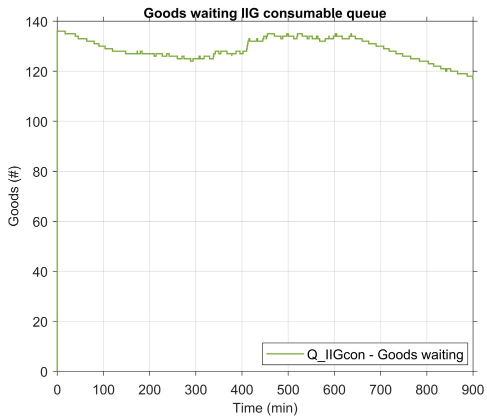
Figure 5.4: Link between WIP, inflow and outflow

- **Turnaround Time:** WIP is a useful indicator to determine the performance of a process at this moment in time or in the future. However, to assess the performance of handled goods in the past, TAT is a more useful indicator. The TAT is defined as the time between a good has entered and left the LHA system. In this simulation, only the TAT of goods that are generated and have reached the terminator block within the simulation time can be calculated, as there is in this simulation no historical data available about the moment goods in the backlog are generated. Therefore, the trend of waiting time in queues is a better indicator for future TAT performance. The waiting time for a queue is calculated by Equation 5.1, and results in a graph as Figure 5.5a and is directly related to the number of goods waiting (5.5b).

$$\text{Waiting time} = \frac{\sum_{i=1}^{n} \text{Processing time}}{\text{Nr. of employees} * \text{Productivity}} \tag{5.1}$$



(a) Waiting time of IIG consumable queue over time



(b) Number of goods waiting in IIG consumable queue over time

Figure 5.5: Link waiting time and goods waiting

5.3. Input data

The input data consists of two main types: fixed parameters, and variable model parameters. The fixed parameters remain constant during the experiments and are based on the analysis of the LHA (chapter 3) and assumptions validated by KLM E&M employees. An overview is shown in Table 5.4. The variable model parameters will change during the experiments and are summarized in Table 5.3.

	Variable 1	Variable 2	Variable 3
Input	Total inflow per run (#)	Standard deviation inflow per run (#)	
Constraints	Backlog per task (#)	Productivity (%)	Uncertainty factor processing time (%)
Resources	Resource allocation per task (#)		

Table 5.3: Variable parameters

5.4. Conclusion

The objective of this chapter is to show how the simulation is created that can be used for experiments to prove the value of a digital twin. The requirements and design from chapter 4 are translated into a Discrete Event Simulation (DES) by using MATLAB Simulink. The simulation's structure allows for the substitution of parameters with real-time data sourced from the physical LHA system. However, this simulation is not connected to any system. To prove the concept of the digital twin, the behaviour of the LHA can be simulated by defining different parameters. After creating the simulation, verifying and validating the simulation is essential to execute accurate experiments.

	Total inflow	T_NRSI	T_ZV	T_RepairOrder	T_PI	T_SH	T_AFIadm	T_IIGrot	T_IIGcon	T_IIGloan	T_Loandesk
Type	**Distribution (%)**	**Processing time (min)**									
Type 1 - Not recognized part	30%	10	15								
Type 2 - Return after loan - Internal KLM	0%									20	15
Type 3 - Return after loan - External KLM	0%				10	15				20	25
Type 4 - US Rotable KLM pool - Internal KLM	2%										
Type 5 - US Rotable KLM pool - External KLM	7%			30	5	15					
Type 6 - US Rotable Non pool - Internal KLM	1%										
Type 7 - US Rotable Non pool - External KLM	3%			20	5	15					
Type 8 - US Rotable AFI pool - External KLM	4%				5	15	25				
Type 9 - SE Rotable AFI pool - Internal KLM	5%						25	30			
Type 10 - SE Rotable new part - Internal KLM	5%							25			
Type 11 - SE Rotable KLM pool - Internal KLM	19%							40			
Type 12 - SE Consumable/Expendable new part - Internal KLM	20%								15		
Type 13 - SE Repairable repaired - Internal KLM	4%								20		

Table 5.4: Fixed parameters

6
Concept verification and validation

The developed design of the digital twin is translated into a simulation model in chapter 5. As the value of the digital twin will be evaluated by some experiments with the simulation, the developed simulation has to be correct. This is evaluated by different verification tests and model checks in section 6.1. The results of the verification can also give a first indication that this method of replication is a valid one. Furthermore, as the developed digital twin and simulation have to be an accurate representation of the LHA, the model is also validated by an expert review (section 6.2). This chapter tries to answer the following subquestion:

Subquestion covered in this chapter
• SQ8: Is the developed design and simulation an accurate representation of the LHA?

6.1. Verification

During verification, checks and tests will be executed to verify that the designed model is translated into a simulation correctly, or in other words: '*Is the simulation right?*' This verification is done based on checks and tests found in the literature. In the research of Sargent [43], different simulation verification and validation methods are described. In the sections below, different model checks and tests are executed.

6.1.1. Model checks

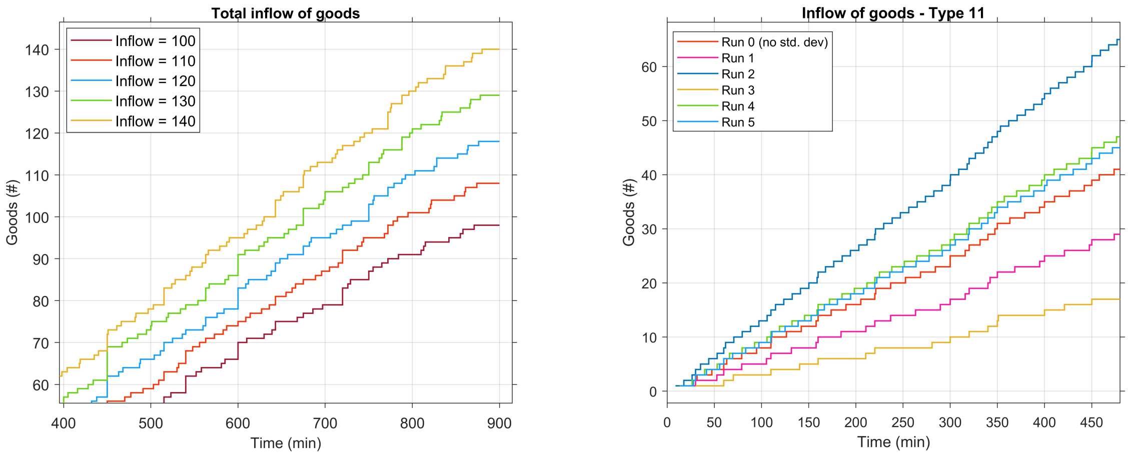
First, checks on the model are executed during the development of the simulation. This includes antibugging, signal tracing and input checks.

Antibugging - Antibugging includes executing additional checks by adding plots and counters. Within the simulation model, many signal analysers are added to track the behaviour of goods within the generator, queue, task and terminator blocks. During the development of the simulation cross-checks are executed to see if the links between the different blocks are also visible within the graphs and counters. No errors were found.

Signal tracing - To verify that all types of goods are following the right path within the simulation, the signal trace function within MATLAB Simulink is used. This shows if the model logic is correct and if the right processing time is used for every task the signal visits. This signal trace function is used to test all thirteen types of goods. During this check, it was verified that the goods follow the route as defined in the design.

Input check - As described in the simulation logic in chapter 5, the total input is based on a defined parameter. The total inflow is distributed over the types of goods by a defined distribution parameter. Then, the inflow per type is equally or normally distributed over the run time of the simulation. As only integers can be handled by the entity generator, the amount of goods per type is rounded to integers.

This results in some differences between the defined inflow and the actual inflow, as can be seen in Figure 6.1a. In these experiments, the standard deviation is defined as zero. However, since this error is the same every run and the physical system also has a deviation between expectation and actual inflow, this error is not considered a problem. In the second test (6.1b), the use of standard deviation is proved. This figure shows that the simulation defines every run a new inflow based on the mean inflow and standard deviation.



(a) Actual inflow vs. defined inflow

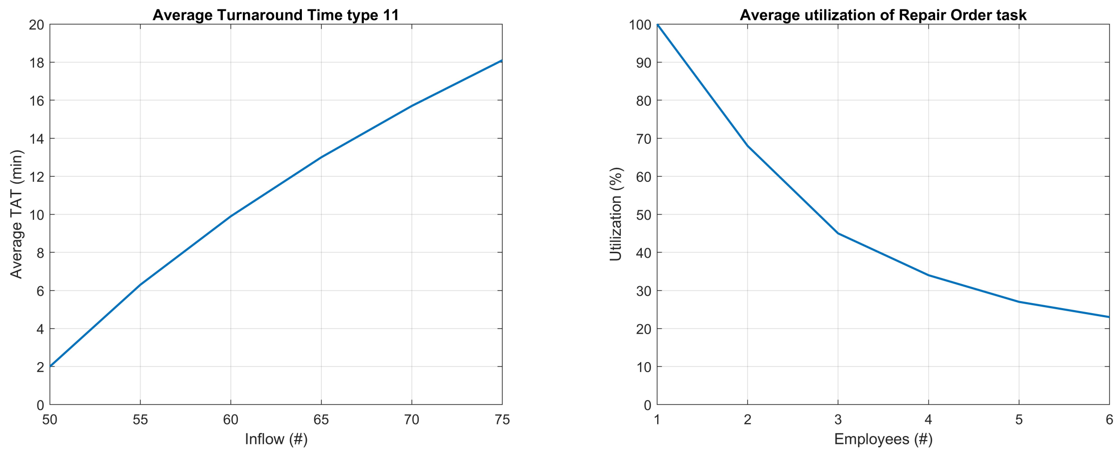
(b) Actual inflow of type 11 with standard deviation

Figure 6.1: Input checks

6.1.2. Tests

Next to model checks, also run tests are performed to see if the outcomes of the simulation are right based on the defined inputs. In this section, the results of three verification tests are described [43].

Continuity test - The continuity test verifies that a small change in an input value in the model will not result in very large output values. In other words, running the model several times with slightly changing one parameter shouldn't result in large differences in the output value. Related to this simulation, the inflow-TAT (6.2a) and employee-utilization (6.2b) continuity are tested, see Figure 6.2.



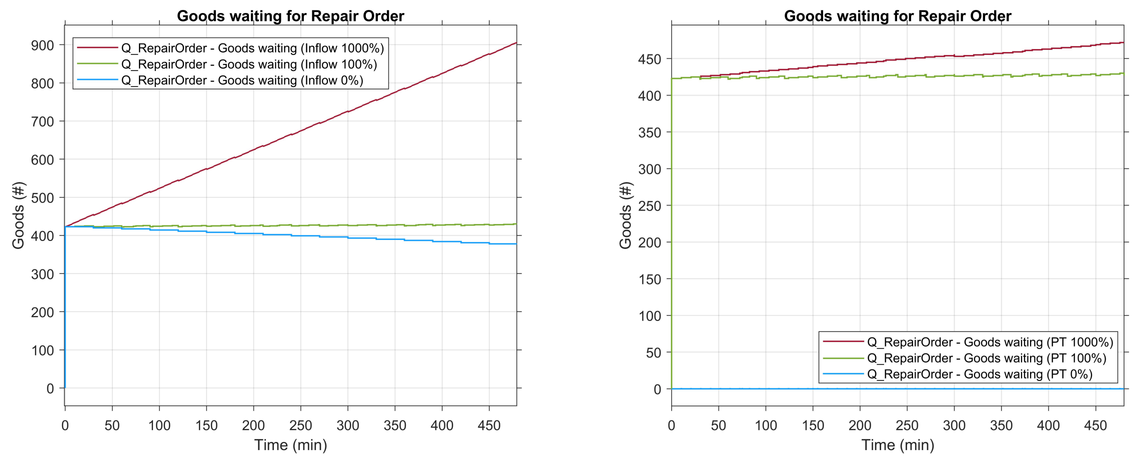
(a) Average Turnaround Time good type 11 related to a different amount of inflow

(b) Average utilization of employees in Repair Order task related to number of employees

Figure 6.2: Continuity tests

As expected, the TAT will increase when the inflow of that type of good increases and other parameters will remain constant. This is the result of a queue at one or more tasks. The decrease in utilisation can also be explained by an increase in the number of workers. This is because allocating more workers to a task results in insufficient goods to keep everyone constantly engaged.

Degeneracy test - The second test encompasses the extreme value test. This test checks if the simulation works for extreme conditions. For both scenarios, the queue length of the Repair Order task is measured. In test 1 (Figure 6.3a), the queue length at regular inflow (100%) is compared with an inflow of zero times (0%) and 10 times (1000%) the regular inflow. In test 2 (Figure 6.3b), the same test is executed but for a changing processing time. In both tests is the backlog of goods at $t = 0$ visible. An extreme inflow directly results in a significant increase in queue length, while at an inflow of zero, the backlog can be decreased by processing goods. In case of a processing time of 0%, the backlog and incoming goods can directly be handled, which results in a queue length of zero. In case of a higher processing time, the queue length will increase as the outflow is lower than the inflow. The outcomes look correct for all degeneracy tests.



(a) Repair Order queue length for different inflows

(b) Repair Order queue length for different processing times

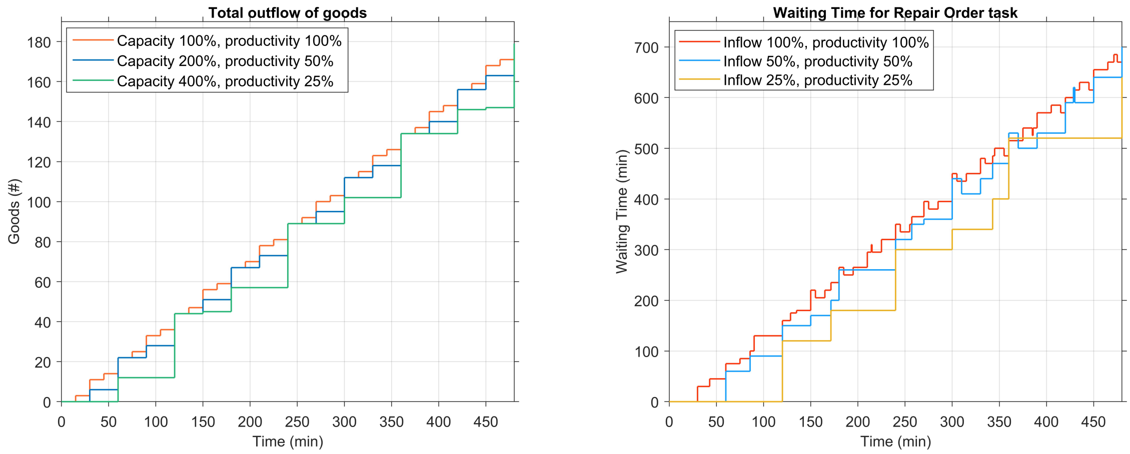
Figure 6.3: Degeneracy tests

Consistency test - The third test, the consistency test, checks if the model produces similar results for parameters that should have equal effects. Test 1, shown in Figure 6.4a, visualises the outflow of goods at a certain number of employees at tasks (capacity) and productivity. Productivity impacts the amount of goods that can be handled per employee per hour. A lower productivity requires more employees to handle the same amount of packages. Therefore, doubling capacity and halving productivity should lead to more or less the same outflow. As can be seen, the outflow is not completely equal for every moment in time, as a lower capacity but shorter processing time results in a smoother outflow compared to a higher capacity and longer processing time. The second test (Figure 6.4b) also checks consistency but is now related to inflow and productivity. A lower inflow should result in less waiting time in a queue, but when the processing time is longer due to lower productivity, the waiting time should be equal. This is tested for three scenarios, and again the result is almost equal. However, this is only the case when a task has no backlog at the start of the simulation.

After conducting different checks and verification runs, it is evident that the model has been accurately translated into the computerized version. In other words, the simulation performs as intended. Next to the fact that it is translated correctly, it also gives a first indication that this way of representing the LHA is valid, as it gives outcomes as expected.

6.2. Validation

Now that the simulation has been verified, it is important to answer the next question: '*Is this the right way of representing the system?*'. This is required to prove that the developed digital counterpart is



(a) Capacity-productivity consistency

(b) Inflow-productivity consistency

Figure 6.4: Consistency tests

accurate enough to be used as a model for the LHA system. In the research of Sargent [43], different validation techniques are described. A common technique is the comparison of the model outputs against the actual system outputs. However, using this technique is difficult, mainly due to the difficulties which the entire supply chain of KLM E&M faces at this moment. This results in the fact that the processes within the LHA are not always carried out as designed, making representative measurement difficult. Therefore, an expert review is executed with different experts from KLM E&M to validate the developed concept. Also, the process operators were involved in this review. During the review, the input parameters, model logic and possible value for the LHA are examined. Starting with model logic, experts agreed that this logic was a valid way to represent the process. The comprehensive overview that is created is an accurate representation of all the processes within the LHA. Furthermore, the interaction between individual tasks and flows was correct, for example the relationship between the disrupted and regular flows. Related to the parameters, the used values were approved by the experts as they were also partly based on their expertise. However, the used values are an average of that type of goods. In the coming months, the used values will be validated by manual measurements by employees. These measurements can help make the model even more accurate. The value they see in applying the digital twin in the process will be used as input for the next chapter. However, they are already taking some steps to turn the concept into an actual application. To conclude, the concept is useful, but some input parameters need to be validated for a more accurate representation.

6.3. Conclusion

In this chapter, the primary objective was to assess the accuracy of the design and simulation in representing the LHA, specifically addressing subquestion 8. This verification and validation process is crucial to verify the value of the concept in operational coordination. Initially, the simulation underwent verification, with model checks and test runs confirming its expected performance. This initial assessment provided an initial indication of the design's correctness.

To confirm the validity of the LHA representation, both the digital twin's design and simulation were subjected to validation through expert review. Since the simulation serves as the computerized version of the developed design, both the simulation and design are validated. The outcome of the validation session delivered only minor recommendations, which, notably, do not directly impact the subsequent experiments demonstrating the value of the concept. These experiments are described in the following chapter.

IV

VERIFY

7

Value assessment

In chapters 4-6, the design and simulation are discussed by focusing on the development of the digital twin and the required transfer of data. This chapter focuses on the interaction between the virtual replication and the physical system, see Figure 7.1. It describes the necessity and value it gives in the context of operational coordination in a system as the LHA. This chapter aims to answer the following subquestion:

Subquestion covered in this chapter

- SQ9: What is the added value of the digital twin on the operation of the LHA?

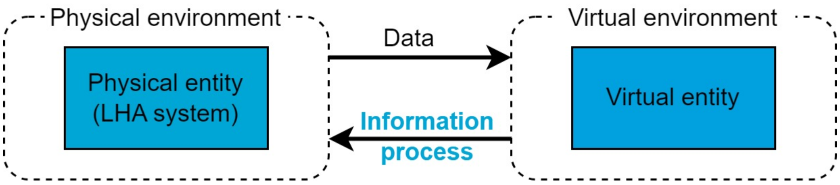


Figure 7.1: Scope of chapter 7 (highlighted in blue)

In chapter 3, four main challenges of the LHA are addressed: influence of a variety of processes; the presence of various bottlenecks; uncertainty and variability in daily inflow; and lack of integral coordination. These challenges result in difficulties in coordinating tasks and scheduling employees. Because of the lack of clarity on how certain decisions affect operational performance, the digital twin aims to provide insight into the past, present and future state of the LHA. This should support operational decision-making.

7.1. Impact of variability

The developed simulation offers the possibility to simulate the behaviour of the LHA, creating insight into the effects of variability in the LHA system. Therefore, several experiments are executed to show the issues the LHA could face. By proving the operational effects of variability, the value of a digital twin application can be supported.

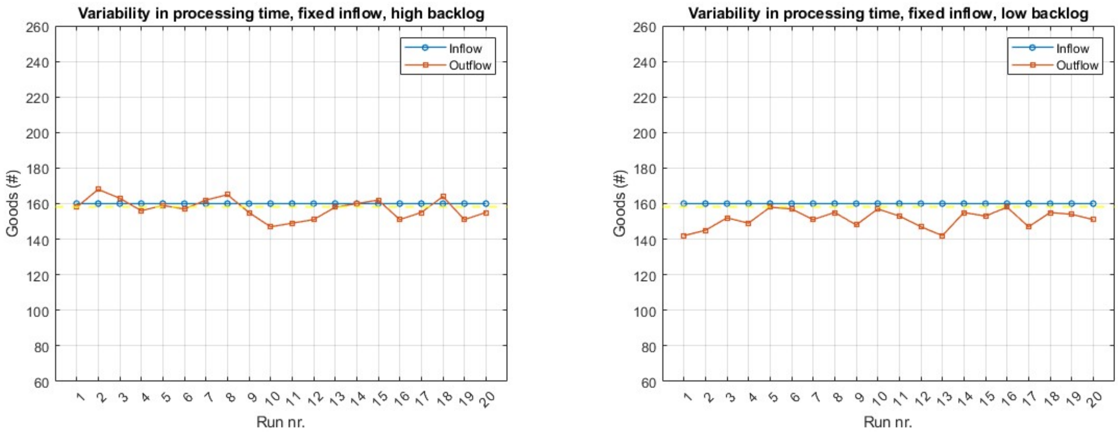
7.1.1. Variability in inflow (distribution)

As outlined in chapter 3, the performance of the LHA is affected by the variability the system faces. Related to the inflow of goods into the system, the variability is caused by two types: variability in the number of goods entering the system and the composition of these incoming goods. The composition of the goods determines the distribution into different types of flows. In Figure 7.3 on page 59, six different scenarios are visualised. The purpose of the simulation is to show the effect on the number of goods leaving the LHA (outflow), as the goods are then further processed in the supply chain. As

explained, a stable flow is desired for other steps of the supply chain. For every variability scenario, the effect with a high backlog (>100 goods) and low backlog (<10 goods) per task is simulated for twenty different test runs. This is relevant, as some effects of variability are only visible when there is a small buffer of goods. Other than the parameters that experience variability, there are no changes to parameters such as resource allocation.
The yellow line visualises the outflow without any variability, while the red line expresses the actual outflow. The inflow is visualised with a blue line. In Figures 7.3a/7.3b, the inflow variability is shown, while in Figures 7.3c/7.3d the distribution is varied. In Figures 7.3e/7.3f, the effect of the combination of the number of inflow and distribution has been tested. From the experiments, a few things are notable. Variability in case of a high backlog per task does not directly affect that day's outflow, as long as the backlog is high enough to absorb the variability. However, as the objective of the LHA is to handle goods within one day, the backlog has to be low. Therefore, also the effect of inflow variability is simulated in this scenario. These experiments show a direct effect on the outflow of that day, as the resource allocation is not adapted to this variability. Especially the combination of inflow and distribution over types of goods shows a negative and unstable impact on the outflow.

7.1.2. Variability in processing times

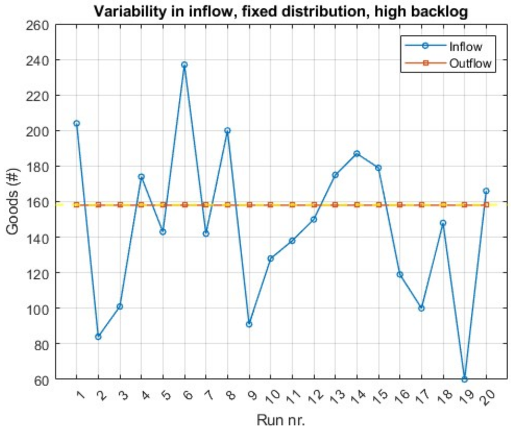
Next to variability in inflow, the variability in processing times is also an issue. The processing time is the time required to execute a specific task. The variability is caused by the wide variety of goods handled within the LHA, however, also identical goods can have a varying processing time. In the operation, this can result in a lower or higher outflow than expected, leading to a certain uncertainty in the outflow. This is visualised in Figures 7.2a/7.2b. Both in the experiments with a low and high backlog, the outflow is influenced by the processing time variability.



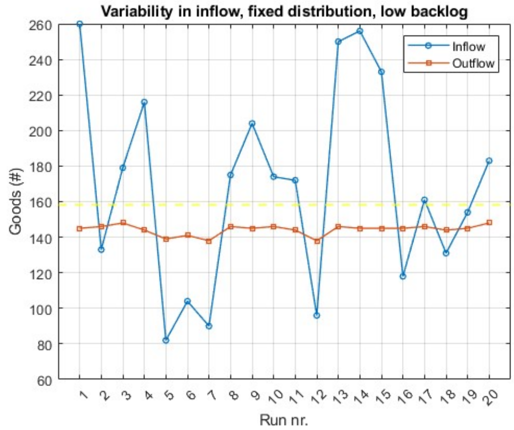
(a) Fixed inflow, variability in processing time, high backlog

(b) Fixed inflow, variability in processing time, low backlog

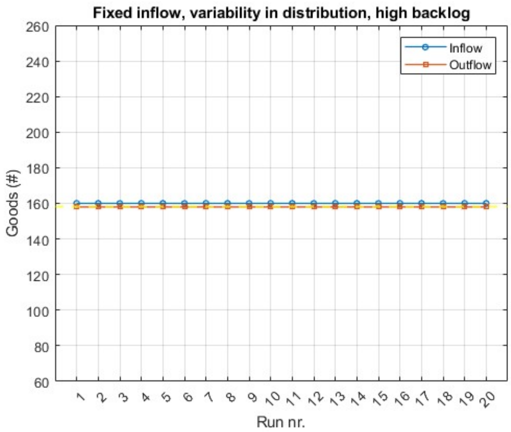
Figure 7.2: Impact of processing time variability on outflow



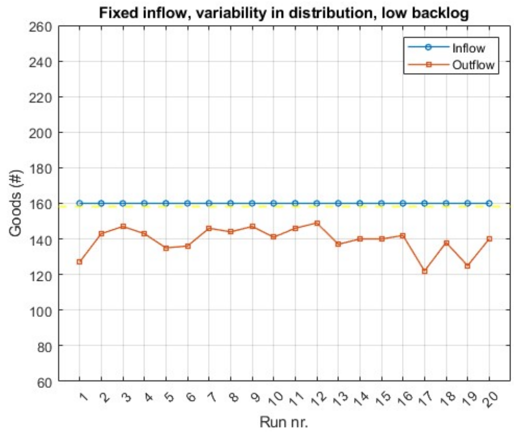
(a) Variability in inflow, fixed distribution, high backlog



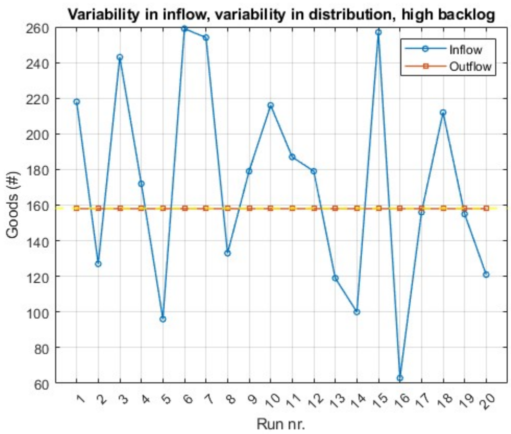
(b) Variability in inflow, fixed distribution, low backlog



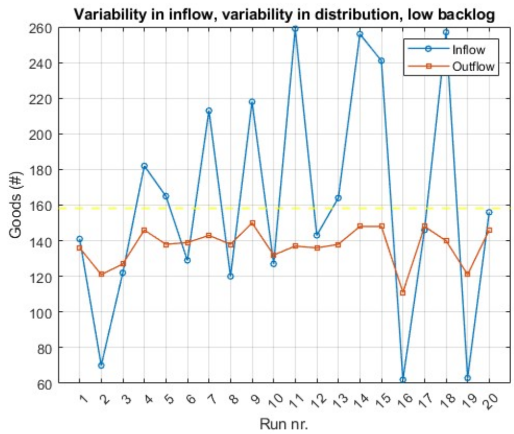
(c) Fixed inflow, variability in distribution, high backlog



(d) Fixed inflow, variability in distribution, low backlog



(e) Variability in inflow and distribution, high backlog

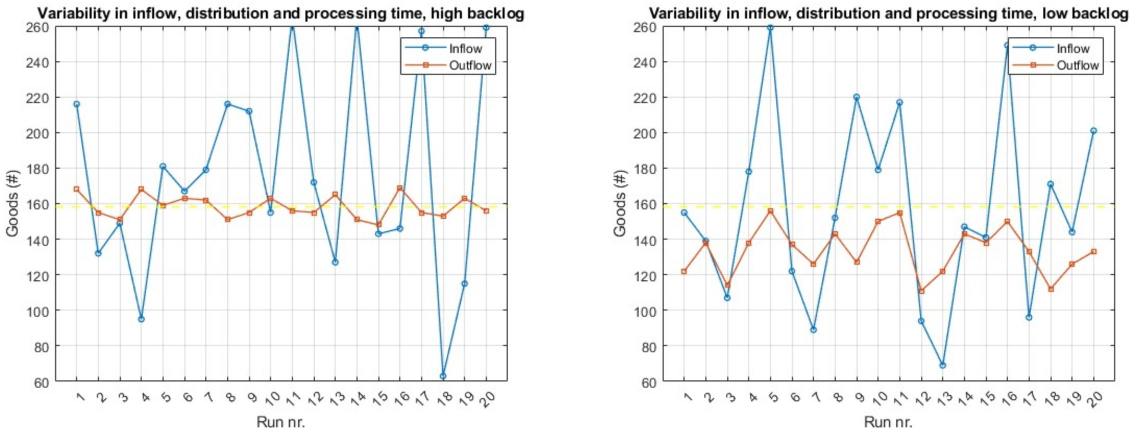


(f) Variability in inflow and distribution, low backlog

Figure 7.3: Impact of inflow (distribution) variability on outflow

7.1.3. Variability in inflow, distribution and processing times

As the variability in inflow, inflow distribution and processing times influence the LHA, also the combined effect is tested. Here the strengthened effect of the processing time variability is (Figure 7.4b) visible compared to only inflow variability (Figure 7.3f). In all tested scenarios, the outflow is lower than in an environment with no variability. However, especially the large differences in outflow create uncertainty and instability in daily outflow, leading to fluctuations within the other steps of the supply chain.



(a) Variability in inflow, distribution and processing time, high backlog (b) Variability in inflow, distribution and processing time, low backlog

Figure 7.4: Impact of inflow, distribution and processing time variability on outflow

7.2. Value for operation

In the previous section, the effects of variability on the outflow are visualised. From these experiments can be concluded that the variability gives a certain unpredictability in outflow, which reverberates through the other process steps in the MRO supply chain. The challenges that come with variability can be solved roughly in two ways: reducing the variability or finding a way to manage this. Within the literature review (chapter 2), buffering of time, inventory or resources is described as the effect of this variability. However, as mentioned, this is very undesirable, especially buffering time and inventory. This section assesses the value of a digital twin, including the value related to managing this variability. Also, the value of the digital twin related to the other issues the LHA faces are discussed.

As visualised in Figure 7.1, there is a real-time transfer of data between the physical and virtual systems. However, the added value lies within the information that can be retrieved from the virtual system and can be applied to the physical system to improve the operation. Figure 7.5 gives an overview of the interaction between the physical and virtual entities, together with the role of the process operators (Figure 3.6). As can be seen, the virtual replication will be implemented alongside the physical process, to support the operation by giving guidance.

The interaction between the physical system and the digital twin starts by executing the process (1). By transferring data towards the digital twin (2), the performance can be calculated by the digital counterpart (3). Based on the state (4), the process operator can decide to make some adjustments, for example reallocating some employees to other tasks. This changing state of the system may, for example, be due to variability that affects the performance. Based on the data of the physical system and predicted inflow, the process operator can execute some experiments to evaluate the effect of certain changes (5). This can be done without interrupting the actual process. If the operator agrees with the new allocation of employees, the changes can be implemented into the physical system, together with new operational targets (6). However, the variability still impacts the operation. While the developed digital twin incorporates specific variability, the unpredictable nature of some variability creates a challenge for a complete accurate simulation of future performance. This can result in a mismatch between the predicted and actual operation. Therefore, the coordination of the process becomes an ongoing cycle involving continuous **monitoring, testing, and target setting**. The values

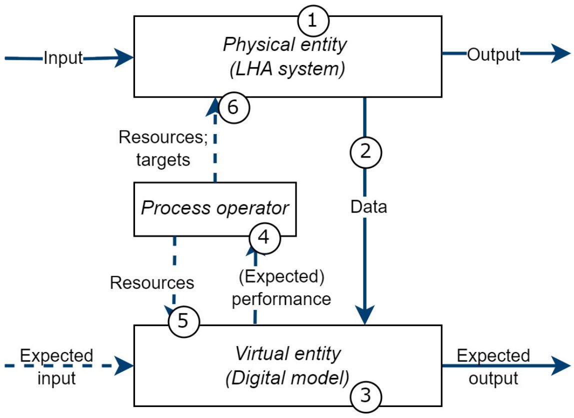


Figure 7.5: Interaction between physical and virtual entity

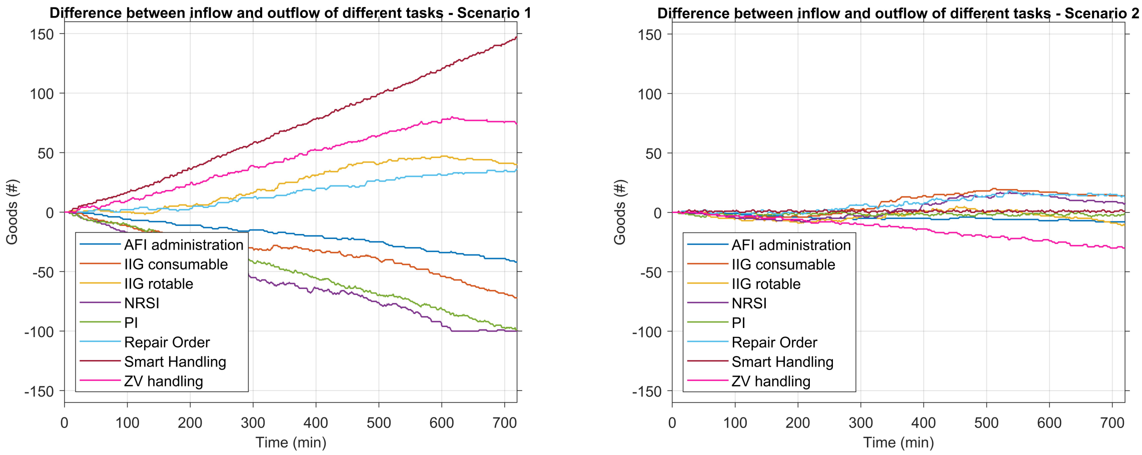
a digital twin gives in relation to operational coordination are described in sections 7.2.1, 7.2.2 and 7.2.3.

7.2.1. Real-time monitoring of KPIs

This value is linked to the descriptive value provided by a digital twin. The developed concept enabled the possibility to real-time measure and analyse the historical and present state of a complex system with many interactions, by calculating the defined KPIs. This presents a significant enhancement compared to the current operation, as the interaction within the system was not transparent. Additionally, various departments responsible for specific tasks currently rely on individual monitoring dashboards, creating a lack of integral coordination. This real-time monitoring of KPIs enables the possibility to shift from a reactive strategy towards a proactive strategy, as adequate actions can be taken. As described, all the information used in this digital twin is extracted from the Warehouse Management System (WMS) SAP P55, resulting in one single, reliable source. Coupled with the developed simplified layout of the processes, this facilitates a clear evaluation of the current system state. A diverse range of information can be visually presented, including Turnaround Time (TAT) for processed goods, actual waiting times, and backlogs (WIP) at specific tasks. This immediate visualization supports the identification of potential bottlenecks in the system, for example, an imbalance between inflow and outflow in a certain task (see example 1). A complete list of indicators that can be monitored is summarized in Table B.2.

Example 1: Monitoring inflow and outflow per task

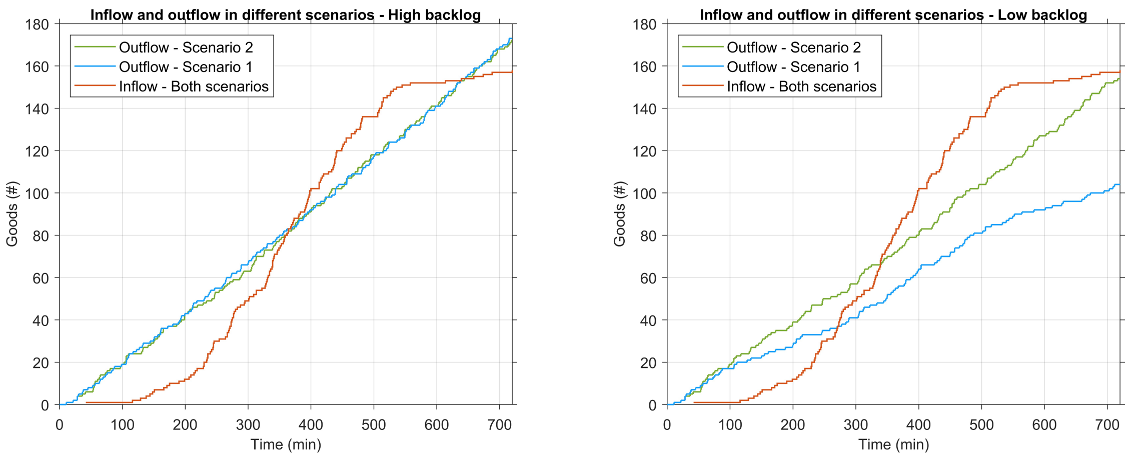
The digital twin provides not only visibility into KPIs, but also insights into the strategies for achieving these KPIs. A consistent and predictable daily outflow is essential for maintaining a stable supply chain. The digital twin assists process operators in managing the system to ensure this stability. Through continuous monitoring of, for example, the difference between inflow and outflow for each task, not only optimal performance can be realized, but also a steady operational state can be maintained. In Figure 7.6, two scenarios for resource allocation are visualised. In both scenarios, the same total outflow is reached with the same amount of employees, as can be seen in Figure 7.7b. However, in scenario 1 (Figure 7.6a), the processes operate less stably, as particular tasks have a significant over- or under-capacity. This results in shifts of backlogs to other tasks in the process. In scenario 2 (Figure 7.6b), the process is more stable, as the difference between inflow and outflow is almost equal for all tasks. The digital twin gives the ability to monitor this operation, which becomes more important when the backlog of goods decreases. In Figure 7.7b, the impact of both resource allocation scenarios with a low backlog is visualised. Here it can be seen, that the imbalance between inflow and outflow directly results in a lower outflow, and thus a lower performance.



(a) Scenario 1: Unstable inflow vs. outflow for different task

(b) Stable inflow vs. outflow for different tasks

Figure 7.6: Scenario 2: Difference between inflow and outflow per task for different scenarios



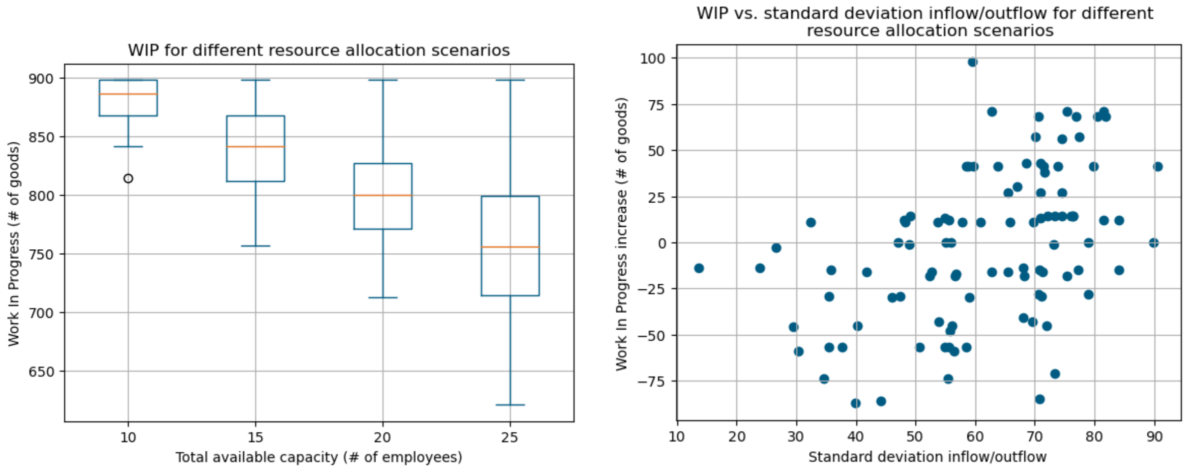
(a) Inflow and outflow with a high backlog of goods

(b) Inflow and outflow with a low backlog of goods

Figure 7.7: Inflow and outflow of goods in for scenario 1 and 2 and high or low backlog

7.2.2. Dynamic testing of needs-based resource allocation

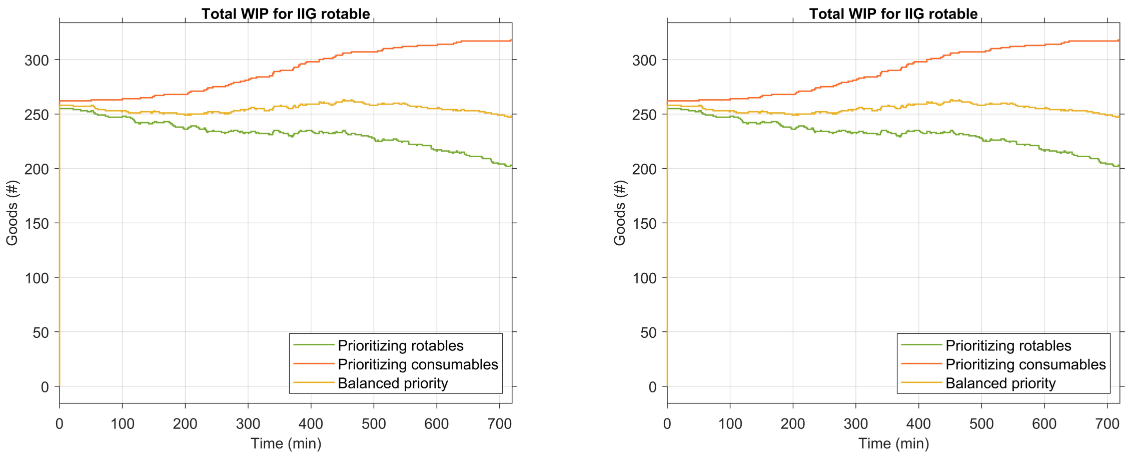
If the process operator discovers by monitoring that the allocation of resources, inflow and outflow in the system are not aligned, for example due to an increasing amount of work for a particular task, the process operator may decide to change the allocation of resources. The change in the allocation of resources may be challenging, as the effects are not directly clear, due to complexity and dependencies. The developed digital twin can assist the process operator in supporting the choice, by simulating scenarios in real-time. As explained in example 1, the focus of the operator should not solely be on minimizing WIP, but rather on achieving a balance between minimizing WIP (and so TAT) and maintaining stability in the inflow versus outflow per task. In Figure 7.8a, various simulated resource allocation scenarios are shown in a boxplot, illustrating their direct influence, whether positive or negative, on the WIP KPI. To make a balanced decision, the operator can also consider the stability of inflow versus outflow (indicated by low standard deviation) for all tasks, as shown in Figure 7.8b. These insights provided by the digital twin help the process operator evaluate possible resource allocation scenarios. Moreover, the decisions related to system objectives can be evaluated, as this can change over time. In example 2, a possible case is demonstrated to evaluate this value.



(a) Spread in WIP for different capacities

(b) WIP vs. standard deviation inflow-outflow (20 employees)

Example 2: Experimenting prioritising certain types of goods
In the LHA, the task of Inspection Incoming Goods (IIG) for consumables and rotables can be executed by the same employees. For these tasks, a shared group of employees is available. Based on a significant backlog in the system, a decision has to be made regarding prioritizing certain types of goods. Based on the developed digital model, the effects of prioritizing certain goods can be predicted (see Figure 7.9). In the case where full priority is given to rotables, as expected, you see a decrease in the WIP of rotables. However, this gives a lower overall WIP than prioritising consumables. By being able to generate such predictions, a more balanced choice can be made by the process operator.



(a) Total WIP for IIG rotable for three scenarios

(b) Total WIP in LHA for three scenarios

Figure 7.9: Trade-off between prioritizing rotables or consumables

This example illustrates one of the operational trade-offs the process operators face daily. As the digital model is fed with real-time data from the LHA system, experiments can be executed constantly, until the best resource allocation is found. The best allocation of resources depends on the objectives the process operators define, which could change over time. As illustrated in the example, they could decide to give priority to certain types of goods instead of focusing on the lowest WIP. This allocation can then be applied to the physical system. As the experiments give an expectation of throughput per task and total outflow, operational targets can be given to the employees. This has to lead to a certain predictable outflow.

7.2.3. Integral operational target setting

The digital twin gives an indication of the predicted throughput per task and system outflow in the simulated period. This is very useful in the process, especially when performing tasks that have some dependency on other tasks. This is because the output of dependent tasks must be balanced, otherwise there will be a shift of the backlog from one task to another, without getting extra output in the LHA. Especially in the case of a low backlog of goods at tasks, a balanced throughput across all tasks is needed to ensure that there is no over- or under-capacity in certain tasks. This value of integral target setting is outlined in the example 3.

Example 3: Balanced throughput by integral target setting
An issue the process operators need to handle is related to the variety of processes that are involved in the handling of all types of goods. For example, the handling of US rotable goods is affected by different tasks and varying processing times. Many US goods are not recognized at the first instant, resulting in additional handling tasks at the NRSI workstation and back office (ZV). After completing the ZV-task, the US goods flow into the regular process. So, the inflow into the queue of Repair Order creation is affected by both regular inflow and inflow from the 'not recognized' goods. As described, the digital twin can give insight into the effects of inflow and resource allocation changes, also in combination with the 'not recognized' process. In Figure 7.10, an example of the effect of adding resources to certain tasks is visualised. In Figure 7.10a, the baseline of throughput per task over time is visualised, resulting in a certain WIP (Figure 7.10b). In scenario 2 (Figure 7.10c) extra resources for the NRSI task are added. However, due to an imbalance between the throughput per task, this does not result in extra outflow. Consequently, the backlog is shifted, but the total WIP remains constant (Figure 7.10d). Therefore, adding resources only adds value when dependent tasks also increase capacity, as can be seen in scenario 3 (Figures 7.10e/7.10f).

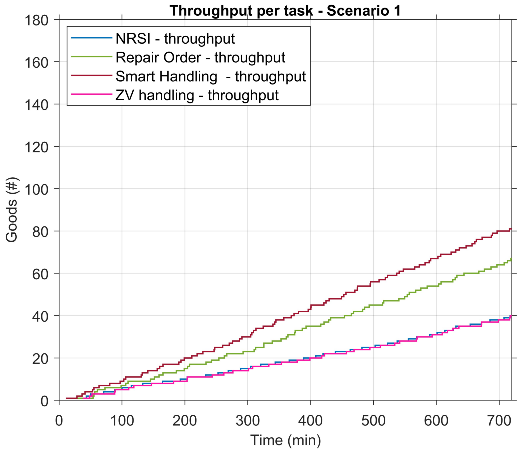
Concluding, the digital twin helps to set operational targets focusing on balanced throughput across all tasks. This integral approach helps to minimize fluctuations within the different backlogs and leads to a more constant outflow over time. Furthermore, it also provides insight if certain departments are under or overperforming. This is because the digital twin also can visualise the achievement of set targets rather than just KPI development, as KPIs can be influenced by other departments and variability.

7.3. Conclusion

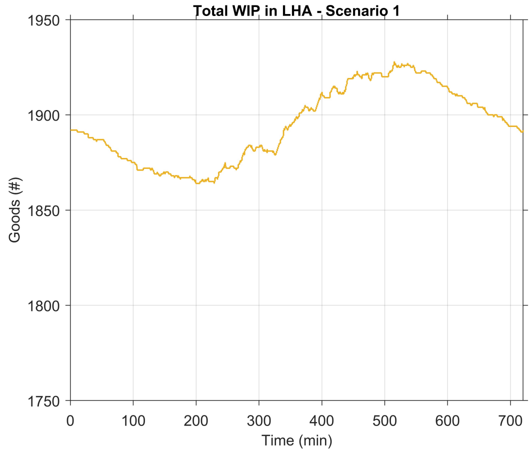
This chapter describes the added value that a digital twin can provide to support coordination within complex systems such as the LHA, aiming to answer SQ9. The value is summarised in Table 7.1, where a comparison is shown between the current and the proposed situation. To summarise, the digital twin creates value by dynamically evaluating the performance of a system. This supports process operators to immediately notice unexpected effects of, for example, variability, which can lead to lower performance (expressed in KPIs) or fluctuations in throughput per task. Then, by having immediate insight into the effects of changes in resource allocation, quick and informed decisions can be made based on resource availability and system objectives. These outcomes of the digital twin support different departments in defining integral objectives to create a stable and predictable outflow.

	Current situation	**Proposed situation**
Tool	Data visualisation by an Excel file	Digital twin with discrete event simulation
Static/dynamic	Static solution for monitoring	Dynamic solution for monitoring, testing and target setting
Coordination	Department-focused	Integral with departments
Performance assessment	Historical state	Historical, present and future state
Update frequency	Daily / weekly	Real-time

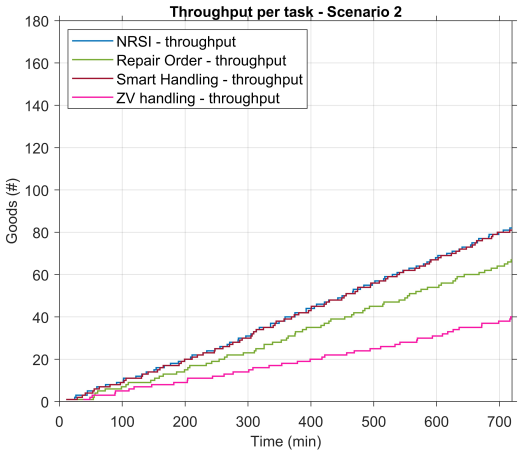
Table 7.1: Comparison between current and proposed situation



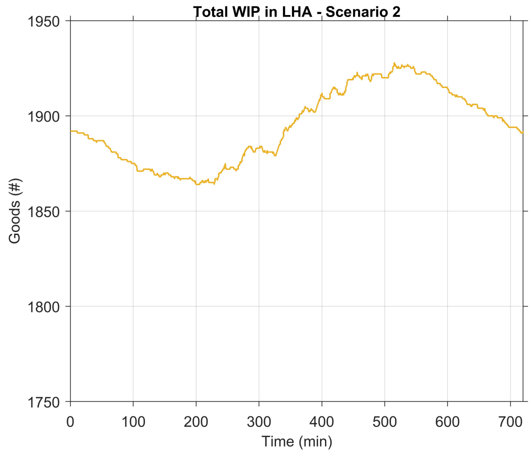
(a) Throughput per task (scenario 1)



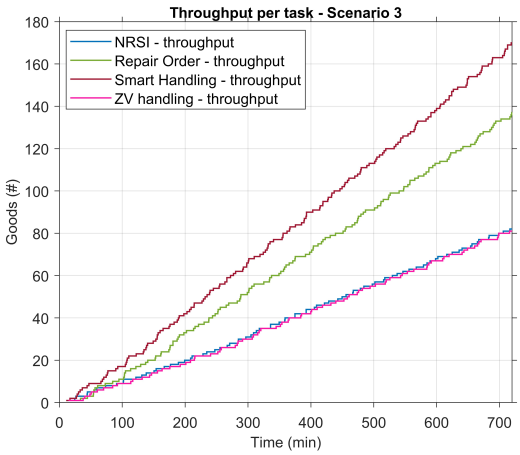
(b) Total WIP (scenario 1)



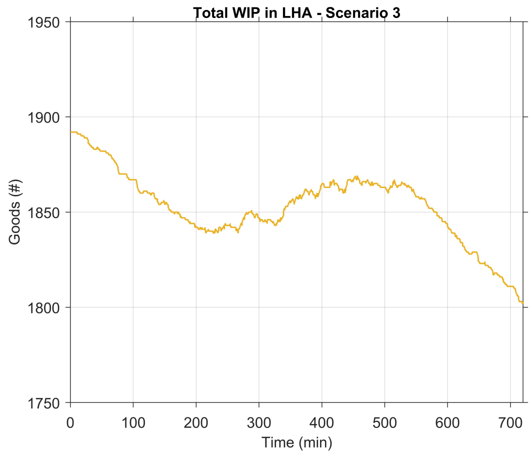
(c) Throughput per task (scenario 2)



(d) Total WIP (scenario 2)



(e) Throughput per task (scenario 3)



(f) Total WIP (scenario 3)

Figure 7.10: Effect of integral target setting for different tasks

8
Conclusion

This chapter presents the conclusions of this research. In section 8.1, the research findings are described, leading to the answer to the research question. Then, the contribution to the academic literature and practice are discussed in sections 8.2 and 8.3 respectively. In the next chapter, the limitations, recommendations and business implementation will be described.

8.1. Conclusion

This research aimed to develop a digital twin that dynamically supports process operators with the operational coordination of a system within a complex and variable environment. The research is executed by a case study in an aircraft Maintenance, Repair, and Overhaul (MRO) company. The research was scoped to the logistic handling of aircraft goods in both Serviceable (SE) and Unserviceable (US) conditions in a Closed-Loop Supply Chain (CLSC) of Component Services (CS). CS is part of KLM Engineering & Maintenance (KLM E&M) and is responsible for the component availability of approximately fifty customers worldwide. The developed concept has to provide support on an operational level. The main research question was formulated as follows:

> **Research question**
>
> How can a digital twin support process operators to dynamically coordinate systems in a complex and variable environment?

The literature review was used to explore relevant knowledge on two main themes: MRO supply chains and digital twins in scheduling and coordination. Starting with MRO supply chains: these types of supply chains are unique, due to their balanced forward and reverse chains. From a customer perspective, only an efficient forward supply chain is required, as this affects the ability to deliver the required aircraft goods quickly. From a supplier's perspective, the reverse supply chain is at least as important, as aircraft goods only add value to their business if they are in airworthy condition. Therefore, there is pressure on these MROs to have a stable and predictable supply chain. In the past, different research studies have been executed on the repair and logistic process within this reverse supply chain, also within KLM E&M. Within these researches, one characteristic is often mentioned: variability. Since the demand rate of SE goods, and so the throughput through the supply chain is affected by the degradation of the aircraft components, there is variability in the amount of goods within the supply chain. This is enhanced by the large variety of aircraft goods. From the literature, it can be concluded that this variability negatively affects operations in different parts of the supply chain, resulting in buffers of capacity, time or inventory. Caused by the high procurement costs of aircraft goods, buffers in time and inventory are especially undesirable. The second part of the literature review involved creating insight into the value of the application of a digital twin in general and scheduling specifically. The use of a digital counterpart, in general, has advantages regarding providing feedback about a system without affecting the physical system, by providing analytical, descriptive, predictive and diagnostic value. Related to planning and scheduling, these values could be beneficial as timely coupling of demand and capacity is required.

The combination of challenges of MRO supply chains related to variability and the value of digital twin applications in other systems, created a potential research gap. Different studies have focused on the utilization of digital twin applications in relatively stable production environments, coupled with longer-term planning. However, this research aims to demonstrate the value of digital twin applications in dynamic operations, specifically concentrating on short-term operational coordination and scheduling.

The reason for this research arose from a low performance of the Logistic Handling Area (LHA) in the supply chain of CS. Therefore, a digital twin has been developed for this system. As an additional check, the performance of the entire supply chain was assessed, indeed indicating a major bottleneck in the LHA. This LHA is further analysed to prove the findings found during the literature review and to find additional challenges the system faces. From the analysis and process observations, different issues are indicated. As expected, the LHA is affected by variability in daily inflow and processing time. Also, the low performance of the entire system cannot be assigned to one particular task, indicating a broader issue. What further stood out was the wide variety of processes carried out in one system, resulting in a complex system with many interdependencies.
The design of the digital twin was based on the current process, as this research did not aim to redesign the process, but rather to demonstrate the added value it could provide to the operation of existing processes. Based on the challenges found in the process analyses, the design focused on the descriptive and predictive value a digital twin could offer. Related to the descriptive value, clear KPI monitoring and a comprehensive process layout have to be included, while for predictive value, the used parameters and replication of the environment need to be accurate. For an accurate representation of the physical system, the sharing of parameters related to (expected) input, processing times, resource allocation and backlog of goods is proposed. Thereby it is assumed that the ability to coordinate the process is related to resource allocation for specific tasks, as the input and processing times cannot be influenced. The allocation of resources can be evaluated by the predicted output the digital twin offers.

For evaluating the value of the application of a digital twin in this context, the conceptual model is translated to a Discrete Event Simulation (DES). This technique fits the handling of goods, as this consists of discrete events. Furthermore, it was helpful in clearly visualising the outputs a digital twin can create related to process coordination. After the simulation setup, the model was reviewed by experts from KLM E&M consisting of operators of the process and employees of the supporting departments. These experts acknowledged the correctness of the developed concept.
To move towards answering the research question, the individual values of this application were evaluated first. The expertise of KLM E&M employees was taken into account, and supported by experiments within the developed simulation model. In addition, the impact of variability on output has been demonstrated, which supports the necessity for this application. The value is distinguished into three parts: (1) real-time monitoring of KPIs; (2) dynamic testing of need-based resource allocation; and, (3) integral operational target setting. The first value offers the possibility to quickly evaluate the performance of the system by calculating KPIs, which is difficult in a complex process with many dependencies. Additionally, the value of dynamic testing with a digital twin is important in a process where KPI objectives may vary over time. Furthermore, it allows process operators to focus not only on the highest performance, but also on how to achieve it in a stable way. The last value refers to the integral coordination that is important to get the desired output. This prevents backlog shifting within the system. These values become even more important once the amount of backlog decreases.

To conclude, a digital twin can support process operators in dynamically coordinating systems in a complex and variable environment. First, complexity can be reduced by creating a comprehensive overview of the processes that shows dependencies between tasks. Moreover, the batch of incoming goods should be divided into several groups, that have nearly the same processing time and share required process steps. A digital twin can then dynamically assign goods to particular tasks and groups, providing structure to the input and workload for all tasks. Moreover, due to the continuous loop of the three mentioned values (monitoring, testing and target setting), a process operator maintains a constant awareness of the system's current state. This enables quick recognition and response to unexpected variability, such as inflow or processing time fluctuations. Therefore, the developed digital twin cannot directly reduce variability, but it gives a method to quickly adapt to it. Consequently, the digital replica supports making operational decisions, considering all process dependencies within the developed concept. The effect on KPIs is thereby immediately visible. Moreover, it assists the various departments in establishing integral targets, ensuring stable throughput for all tasks. These elements together facilitate operational predictability and stability, which have positive effects on the entire supply chain.

8.2. Contribution to academic literature

This research contributes to the academic literature in several ways. First, as mentioned in the conclusion, not much research is available on digital twin applications in complex systems with high variability. Although the elaboration of this research focuses on the specific system within KLM E&M, the method of creating the design and application is much more broadly applicable. This is useful because more systems are affected by variability. The method of creating a digital twin for process coordination also opens up opportunities for process improvement projects. This research showcased that information provided by a digital twin can help in understanding processes, which helps in defining actual process difficulties. Moreover, in this context, a digital twin can help evaluate redesigns before they are implemented, with the input of real data. This can help reduce the impact of such trajectories on operations. Third, this research also provides another perspective to deal with variability. Whereas improvement processes often revolve around reducing variability, for instance by using Six Sigma, this research offers a method to reduce the impact. This provides new opportunities for processes where reducing variability is not possible, e.g. due to external factors.

8.3. Contribution to practice

In addition to contributing to the academic literature, this research also contributes to practice. For CS, this digital twin is the first digital twin developed for their operation, which gives them great insight into the possibilities of applying such technology. Within the organization, they are therefore exploring the possibility of actually deploying this developed concept, as they see the benefits of being able to stabilize their operation and ultimately reduce handling time. A reduction in handling time has direct benefits concerning the availability of aircraft components and consequently, on finances. The recommendations regarding business implementation are described in section 9.3.

9

Limitations and recommendations

The previous chapter described the conclusion of this research. However, some limitations are noted that have to be discussed. These limitations are described in section 9.1. Based on the conclusion and these limitations, there are some recommendations for further research, see section 9.2. Furthermore, some recommendations are written for KLM to implement this concept into their business (section 9.3).

9.1. Limitations

The use of digital twins has different levels of advancement. Therefore, this research should not be seen as the end product, but as a solid foundation for adopting other technological developments. This research mainly focuses on monitoring systems and supporting operators' choices by providing insight into the effects. However, the research opens possibilities for new technology to (partly) take over these decision-making tasks from process operators, which can be included in this digital twin. However, this step-by-step development helps ensure that sufficient process information is gained first, enabling considered choices to be made on which new technology should be adopted first.

Regarding this research, also some more specific limitations are found:

- **Real-time connectivity -** The developed digital twin concept has no real-time connectivity with systems associated with the LHA, as it does not receive real-time data from the physical system. To show the value of the digital twin, as is done in this research, this was not directly required. However, when the digital twin has to be implemented within the daily operation as described in this research, a connection to the Warehouse Management System (WMS) has to be made. The implementation of this connection is already taken into account in the design of the digital twin. For example, the necessary IT systems are described along with available data that can be used.
- **Parameter validation -** The expert review validation highlighted the need for validating certain values used in the simulation model. As these validation measurements take place in the coming months, these validations could not be incorporated into this research. However, a small deviation in these parameters has no direct impact on demonstrating the value of the concept. Additionally, not all utilized parameters are designed to be linked to real-time data, necessitating periodic validation of the values in the future.
- **Challenges in validation -** The disturbance in the current operational environment of the LHA created a challenge to execute representative tests in the physical system. This limitation prevents the validation of the practical value by real-world experiments. Because of this, the value could only be proved by experiments in the simulation and by the expert review.
- **Inflow prediction -** The fourth constraint relates to the ability to predict inflows into the system. In this concept, inflow in a certain period and the distribution over the different processes are based on historical inflow data, taking into account some variability. But this historical inflow, of course, does not guarantee future inflow. A larger difference between actual and expected inflow may result in the need to reassess the best allocation of resources more frequently.

9.2. Recommendations for further research

The research that is executed opens some possibilities for further research. Below, two main recommendations are described:

- **Inflow prediction model -** In the previous section, a limitation related to inflow prediction is addressed. To create a better prediction of daily inflow, further research can be executed on a prediction model that will be included in the digital twin. A possible approach for this is to use the demand rate of SE goods by the customer, as this will eventually result in an inflow of US goods into the LHA some time later. However, in order to create such a model, the supply needs to be more predictable and stable.
- **Optimization model -** The developed concept cannot give an optimal allocation of resources based on the available capacity, but it gives insight into the effects of possible operational decisions. Further research can therefore focus on the implementation of an optimization model within this concept, where the decisions of the process operator will be (partly) replaced by a mathematical model. This can be seen as a new level of advancement, as addressed in the previous section. However, before implementing this, it is important to be able to accurately predict inflow, so therefore research on the previous recommendation is required first.

9.3. Business implementation

As this research is theory-oriented, the developed concept cannot directly be implemented into the operation of KLM E&M. Therefore, this section describes some recommendations for business implementation. The value of the application of a digital twin for supporting operational coordination is described in the previous chapters. However, to reach a successful business implementation, the following elements have to be taken into account:

- **Software selection -** The digital twin concept is developed in MATLAB Simulink, which is not optimal for integration with a Warehouse Management System (WMS) like SAP. A software solution capable of seamless integration with IT systems is required. It should also support real-time and historical monitoring and predictive simulation. Future improvements, as suggested in the recommendations section, also have to be taken into account when selecting a software tool.
- **Data availability -** Availability of data is a key requirement of the digital twin application. When translating the developed design into a digital version, the accessibility of the required data has to be ensured. Therefore, an IT architecture has to be developed to transfer the data from the WMS towards the software of the digital twin. Additionally, considerations must be made for the storage, accessibility, and performance assessment of historical data.
- **Data quality -** Next to data availability, also data quality is an important aspect. As the process operators have to trust the outcomes of the digital twin, the used data always has to be accurate. Data quality can be covered by good data governance. Data governance involves exercising authority and control in managing data. Its primary objective is to improve the value of data, while minimizing associated costs and risks [44]. From a practical point of view, this means assigning responsibility for monitoring and cleaning data to designated employees.
- **Process ownership -** Clarity in process ownership is essential for coordinating the process with the support of the digital twin. This means that it is clear which departments are responsible for reaching certain targets set by the digital twin. Also, it is helpful when one process operator becomes responsible for the final decision regarding resource allocation and targets, as this helps to further support adequate operational coordination. Furthermore, all the stakeholders have to support the value of the digital twin, as this integral approach only adds value when all stakeholders rely on the outcomes of this tool.
- **Resource flexibility -** To further improve the value of the digital twin, the flexibility of resources also has to be re-evaluated. By enabling more flexible deployment of workers, the impact of variability can be further reduced. This requires a broader skill set per employee.

- **Complexity reduction -** The last recommendation regarding business implementation is not directly related to the digital twin, but the operation of the LHA in general. The variability faced by the LHA is partly the result of the complex design of the process. This is caused by the aeronautical regulations, but also due to the different types of contracts that are provided to customers. This leads to a lot of variability in the tasks that have to be executed. Therefore, reducing this complexity should be critically examined.

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A

Research paper

Digital twin for dynamic coordination of systems in complex and variable environments - A case study at KLM Engineering & Maintenance

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***Abstract*—This research investigates the application of a digital twin in managing challenges of variability and complexity within systems by using a case study at KLM Engineering & Maintenance. Using the DMADV (define, measure, analyse, design and verify) methodology, the research evaluates the problem using a literature review, measures and analyses the current state of the Logistic Handling Area (LHA), designs a digital twin concept and verifies its value. The literature review highlights the variability in the Maintenance, Repair and Overhaul (MRO) industry, which enables the investigation of digital twin applications for dynamic coordination. The analysis phase reveals significant operational challenges arising from variability in inflows and processing times, enhanced by system complexity and integral coordination issues between departments. To address these challenges, a digital twin is designed that enables real-time monitoring of KPIs, testing of dynamic resource allocation and integral operational target setting. The value assessment shows that the digital twin can support process operators by managing variability through continuous monitoring and evaluation of resource allocation, ultimately achieving predictable and stable system performance in a complex and variable environment.**

***Index Terms*—Digital twin, variability, complexity, operation, system, coordination**

I. Introduction

The Maintenance, Repair and Overhaul (MRO) companies are an important factor within the aeronautical industry. The activities of these companies play a crucial role in ensuring safety, by mitigating the effects of ageing and wear on aircraft structures, components and engines. With the support of Original Aircraft Manufacturers (OAMs) and system suppliers, this industry is responsible for executing preventive, corrective, and predictive maintenance on aircraft [1]. The growth in fleet size by 3.4% in this decade will lead to a higher demand for service at MRO companies. However, intense global competition significantly influences the business environment of MRO companies. Additionally, more robust aircraft systems and improved materials and designs result in less required maintenance per aircraft [2]. This competition and quality improvement force MRO companies to find solutions to stay profitable. KLM Engineering & Maintenance (KLM E&M), an MRO service provider of Royal Dutch Airlines (KLM), acknowledges these challenges. Component Services (CS), one of their business units, is responsible for the availability, repair and logistics of aircraft components for KLM's fleet and external customers. The main objective of CS is to guarantee this availability of components, and additionally minimise the repair, logistic and stock costs. The availability of components and the stock costs are influenced by the time between the delivery of an operable, serviceable (SE), component until the returned inoperable, unserviceable (US), component is repaired and placed in stock again. This period is defined as a component's Turnaround Time (TAT). A lower TAT will require fewer components of a specific type to guarantee the same availability. Therefore, CS is constantly looking to make its Closed Loop Supply Chain (CLSC) of aircraft components more efficient and reliable. The Logistic Handling Area (LHA) is part of this supply chain, where incoming goods from different external parties are handled, inspected and distributed to other internal or external parties. The case study of this research is focused on this area, as this area is confronted with a higher TAT than desired, leading to challenges in the availability of aircraft components. While various factors within the business contribute to this problem, it can be primarily assigned to the interaction between variability and adaptability. The LHA deals with various aircraft goods, each with unique requirements, technical complexities, sizes, and weights, which results in variability in processing times and the creation of a complex operation. Coupled with fluctuating daily supplies, this variability poses challenges in maintaining stable and reliable operations, as the system is not able to adequately adapt to changing circumstances. The lack of insight into the current operation and potential operational decisions creates difficulties for the process operators to coordinate the system effectively. Therefore, this research aims to develop a concept that supports process operators in dynamically coordinating a system in a complex and variable environment. As the application of digital twins in this context could potentially be helpful, the research is focused on this technology. The scope is related to a solution that supports the process operators on the short-term operational level, but the outcome can contribute to tactical and strategic control. The research aims to answer the following research question: *How can a digital twin support process operators to dynamically coordinate systems in a complex and variable environment?*

To systematically answer the main research question defined in the previous section, the DMADV (define, measure, analyse, design, verify) methodology is adopted. This methodology is related to the DMAIC (define, measure, analyse, improve, control) methodology of Lean Six Sigma, but this method is more suitable for trajectories where a new way of working or product is introduced [3]. The research is executed by a case study at KLM E&M, but this research has as objective to contribute to the development of theory. The researched case is used as a storyline for this research to visualise the value it could create.

II. DEFINE

Next to the problem definition, the *define* phase includes a literature review. Topics related to MRO supply chains, digital twin technology, and Key Performance Indicators (KPIs) are researched to acquire a deeper understanding of these subjects and to identify a potential research gap.

A. Aircraft MRO supply chains

Identifying characteristics of the aircraft MRO supply chain is relevant, as these could potentially impact the operation of the LHA. The activities of the MRO supply chain are mainly related to the repair and logistics of products. However, MRO supply chains differ from regular supply chain models, where 'consumable' products usually flow in one direction towards the customer. In the case of MRO supply chains, there is a balanced exchange of products from the customer towards the supplier, while repaired items follow the traditional downstream flow. This combination of forward and reverse logistics creates a Closed Loop Supply Chain (CLSC) that enables the flow of 'rotable' items, as is also visualised in Figure 1 [4, 5]. The decision to create a CLSC is mainly driven by economic factors. Related to these factors, quick component repairs, reliability, and meeting delivery schedules are essential. However, fluctuating demand, influenced by irregular damage patterns of these components, creates challenges for capacity planning. Uncertainties in product return timing, quality, and processing times further complicate the situation [6, 7]. According to Hopp and Spearman [8], this variability negatively influences a system to operate at its highest efficiency, leading to buffering within three dimensions: inventory, time or capacity. Eliminating all three types of buffers is challenging, therefore the primary focus should be on effectively managing these buffers by focusing on the 'best buffer'.

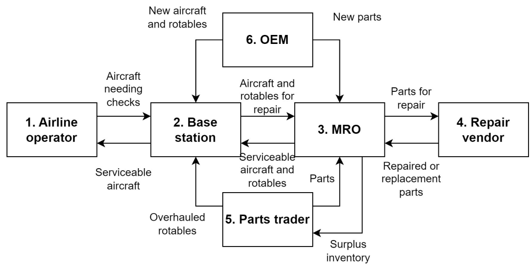

Fig. 1: Aircraft MRO supply chain [4]

B. Digital twins (for scheduling and coordination)

The literature research about digital twin applications has to bring the stated challenges and a potential solution together. In general, a digital twin is an intelligent virtual replica of a physical system [9], that can provide companies feedback about their system [10]. It consists of three main elements: the physical system, the virtual system and a two-way link between them (see Figure 2). By assessing the system's effectiveness or performance, different scenarios can be evaluated. A digital twin can show historical insights, improve current operations, and assess the impact of potential changes in a safe way [9, 11]. The value is related to (1) analytical value, (2) descriptive value, (3) predictive value, and (4) diagnostic value [12].

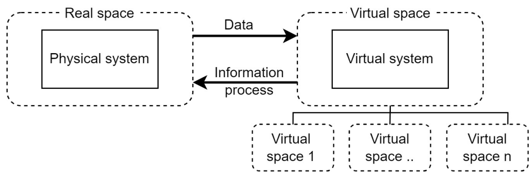

Fig. 2: General model of a digital twin (based on [9])

In the study of Agostino et al. [13], a research gap is addressed by using simulation and optimization models to enable data-driven decision-making within an operational environment. This environment includes resource planning and scheduling, as quickly aligning available capacity with demand is crucial for achieving optimal production [14, 15]. The challenges described by Koulouris, Misailidis, and Petrides [14] support the difficulties of matching capacity with demand, given characteristics like seasonal fluctuations, variations in product mix, and short cycle times. These factors contribute to a dynamic and unpredictable production environment. Consequently, there is an urgent need for adaptable and dynamic production plans, highlighting the potential benefits of digital twins in this context. Three key requirements are stated for creating a digital twin for planning and scheduling: (1) the available resources have to be identified, (2) the processing

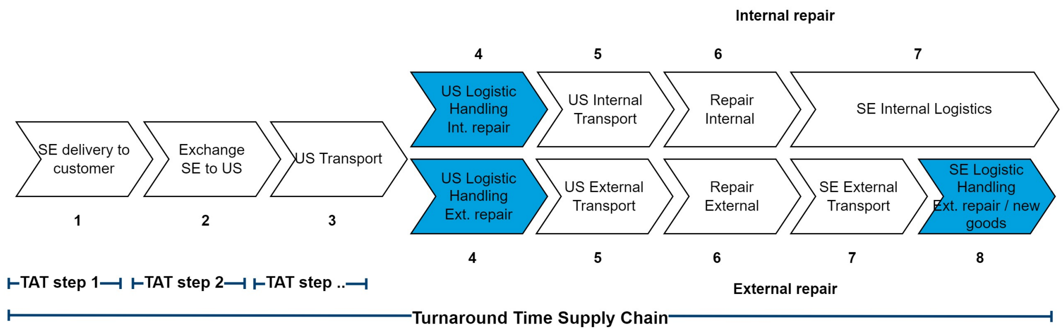

Fig. 3: Overview of the Component Services Supply Chain

times have to be determined, and (3) the distribution of variant input has to be known. Based on this, potential bottlenecks and free capacity can be identified [16].

C. *Key Performance Indicators for MRO supply chains*

Key Performance Indicators (KPIs) can give insight into the state of a system, by periodic measurement and comparison of actual levels of achievements with objectives [17]. Therefore, research is executed on the KPIs regarding an MRO supply chain, focused on operational indicators. The research of Cornelisse [18] summarized the KPIs of the aircraft MRO Closed-Loop Supply Chain. Regarding this research, which is focused on the logistic handling of aircraft components, KPIs such as Service Level to the customer and Lead Time are less relevant. In the scope of this research, the following KPIs are considered relevant: *Time in Handling*, *Workforce Productivity*, *Work In Progress*, *Throughput*, and *On Time Performance*.

To conclude, the literature review shows the complexity of managing the supply chain within the aircraft MRO industry. The focus has been on understanding the characteristics of the MRO supply chain, the challenges it faces, and the potential benefits of integrating digital twin technology into its scheduling and planning process. The review supports the expectation that the MRO supply chain faces variability, that potentially leads to buffers. Effective management of resource capacity appears as a crucial factor in minimising these buffers. Digital twin technology presents a promising method for improving planning and scheduling within the MRO supply chain. While existing research has explored the benefits of digital twins in planning and scheduling, much of it focuses on more stable production environments wi th longer time horizons. The dynamic and unpredictable nature of the aircraft MRO supply chain presents a unique challenge, underscoring the need for further research into applying digital twins to short-term scheduling and coordination in such an environment.

III. Measure & Analyse

In the *Measure & Analyse* phase all the necessary data from the physical system is gathered and analysed to determine the issues the Logistic Handling Area (LHA) is facing. Also, process observations are executed to gain knowledge about the current operation.

A. *Closed-Loop Supply Chain*

The CS supply chain is a two-way flow, comprising both forward and backward flow. The supply chain consists of eight sequential steps, with the LHA involved in two steps (see blue steps in Figure 3). As indicated in the introduction, component availability is affected by the Turnaround Time (TAT) of the supply chain. To identify potential bottlenecks in the supply chain, the TAT of each step in the supply chain needs to be measured and analysed. Due to limited data availability, it was not feasible to measure the TAT of each individual step. Instead, bottlenecks are identified based on the Work In Progress (WIP) KPI, which reflects the backlog of work for each process step. This analysis indicates performance problems within the logistics handling of US and SE goods, as the backlog of goods is between 2 and 11 times higher than desired. Further analysis of the LHA is needed to identify the main problems of the system.

B. *Logistic Handling*

The Logistic Handling step within the CLSC, operated within the LHA, plays a crucial role as it serves as the connection between customers and repair shops. Its primary goal is to efficiently manage incoming goods in both US and SE conditions, in alignment with aeronautical regulations. This complex system involves sorting, inspecting, and distributing goods to relevant departments or storage locations, as well as preparing items for external destinations (see Figure 4). Any disruptions within this system can have negative effects throughout the entire supply chain, affecting repair shops and other departments. With the coordination of 36 main handling categories, containing 115 unique process flows with dependencies, the complexity of this system is evident. Briefly, logistic handling can be divided into the handling of SE or US goods. For US goods, the process involves receiving incoming goods in the LHA, generating a repair order and proforma invoice (PI) in the back office, and then preparing the package for shipment. In the case of SE items, incoming goods undergo inspection to ensure the appropriate certificates are attached.

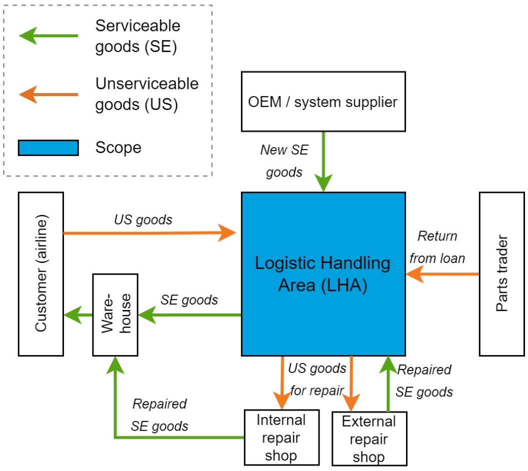

Fig. 4: Interaction of LHA with other departments

C. Performance and inflow analysis

The literature review addressed issues related to variability in inflow due to irregular damage patterns of aircraft components. This variability is proved by an inflow analysis that is performed, see the boxplot in Figure 5. An average daily inflow of 160 goods is measured, however, a standard deviation of 62 goods results in a large spread. This variability in inflow, together with the unpredictability has a negative impact on the operation. The low performance is visible in the high backlogs of work (WIP) for almost all tasks of the US and SE processes, see Figure 6. These queues result in a significantly longer Turnaround Time (TAT), as only less than 25% of goods are handled within the desired two days.

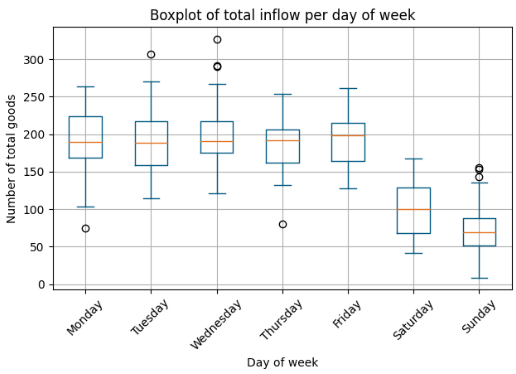

Fig. 5: Boxplot of total inflow per day of the week

From the process observations and data analysis can be concluded that the system faces four main issues: (1) the influence of a variety of processes, (2) the presence of various bottlenecks, (3) uncertainty and variability in daily inflow, and (4) lack of integral coordination. To summarize, the reason for poor performance cannot be assigned to one process task. Rather, it arises from a broader issue related to a lack of comprehensive process understanding due to limited data

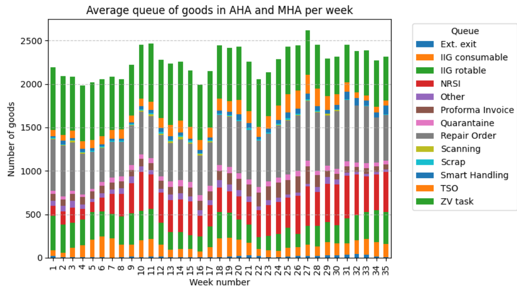

Fig. 6: Work In Progress per task over time

availability and the complexity of the processes itself. Consequently, adequate coordination of employees across tasks becomes notably challenging.

IV. Design

The *design* phase focuses on the design, simulation, verification and validation of the digital replication, called the virtual entity. The objective is to create a digital twin that provides real-time insight into the historical, present and future state of the system. Five key requirements are established to achieve this goal, with the foremost being (1) the ability for KPI calculation. Additionally, (2) a comprehensive and structured representation of processes is essential, alongside (3) sourcing data from the physical system. Moreover, (4) incorporating the environmental characteristics of the system is crucial, and (5) the created design must be assessable through simulation.

A. Virtual entity

The design of the virtual entity is structured according to the IDEF diagram visualised in Figure 7, which visualises the input, output, constraints, resources and performance measurements. The design is partly based on the recipe-based representation of Koulouris, Misailidis, and Petrides [14]. On the system level, the model should include all available resources and constraints. For every unique type of good that is handled (the recipe), the processing steps, processing times and necessary resources must be defined.

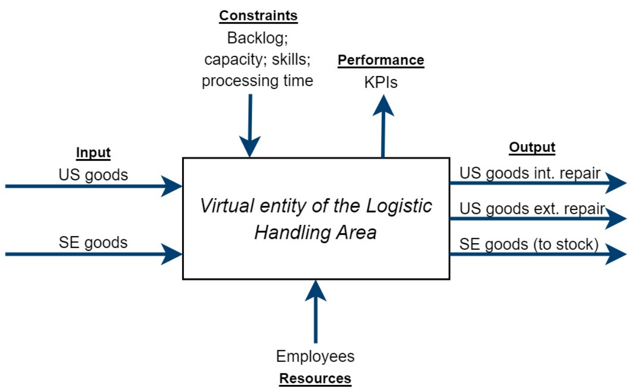

Fig. 7: IDEF0 diagram of the LHA process

- **Layout -** The layout includes the processes that are executed within the borders of the LHA. The *analyse* phase indicated the complexity and dependency between all 115 process flows. The process flows are structured in a comprehensive layout, see Figure 9. The goods are first clustered based on possible combinations of process characteristics, such as pool type, operation state and destination, resulting in thirteen different good types. For all these unique good types, the processing steps, processing times and resources are defined. The method of visualising the process in this way supports process operators by directly having insight into the system's state. It visualises the process steps per good type and highlights shared tasks and buffers. Furthermore, the impact of the disrupted process flows on the regular flow is also visible.
- **Resources and constraints -** For an accurate representation of the physical system, data is extracted from the physical system by using the Warehouse Management System (WMS). For this case, three elements are transferred: backlog of goods, processing time and resource allocation. The backlog of goods includes the number of goods waiting per task as defined in the process layout. Furthermore, the processing time is transferred, as this includes the time required per task. This processing time is defined per good type, together with a certain productivity and variability factor. The third element includes resource allocation, which is defined as the number of employees scheduled per task, taking into account the skill requirements.
- **Input -** The input into the process also has to be defined, to enable the possibility of assessing the expected system's future state. The inflow is not based on a prediction model but on historical data including certain variability. Additionally, a distribution factor is incorporated to allocate the expected total inflow across various types of goods. Table I provides a summary of all data elements included within the virtual entity.
- **Output and performance -** The decision-making support for process operators will be mainly based on the output the digital twin produces. This includes the actual and expected number of goods that leave the system, together with KPI calculation. The process operator requires information about the historical, present and future state. For the evaluation of the present and future state, Work In Progress (WIP) is used as a KPI, as this gives clear insight into process bottlenecks. For assessing historical performance, it is beneficial to evaluate the Turnaround Time, as this indicates if the requirements regarding component availability are met.

B. Simulation model

To evaluate the created design, the design is translated into a digital simulation model. In the context of handling goods within the LHA, what matters are the process steps rather than the intermediary tasks, such as transportation, between these steps. Therefore, Discrete Event Simulation (DES) is an appropriate method for evaluating the design and its application [19]. The developed design is replicated in MATLAB Simulink. Whereas an actual digital twin is supposed to be linked to the physical system, for example by using the WMS, this model is based on defined parameters. However, for evaluating the effectiveness of digital twins in variable and complex environments, this isn't an issue. To ensure that the developed simulation is an accurate representation of the LHA, both verification and validation are executed. During verification, the simulation is checked by model checks and tests, as recommended by Sargent [20]. The model checks included antibugging, signal tracing and input checks, while continuity, degeneracy and consistency tests were executed. It can be concluded that the model is accurately translated into a digital version. The validation is executed by an expert review, as experiments in the physical system were not possible. The experts, consisting of process operators and process specialists agreed that the developed design and simulation were correct. While they recommended evaluating certain used values for parameters, this does not influence the verifying phase.

Level	Variables	Parameters	Constants
System	Employees per task (#) Inflow with std. deviation (#)	Employee productivity (%) Uncertainty factor processing time (%)	Skill level per task Number of workstations (#)
Goods	Backlog per task (#) Inflow distribution factor (%)	Processing time per task (min)	

TABLE I: Variables, parameters and constants for representation of the physical entity on system and part group level

V. VERIFY

The last phase, *verify*, includes the value assessment. The objective of this section is to verify that the developed design adds value to operational coordination. The interaction between the physical and virtual systems is assessed, as a digital twin only adds value when information retrieved from the digital twin can be used for improving the physical system coordination. The verification is divided into demonstrating the impact of variability, and the value for the operational coordination of systems.

A. Variability impact

The impact of variability on the system's performance is evaluated by the simulation. Figure 8 shows a fluctuation in outflow due to variability in inflow, distribution and processing time, while all other parameters remain constant over the runs. This graph visualises the negative impact and uncertainty that variability creates, especially when the backlog of goods is low.

B. Value for physical system

The developed digital twin has value in several ways, with the following three values being the most important for this system:

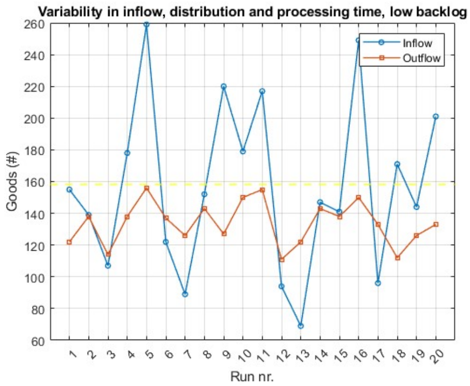

Fig. 8: Impact of variability

1) **Real-time monitoring of KPIs -** The developed digital twin facilitates the real-time measurement and analysis of historical and current system state, allowing for the calculation of KPIs. The designed comprehensive and structured overview empowers process operators to proactively respond to operational changes, by monitoring individual task performance and inflow-outflow balance, which becomes increasingly crucial when the backlog of goods decreases.
2) **Dynamic testing of need-based resource allocation -** Related to predictive value, the digital twin enables process operators to make informed decisions within a complex environment, without disrupting physical processes. By directly illustrating the effects of parameter changes, such as resource allocation adjustments, operators can evaluate decisions like prioritizing goods or minimizing overall work in progress (WIP).
3) **Integral operational target setting -** Through the digital twin, process operators gain insight into expected inflow, task throughput, and total outflow based on the defined parameters. These insights facilitate the creation of operational targets, aligning objectives across departments. This results in a collaborative approach to achieving shared system goals, thereby transcending departments' objectives.

To conclude, the digital twin creates value by dynamically evaluating the performance of a system. This supports process operators to immediately notice unexpected effects of variability, for example, which can lead to lower performance (expressed in KPIs) or fluctuations in throughput per task. By then having immediate insight into the effects of changes in resource allocation, quick and informed decisions can be made based on resource availability and system objectives.

VI. Conclusion

This research aims to explore how a digital twin can support process operators in dynamically coordinating systems within a complex and variable environment. The reason for the research stemmed from a logistic handling system within the aircraft MRO industry that was experiencing low performance. Through process and data analyses on the system, supported by a literature review, issues related to variability and complexity were identified. The lack of ability to respond adequately to these challenges opened a research direction for digital twin applications in such systems. This research led to the following conclusions:

- To effectively coordinate a complex system, it's essential to create a comprehensive and structured overview of the process, that highlights task dependencies. Additionally, incoming goods should be grouped based on similar processing times and shared process steps. A digital twin can then dynamically allocate goods to tasks and groups, which results in clearly visualising input and workload.
- The developed digital twin provides significant support for operational coordination through three main benefits. Firstly, it enables real-time monitoring of KPIs, facilitating quick evaluation of current and past performance. Secondly, it allows for dynamic testing of resource allocation based on specific objectives, showcasing the potential effects of different allocation scenarios to operators. Lastly, it assists in setting integral targets, enabling departments to contribute to overall performance optimally.
- Furthermore, the continuous loop of monitoring, testing, and target setting ensures that process operators maintain constant awareness of the system's state. This enables quick recognition and response to unexpected variability, such as fluctuations in inflow or processing times. While the developed digital twin doesn't directly reduce variability, it provides a method for quick adaptation to it.
- This research lays a foundation for the adoption of digital twin technology, by focusing on monitoring systems and supporting operators' decisions. The concept developed is not an end product, but a starting point for integrating new technologies, as it opens up opportunities for new technology to (partially) take over these decision-making tasks from process operators. This incremental approach ensures that sufficient process information is collected to make informed decisions on the integration of new technologies. This research opens up possibilities for further research into inflow prediction models, which will make the predictive element of the digital twin more accurate. Optimisation models for the most optimal allocation of resources based on objectives could also be investigated.

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Appendix

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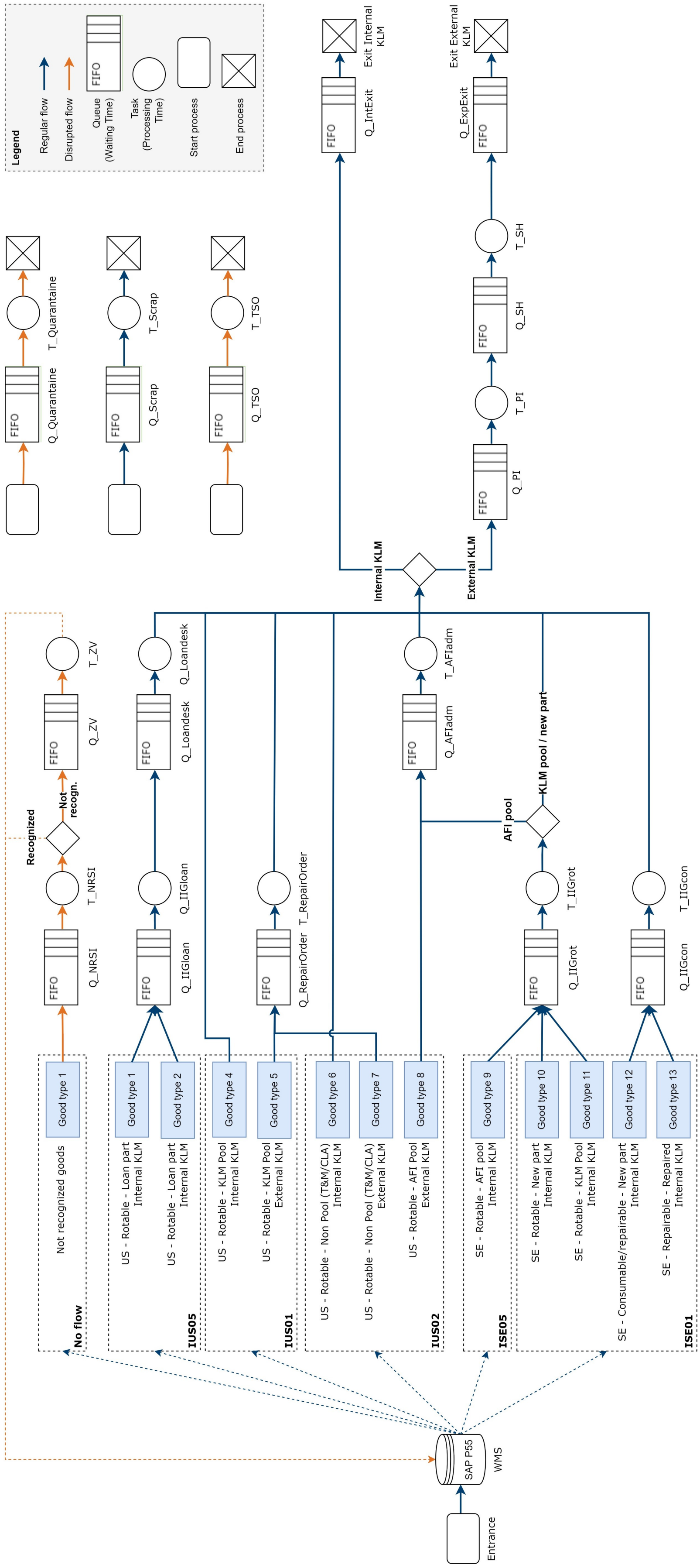

Fig. 9: Process layout of the digital twin

B

Appendix B

Overview of the LHA process layout

This figure gives an overview of the processes and tasks involved within the operation of the LHA. It shows the complexity and dependency between different tasks of the system.

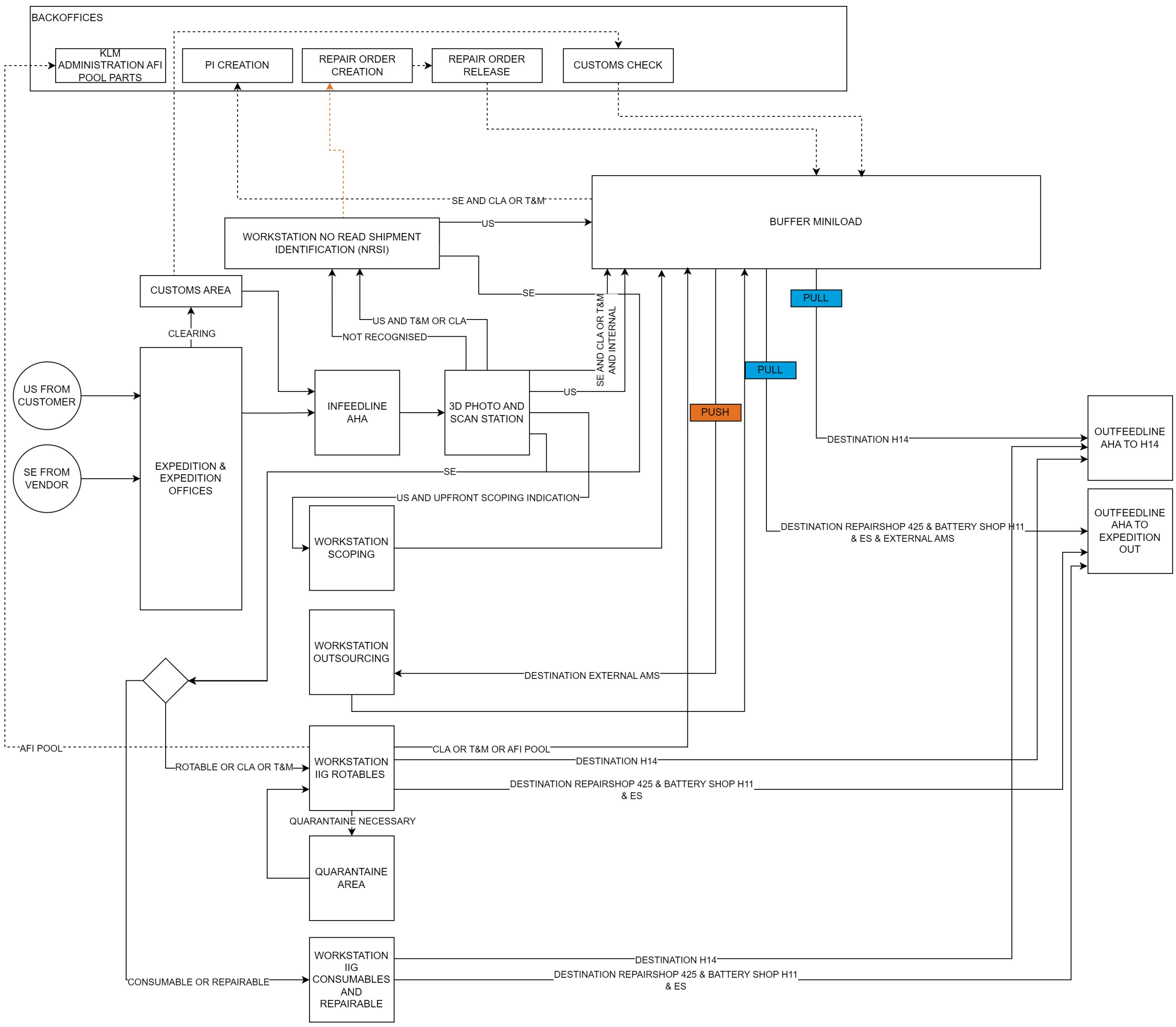

Figure B.1: Overview of LHA process layout and choices

Overview of all process steps for different types of goods

The thirteen defined types of goods have specific tasks that have to be executed before the goods can leave the LHA. An overview of the steps is shown in Table B.1.

Operation state	**Type of goods**	**Type of contract**	**Desti- nation**	**Expedition delivery**	**Expedition Infeed**	**Identification**	**NRSI**	**IIG rotable**	**IIG consumable**	**IIG loan**	**Adm. loandesk**	**Adm. AFI pool**	**Proforma Invoice**	**Smart Handling**	**Expedition Outfeed**	**Internal Outfeed**
US	Rotable	KLM pool part	Int. KLM	1	2	3									4a	4b
			Ext. KLM	1	2	3							5	6	7	
		Non-pool part	Int. KLM	1	2	3	4								4a	4b
			Ext. KLM	1	2	3	4						6	7	8	
		AFI pool part	Ext. KLM	1	2	3						4	5	6	7	
		Loan part	Int. KLM	1	2	3				4	5				6a	6b
			Ext. KLM	1	2	3				4	5		6	7	8	
SE	Rotable	New part	Int. KLM	1	2	3		4							5a	5b
		KLM pool part	Int. KLM	1	2	3		4							5a	5b
		AFI pool part	Int. KLM	1	2	3		4				5			6a	6b
	Consumable / Repairable	New part	Int. KLM	1	2	3			4						5a	5b
		Repaired part	Int. KLM	1	2	3			4						5a	5b

Table B.1: Process steps for part groups

List of monitoring indicators

The developed digital twin can give insight into the following indicators to coordinate the process.

Indicator	**1**	**2**	**3**	**4**
Total system	Total inflow (#)	Total outflow (#)	Total WIP (#)	Avg. TAT (min)
Per good type	Inflow (#)	Avg. TAT (min)	Total waiting time (min)	
Per queue	Goods waiting (#)	Waiting time (min)		
Per task	Throughput (#)	Avg. utilization (%)	Inflow (#)	
Per exit	Outflow (#)			

Table B.2: List of indicator monitors

Data rules for WMS

The backlog of goods per task is based on a dataset where the following data rules are applied. These rules are also helpful for business implementation.

Flow	Queue	Notation	Data rules - SAP P55 (HA Global view)
Regular	Repair Order creation	Q_RepairOrder	Flow Type = US Notification Type = K1/KT User Status ≠ ZB12 Final destination = VCA...VCT
	Proforma invoice creation	Q_PI	User status = ZB12/ZB09 User status ≠ ZB25, ZB26 Final destination = VC
	Smart Handling	Q_SH	User status = ZB12/ZB09 & ZB25 User status ≠ ZB26 Final destination = VC
	IIG rotables	Q_IIGrot	Flow Type = ISE Material Group = 105 User Status ≠ ZB12/ZB09
	IIG consumables	Q_IIGcon	Flow Type = ISE Material Group ≠ 105 User Status ≠ ZB12/ZB09
	IIG loan/borrow	Q_IIGloan	User Status = ZB18
	Loan administration	Q_Loandesk	User Status = ZB41
	AFI administration	Q_AFIadm	Flow Type = US Notification Type = K1/KT User Status ≠ ZB12 Final destination = VCU..VCZ
	Scrap	Q_Scrap	User Status = ZSCR/ZB16
Disrupted	Not recognized shipment identifcation	Q_NRSI	Flow Type = empty OR User Status = ZB38
	ZV status handling	Q_ZV	Notification Type = ZV
	Quarantaine	Q_Quarantaine	User Status = ZB20
	Troubleshooting	Q_TSO	User Status = ZB04/ZB12

Table B.4: Data rules for assigning goods to queues of tasks

C

Appendix C

Layout of the MATLAB Simulink simulation

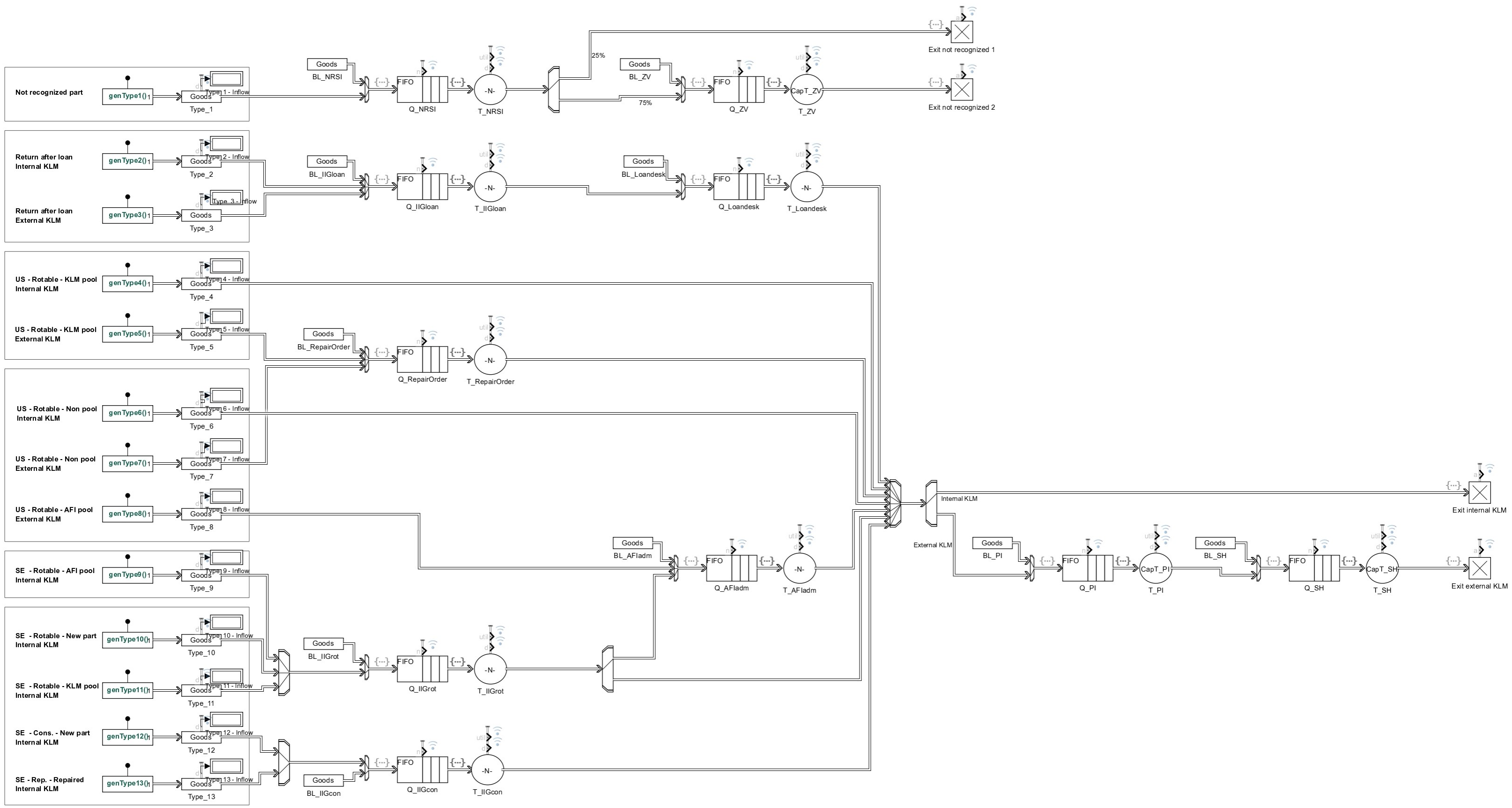

Figure C.1: Layout of the MATLAB Simulink simulation