A green field design method for production control in Maintenance, Repair and Overhaul

Integrating information and process dependencies for control

L.F. Svedhem

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L.F. Svedhem

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Abstract

A design framework for the initial design of a Shop Floor Planning and Control (SFPC) system for a Maintenance, Repair & Overhaul (MRO) component supply chain has been developed. It combines proven design methods developed for the control challenges present for MRO processes and introduces an information requirement mapping that reaches beyond the control boundary of the SFPC system. This is achieved by integrating these with the design criteria for current methods for production control design. The goal was to develop a deployable production control system in the component MRO organization.

The study developed the criteria for an information integrated production control by exploring a generic MRO process control function and concluded that information must be regarded an integrated part of the control design as it drives this process and stretches from supply chain level, down to the shop floor. The criteria are detailed with specific information requirements of the process. System robustness and stability must be considered when evaluating these criteria and deal with the lack of validated design data in the initial design phase.

The framework is developed for exploration of information quality and dependencies of the process. It calls for graphical representation of the logistic and information flows of the process, before configuring the entire production control with known methods. With the selected production control configuration, the control driving information can be characterized and improved for robust and stable parameter design, using Taguchi's approach.

In a case study valid and functional designs were generated for production control systems in general. These could, however not be deployed directly due to the lack of a validated model for the specific performance environment. Robust and stabilizing potential are significant but also revealed a negative correlation.

The study demonstrates the importance of information modelling within complex production systems. It presents a structure for information requirement integration into control design of control layers. It is recommended that the framework is subjected to validation studies for specific environments. With a development such as *Industry 4.0*, control in component MRO supply chains should make use of an integrated approaches over the different control layers.

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Preface

The concept of maintenance covers a broad spectrum of subjects and sparks many different thoughts in different individuals. From the annoying remembrance of a required stop of your car to the garage, to the return of a beloved and precious mechanical watch that is set for yet a new period of trustful timekeeping.

From an industrial or business perspective the general view on maintenance varies over the different stakeholders of the asset of interest. From a bookkeeping perspective all forms of production down-time for maintenance is considered lost time, whereas from a maintenance engineering perspective maintenance is a prerequisite for any production at all. These views lead far too often to an almost classical conflict between engineering and production departments. The maintenance policy usually reflects the turn-out of this struggle, which in its turn, determines the way maintenance processes are considered within the respective organization. As in commercial organizations the economical argument usually is considered the strongest, maintenance is often treated from a cost perspective. This has far reaching consequences that manifest themselves in interesting phenomena. It should be noted that risk plays a special role in this equation. Accidents and fear of, have often sparked increased attention to maintenance and maintenance processes, leading to local buildup of knowledge. This phenomenon is clearly visible in industrial practice where high risk asset operations (or considered as high risk) usually have more extensively designed maintenance programs and processes than operations involving less (known!) risks. This makes the knowledge field regarding maintenance and its related aspects rather fragmented. Hence, much research regarding a process design practice involves case studies conducted at one or few organizations.

With a simple thought experiment, maintenance can be considered as any other production process, but with a special set of characteristics the system is to obey to. This thought experiment developed a research idea resulting in this conducted study.

This work would not have seen light today if I would not have been supported by a range of people that I would like to acknowledge with much gratitude.

First, I would like to thank my supervisors at KLM, Alex Gortenmulder and Guus Philips van Buren, for offering me this opportunity and providing me with their unfiltered insight and experience of aviation maintenance. They have greatly contributed to my understanding of the problem at hand and my knowledge on operational excellence.

Second, I should dr. ir. Schott and dr. Beelaerts Van Blokland, my supervisors at the TU Delft, for their honest reflections and patience that provided me with the insight and peace of mind needed to finalize my conclusions.

Third, I thank Djim Molenkamp, whose software development skills and help have enabled me to develop a functional simulation and my father, Håkan Svedhem, whose skill on scientific writing I should greatly acknowledge.

Special thanks I would like to express to both Roel and John for being the elder brothers in time of need and Anne-Minke, Mercedes, Adinda, Liz, Katrijn and Jurre that took time to listen in time of need and put me back on my horse again. And again.

My parents teaching me on what unconditional belief and support is.

And finally, I would like to thank Willemijn, for your patience.

Delft, University of Technology L.F. Svedhem
March 11, 2020

To the ones that did not live to see this day:

Nadine
Laurens
Julius
Lars

I will all ways be proud and grateful for what you have meant to me

Chapter 1

Introduction

1-1 Research context

During the last decade, the developed world has seen a rapid increase of interest in the environmental impact of production and production systems. Resources used to manufacture a product are lost in great numbers when a product is wasted after its life cycle [1]. This interest has led to the development of the concept of the Circular Economy. This concept builds on the philosophy of a zero-waste society where all physical elements of production; resources, assets and final products re-loop in endless life cycles after initial creation. After a life cycle spent, the element will form a resource for a new element, making a closed loop cycle. This opposes the current concept of a Linear Economy, herein resources are formed to a product and after a life cycle is spent, the product is discarded, making an open loop cycle [2]. Figure 1-1 depicts an interpretation of this circular system versus the linear system.

It can be seen that several loops are possible for the closed-loop route. All have their own properties and characteristics [3, 4]. The closed loop system recognizes three paths for products that reached an End-of-Life, all with different lengths. It should be noted that the status "End-of-Life" has multiple interpretations. These correspond with the different paths in the figure and relate directly to the quality state of the product. The length of the pathway correlates positively with the reduction of environmental and economic loss in comparison with the open-loop cycle. The pathways of *"Remanufacturing"* and *"Reuse/Repair"* form a special fraction as the initial value-added is recovered rather, saving the resources for the manufacturing of a new product. Estimations range from 9% to 14% of energy required and 11% to 15% materials required compared to the creation of a new product [1, 2, 4].

Traditionally seen, remanufacturing and refurbishment are labour intensive and custom project-oriented practices. Each product or part requires some form of custom treatment. This makes the activity rather challenging in economically developed areas that tend to have a higher price on man-hours [3, 5, 6].

The subject of mass customization in relation with labour required, has been one of the driving factors that lead to the development of the **Industrie 4.0** concept in German industry.

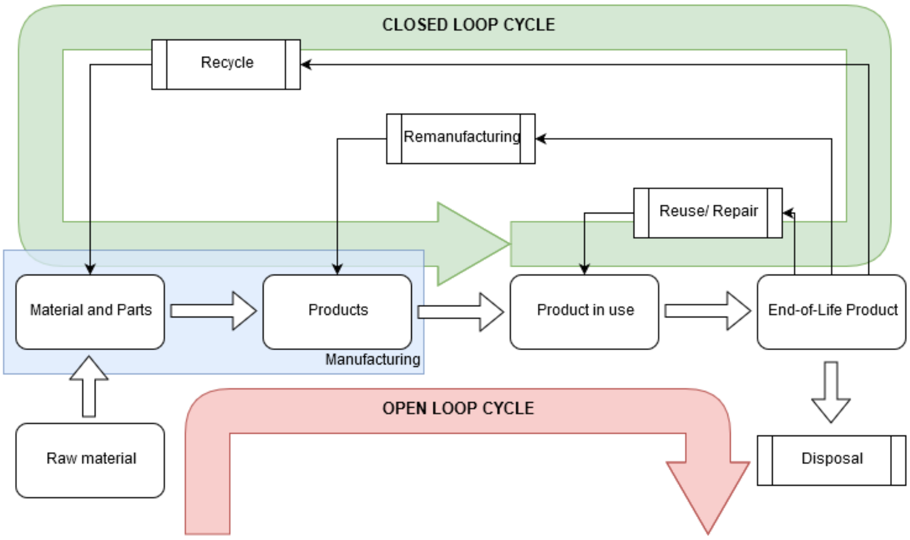


Figure 1-1: Closed loop and open loop product life cycles adapted from Lee, Woo and Roh [3]

With the arrival of distributed computing power over the last decade, manufacturing has been taken to a new dimension by virtualizing and decentralizing the many components of manufacturing control. Adaptable networks that should enable the mass customization in automated and semi-automated production systems with a high degree of human-machine interface integration have been formed [7, 8, 9].

1-2 Research field

This research project was conducted at the maintenance division of Koninklijke Luchtvaart Maatschappij (KLM); KLM Engineering & Maintenance (E&M). KLM E&M is part of the larger airline merger of Air France and Koninklijke Luchtvaart Maatschappij. Their respective maintenance divisions are grouped under Air France Industries (AFI) and KLM Engineering & Maintenance (E&M). Both have extensive histories in aeroplane maintenance.

Within the aviation industry, maintenance is labelled as Maintenance, Repair & Overhaul (MRO). This term covers all activities aimed at ensuring airworthiness of an aeroplane. In a plane every part has a separate identity with a prescribed service requirement and maintenance schedule. Regulation determines that any component is deemed *Serviceable (SE)* if - and only if - a prescribed certification test has been passed, performed by an organization authorized by the respective aviation authority to do so. Only SE components may serve as spare parts during line exchanges. All other components are deemed *Unserviceable (US)*. A component removed from a plane will lose its SE status and therefore requires a new certification [10].

MRO activities are heavily regulated to ensure the safety of passengers. National and international regulatory bodies determine what parts may be worked on by an organization. The ability to perform works on a specific part or even certain works on the respective part are to be certified by a standardized process. After certification the organization is deemed *"ca-*

pable" for the particular works and hence has acquired this *"capability"*. It may then compete with other organizations that hold the capability status. These do not necessarily have to be other airliners; independent parties may also develop capabilities and the Original Equipment Manufacturer (OEM) of a component holds one by default due to its role in the creation of the Component Maintenance Manual (CMM). The exact role of the OEM will be covered additionally in section 2-1-1 [10].

The MRO business distinguishes three main part groups where work is performed; airframe, engines and components. The airframe comprising the planes hull and strengthening structures, the engines being the unit or units that enables propulsion of the plane, and components, being everything not belonging to the earlier mentioned categories. Components and engines can be removed from the hull and treated separately in the MRO process [10]. At KLM E&M the MRO activities of the different categories are divided over equally named business units: Airframe, Engine Services (ES) and Component Services (CS). KLM E&M provides MRO services for its own fleet and for other airlines. It competes with other organizations on the global market. Table 1-1 shows unit turnover in individual parts.

year	2017	2018
throughput - items	[redacted]	[redacted]

Table 1-1: Components received by E&M for service

From a perspective of mass customized works, it has here been chosen to study the repair processes at CS as components are generally seen as a more dynamic parts category, meaning new designs and new components are introduced constantly. Additionally, the processes within CS are much more part oriented in comparison with the two other categories, that are project oriented to its respective assemblies. A part-oriented approach is expected to show more similarities with parts repair seen in remanufacturing.

CS runs component pools where participants can share a specific part to ensure rapid exchange of parts without the need for own sufficient stock of spare parts. This closed-loop supply chain reduces costs for all participants in the pool [11]. E&M manages the pool by operating the distribution logistics and ensuring component availability for all pool participants. Individual repairs could also be performed under a time-material contract, these are sent in directly. Figure 1-2 depicts the overall component supply chain being managed by CS.

Recently new aeroplane models have been introduced with new technology incorporated in their components. Their appearance on the MRO market calls for service portfolio expansion of MRO providers.

1-3 Problem statement

For any organization to run any process - a simple expansion or a new venture - the process design is required to structure the activities. Within the field of operations management, Slack, Chambers and Johnston describe a process that follows a cyclic path as given in Figure 1-3 and can be described as follows: From a strategical decision, a design is developed. The design is then run with a planning and control scheme and later, when operational

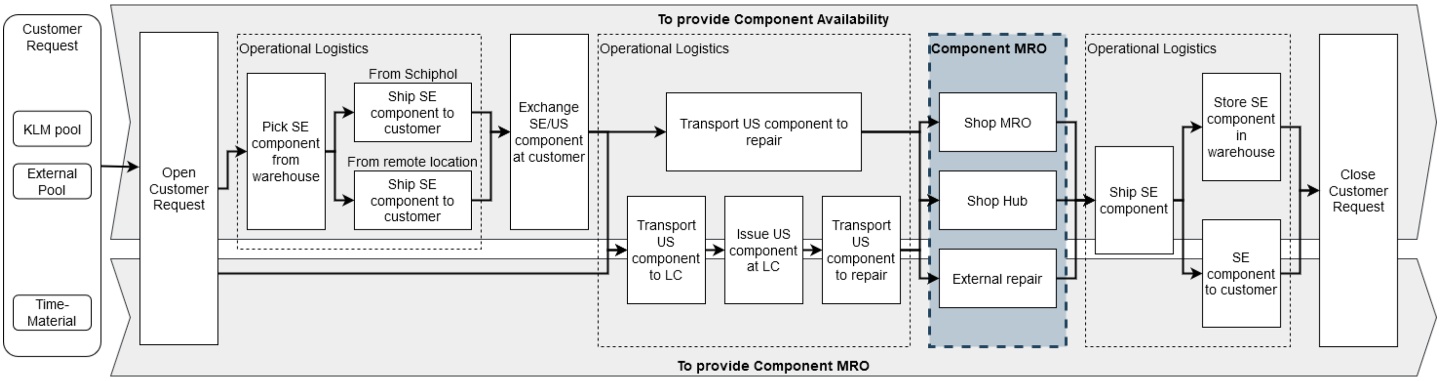


Figure 1-2: An overall view of the component supply chain managed by Component Services as depicted by Lemsom [12]

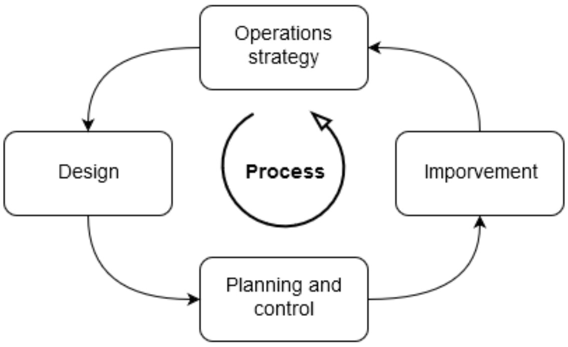


Figure 1-3: The process evaluation cycle [13]

experience allows, improvements can be made to the process, prompting the development of a new strategy.

Given that design development is triggered as part of the execution of some strategy, the design should reflect the characteristics of the elements included in this process [13]. Figure 1-4 depicts a generic process design with its elements as presented by Slack, Chambers and Johnston. The different design elements have been studied by multiple scholars in the general field of remanufacturing processes and MRO specific process environments. Several of these works concern remanufacturing within aeroplane MRO specifically [14, 15, 16, 17]. Several literature reviews were made regarding the subject. These studies conclude that whatever problem is evaluated within remanufacturing process design, its solution should deal with the following complicating factors [4, 6, 3]:

1. Uncertain timing and quantity of returns
2. Need to balance returns with demands
3. Disassembly of returned products
4. Uncertainty in materials recovered from returned items
5. Requirement for a reverse logistic network

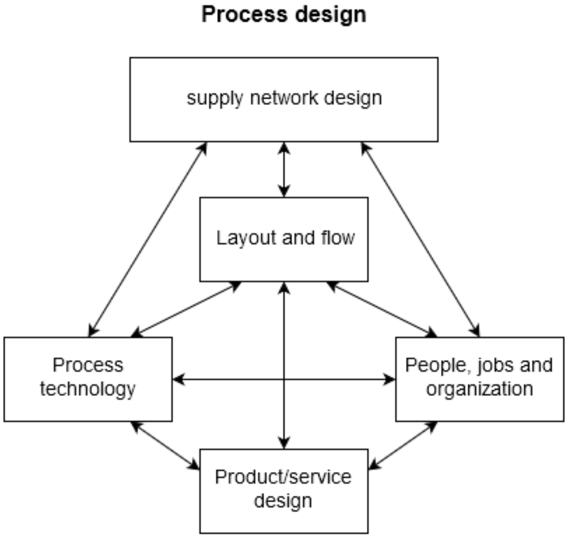


Figure 1-4: Process design elements and their interrelations by Slack, Chambers and Johnston [13]

6. Complication of material matching restrictions
7. Highly variable processing times
8. Stochastic routings for materials for remanufacturing

These complicating factors mostly affect flow, due to the stochastic property of the flows themselves. This, in turn, complicates the planning and control of the process during operation [6]. Shop Floor Planning and Control (SFPC) methods have been studied with this in mind and its results indicate substantial differences between dispatching and control strategies on shop floor level [14, 18, 15]. However, none of these control mechanisms seem to utilize information of the current work in system. This is indicated to be an accelerator for operational performance [19, 20, 4, 6]. Additionally, all studies do make use of real process data harvested from their respective process. This provides detailed information on the stochastic nature of process factors. In the design phase of a none-existing process, this information is scarce.

During the last decade several scholars have explored the control issue on an aggregate level considering one or a few complicating factors. Junior and Filho conclude that literature has mostly covered specific cases of the control problem or increased solution complexity of solutions developed earlier [6]. The same authors discovered in case studies that remanufacturing companies rarely utilize control methods or models specially developed for the characteristics stated earlier [5].

The picture painted by literature is confirmed when evaluating the process design of the capabilities at KLM E&M. Initial evaluation on their capability design procedure reveals that no SFPC method is part of the design requirements. Interviews reveal that the control scheme is expected to "emerge" from the initial stages of operation. The operational data from the early stages is then used to construct an SFPC system if deemed necessary. Their experience shows that this period is troublesome and often requires high amounts of effort for the capability to achieve stable performance. This shows particularly for capabilities for components with newly introduced technology or complex components or both. Their argument for this policy is that the high variability in the component stream characteristics and their lack of process data would make efforts to include an SFPC design into the capability design procedure useless as the SFPC system would be impossible to configure for the future process characteristics. Manufacturing fundamentals state that the absence of any control leaves a process extremely vulnerable to flow problems [13, ch. 7]. Combined with the high variability of the stochastic properties of this particular environment, this approach should lead to a process wherewith operational performance is virtually impossible. This scenario is royally displayed at several capabilities at E&M involving new technology.

A complete generic process control design for MRO has not been presented by literature so far. This is deemed impossible by several workers [9] [21] due to the diversity of:

- product design
- remanufacturing volume
- process layouts

These are the same factors stated by Slack, Chambers and Johnston for the absence of a generic manufacturing process design. Manufacturing design methods do deliver functioning process designs [13], however the remanufacturing characteristics do not allow the simplistic approach used in manufacturing design as remanufacturing has to deal with the previously stated complicating factors [5].

A returning theme in reviews about remanufacturing process control is the use of component arrival quality information as a resource for process control. The quality information interferes directly with several of the earlier mentioned complicating factors. [4, 6] Whereas much research has been directed towards ensuring quality of the final product in remanufacturing, none of the existing literature on SFPC develops integrated systems for planning and control with this information. Literature directed towards the *Industry 4.0* approach in production systems reveals that information enables the mass customization of orders in regular manufacturing [7] and concepts have been proposed for *smart* MRO systems that optimizes the use of component quality information for the control of maintenance activities [22, 23, 24]

Summarizing: The absence of a proper SFPC design for remanufacturing has proved to cause difficulties in SFPC and product flow throughout the remanufacturing industry. KLM E&M is no exception. The capabilities that ought to be designed require a control design that could take the uncertainty of design parameters and product nature into account. Recent insights on information management have shown that remanufacturing could benefit from the formalization of information systems in process control. Exploring the combination of these subjects could potentially bring benefit for the practice and uncover this research field further.

1-4 Research scope

With the rather conceptual information modelling in MRO, the rather defined SFPC policies for remanufacturing, but not practical in design and the absence of a design method/sequence, it was sensible step would to attempt to design a applicable SFPC system that integrated the information requirement for mass customization capability for an MRO process of a component with unknown processing characteristics. To integrate these various subjects into the design, a framework was developed from the various research subjects. The control design would have to be applied in a new capability, which was under development at KLM E&M at the moment of writing. This meant the system should, additionally to the complicating remanufacturing characteristics, answer to all the limitations found in aviation MRO and the practical limitations of the operational environment at E&M, but not be restricted in the direct control range. By this is meant that the control system itself should not be limited by the existence of control systems at its level of operation, a so called "green field" is assumed for this systems range. This subject will be detailed later in the study.

In order to design any control system, the control environment must defined first [25, 21]. Figure 1-2 shows the complete E&M supply chain. Repair and remanufacturing is performed in the respective component shop. This stage is marked with the thicker dashed line, labelled "component MRO". The respective component shop is an individual entity in the supply chain and as components are pushed through the supply chain, the shop has little to no control over activities in the rest of the chain. Therefore the control boundary was set to surround the repair shop and all connections to its direct surroundings. This control boundary was seen in several other designs for remanufacturing presented by literature [15, 26, 18, 14, 19]. It has been realized that setting the system boundary to surround the shop, only available information sources will be eliminated from the final control design. Research in the practice confirms that ideally the overlying supply chain control and SFPC are designed along, however this is not guaranteed an optimal solution to the entire manufacturing control problem and the opportunity to design both alongside seldom occurs [27, ch. 29]. With the current situation at E&M not allowing for vast amounts of data mining from the entire supply chain, the loss of this information has been deemed acceptable for this study as doing otherwise would jeopardize the immediate applicability requirement of the developed design.

The capability selected for the design regards the components of the liquid cooling system of the Boeing 787 Dreamliner aeroplane. The process control is to be applied to a dedicated MRO process that handles two somewhat similar refrigeration units with integrated compressors. Their exact characteristics will be explored in section 3-1. The capability was selected as it came closest to the initial research scope in terms of component complexity, expected nature of variance and to E&M unknown, new technology as moment of writing.

Given the proposed SFPC design, propositions were developed on to what degree the design satisfies the targeted problem areas and additional features within the MRO and remanufacturing environment. These propositions were evaluated by comparing performance in a process simulation.

1-5 Research questions

The development of the design framework was be guided by several research questions centred around the main question. Considering the problem statement analysis and the scope described the following main research question could be formulated:

How is an information integrated Shop Floor Planning and Control system designed for component Maintenance, Repair & Overhaul in a green field process design situation?

To answer this research question insight in the matter is obtained by answering the following sub-questions:

1. *What is a generic MRO process design according to literature?*
2. *What criteria are essential for a solid MRO production control design?*
3. *What are elements of a production control system?*
4. *How is a production control system designed?*
5. *How can the role of information in the greenfield design of the MRO process be defined?*
6. *What framework from literature for an MRO process shop floor planning and control can be stated?*
7. *What is an MRO process SFPC design for the Liquid Cooling MRO process considering the process criteria for general MRO Shop Floor Planning and Control?*
8. *What is a performance testing environment to evaluate a production design?*

With the research questions defined a design for the research could be drafted and methodologies could be selected. The upcoming sections describe the methodologies that have been to make up the design of the research.

1-6 Research design

This study contributes to the field of Shop Floor Planning and Control (SFPC) design in MRO with an integrated information dimension. MRO is a broad domain with many aspects. As this research will study the subject within one organization dealing with a specific field within MRO, the case study for business structure by Dull and Hak was applied.[28] This method distinguishes between research for practical and theoretical purposes. Practice-oriented research serves the expansion from knowledge of a specific group of practitioners within an industry. The theory-oriented research is conducted to contribute to theory development on the relevant issue. As this research was aimed to contribute to the scientific knowledge on shop floor planning and control design by developing a proposition, the theory-oriented approach was chosen to structure the basic design of the research [28].

With the research specific objective and main strategy determined, this research was divided into three main phases [28]:

1. Framework formulation
2. Development of an SFPC design for the selected case
3. Evaluation of resulting design and evaluation of the design framework

The following paragraphs will elaborate on these phases shortly.

Framework formulation phase Within theory-oriented research Dull and Hak distinguish two types of research: theory-building and theory testing.[28]Theory-building aims to formulate new propositions to complement the current state of theory. The theory-testing aims to evaluate of yet formulated propositions within specific fields of the research domain. As the research scope is aimed at the development of framework, this work was considered to be theory-building. The specific design framework will be developed by a literature study and expert interviews at E&M. The framework was to structure the development of a generic control model.

Development of an SFPC design With the final design goal well defined, the theory by Dull and Hak suggests the use of a comparative case study for the evaluation of the candidate proposition. Therefore this was used as the main research strategy. Where for the case study the Boeing 787 Liquid Cooling capability was selected and the design requirements for the process were distilled from the literature study and the case specific information.

Evaluation of design and framework The concept control design was developed and evaluated by exposing the resulting control design to a performance environment at E&M where the design is thought to operate. As an immediate implementation in the real shop was out of scope, an Discrete Event Simulation (DES) computer model was used to test the design for specific performance and the framework for its general application. The DES model was developed to simulate the performance environment at E&M. The use of DES modelling is advised in case a real-life experiment is not within scope.[25, 29] Many previous studies on manufacturing and remanufacturing shop floor control make use of DES for control element testing [30, 15, 18, 26, 17]. The results of the testing will then be discussed within the context of the current theory and reported on.

Data gathering The control design framework and the MRO process properties were composed from literature and practitioners' knowledge. The specific proposition for testing and the performance environment have been developed by studying business documentation such as investment proposals, business cases and technical product documentation completed with expert knowledge. DES model validation was done with a data set developed from historical operational data.

This chapter will be concluded with a short overview of the report of the study. Figure 1-5 provides a schematic overview of the main and -sub phases of the research, their intermediate deliverables and their respective chapters . After this introductionary chapter, the practice and theory study are in chapter 2 to form the design framework. With the experimental framework established, the case study was performed. This is described in chapter 3. The experimental design evaluation strategy and simulation description are covered by chapter 4. The evaluation strategy is translated to experiments for the test environment. The experiments, their results and their implications that are covered in chapter 5. Ultimately there is concluded on the research in chapter 6

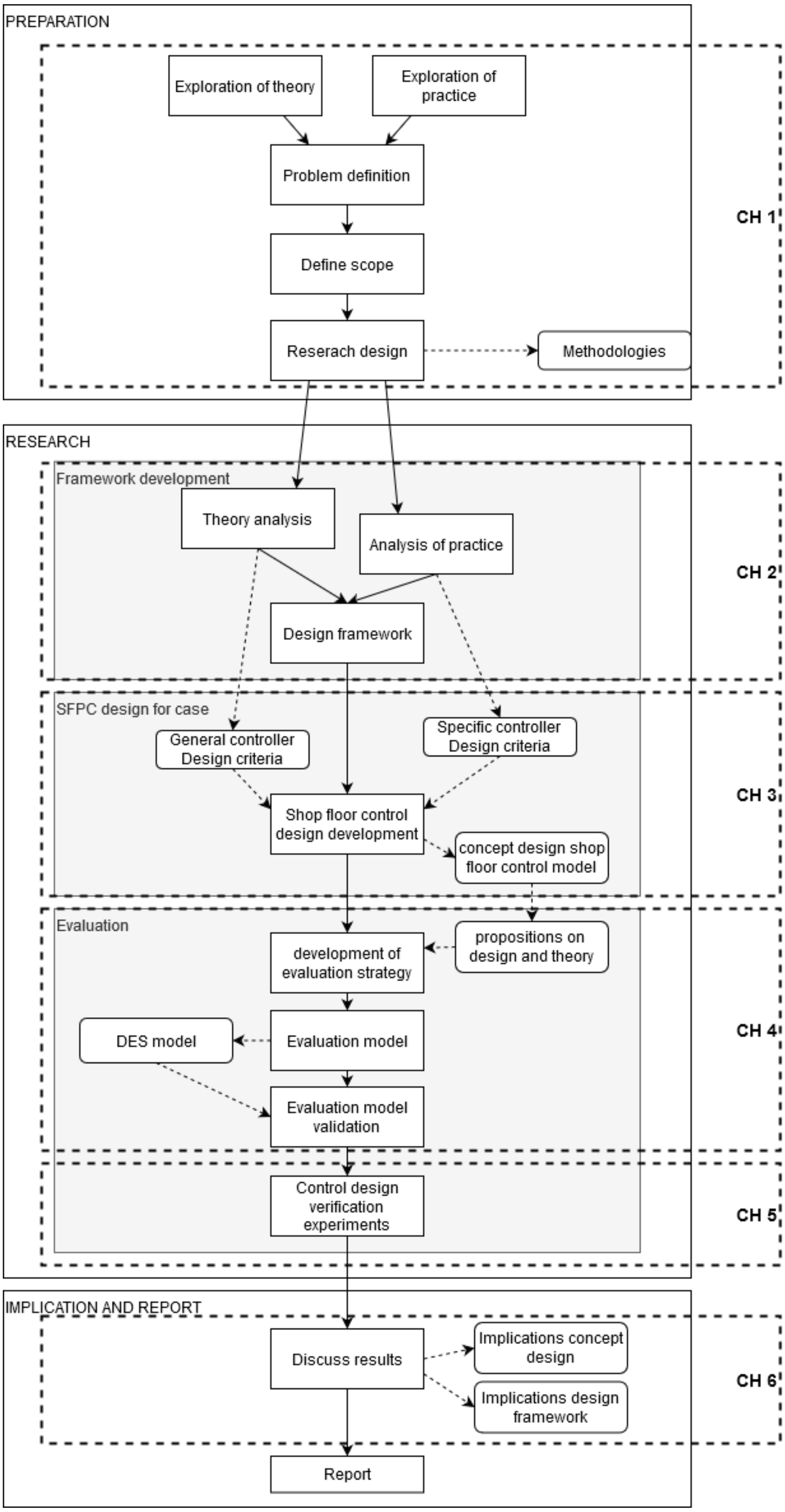


Figure 1-5: Research design

Chapter 2

Analysis of theory and practice

To evaluate the relationships between Shop Floor Planning and Control (SFPC) and the Maintenance, Repair & Overhaul (MRO) process design, the MRO environment and the theory of SFPC system is to be properly defined and understood. This will be done by a theory analysis in this chapter centred around the following research questions:

1. *What is a generic MRO process design according to literature?*
2. *What criteria are essential for a solid MRO production control design?*
3. *What are elements of a production control system?*
4. *How is a production control system designed?*
5. *How can the role of information in the greenfield design of the MRO process be defined?*
6. *What framework from literature for an MRO process shop floor planning and control can be stated?*

The generic MRO process will be explored starting from a generic point of view in Section 2-1. With the established definitions of the generic MRO process, criteria are developed for process and production control in Section 2-2. The relation between the control criteria and information is evaluated in Section 2-3. Section 2-4 explores the current understanding of control design on a process level and production level. Finally, in Section 2-5, with developed knowledge an experimental framework sythesized for the design of a control system. Every section will be closed by answering its respective research questions.

2-1 Defining Maintenance, Repair & Overhaul

Maintenance, Repair & Overhaul comprises "all actions that have the objective of retaining or restoring an item in or to a state in which it can perform its required function. The actions include the combination of all technical and corresponding administrative, managerial and supervision actions."[31] The view of this collection of activities as one practice originates from the military equipment resupply operations during the later stages of the second world war. Over time, MRO has developed for many industries that are dependent on capital assets for their operations.[32] Examples are: naval vessels [33], industrial Robotics [34], telecommunication stations [35], heavy industrial equipment [36] and aeronautical vehicles [37]

Evaluating the content of Maintenance, Repair & Overhaul over the different industries reveals different terminology and standards, if any are defined. If so, the respective regulatory bodies show difference in the extent wherewith the requirements are described and the strictness of the implementation [37]. The strictness can vary between global directions or circumstances under which the work should be executed to detailed stepwise descriptions of individual tasks. After general dissection of the abbreviation MRO the following definitions can be formulated:

$$\begin{aligned}\text{Maintenance} &= \text{activity to prolong functional state of an asset}\\ \text{Repair} &= \text{activity to restore the functional state of an asset}\\ \text{Overhaul} &= \text{activity to restore an asset in "as-new" state}\end{aligned}$$

The general term "*maintenance*" is often used as a collecting term for all MRO activities. In this report "*maintenance*" will be defined according to the above stated definition unless stated otherwise.[31] For the collection of activities the abbreviation MRO will be used. The collecting term for MRO will be refered to as *service*.

The broad coverage of MRO as a concept makes it a rather interdisciplinary field. With many aspects that are studied as separate subjects by researchers and practitioners, all with own preferred categorizations. Driessen *et al.* distinguishes the works of an MRO organization from a supply chain point of view: [11]

- Line MRO activity
- Line replacement logistics
- Shop MRO activity

Activity *on the line* concerns the works done on the capital asset as a whole or a specific sub-system. Here the assets remains largely in its operational environment and its state whilst being served, separable sub-systems or components could be exchanged, defined as Line Replacement Units (LRU). In capital asset maintenance LRU find extensive use, as they reduce the down-time of the entire system [11]. The term *line* refers to the production environment where the production *line* is the physical object where all MRO activity is centred around. This is not limited to a production environment; rolling stock, road, naval and aeronautical vehicles are also included in this category.

To enable the line MRO activity LRU's should be available. These can be supplied as newly produced units or as rotables. Additionally, the replaced units should be treated in accordance to their condition. As they have been separated from particular asset, they can be treated

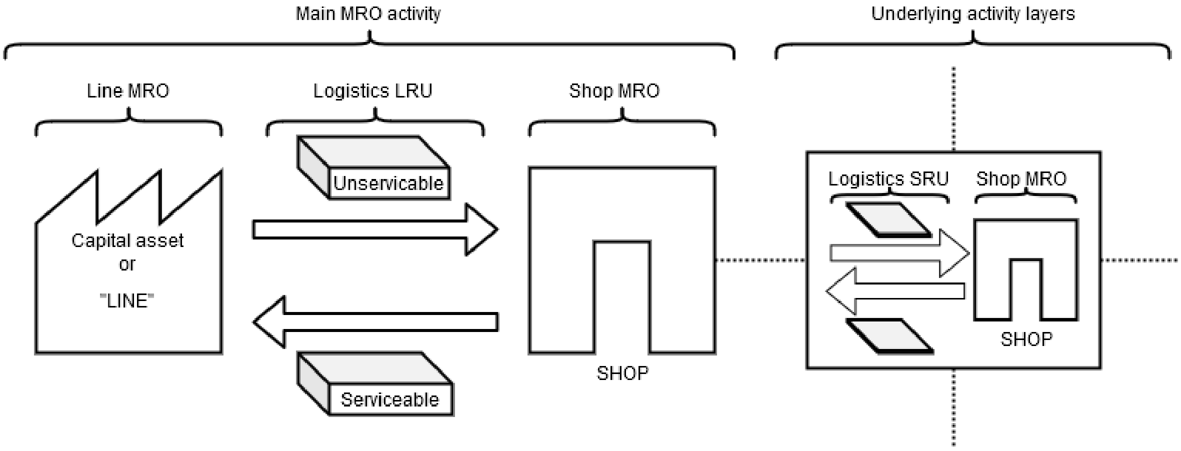


Figure 2-1: Categorization of MRO activities from a supply chain point of view *et al.* [11]

separately in accordance with their need. This could be discarding, repairing or other forms of service and hence can be distributed over different locations for treatment. This logistical step is regarded as a separate activity by the framework.

The logistical step delivers a component to a work shop for shop based MRO activities. In the workshops activities are organized to optimize the works on the LRU's. MRO activities may include the replacement of sub-systems in the LRU's, described as Shop Replacement Units (SRU). These require an additional layer of logistics to be treated. The organization of shop activity is seen as a separate activity in the framework, but it should still serve the aggregate supply chain. The separation of activities can continue over multiple levels up until the smallest component layer has been treated. Figure 2-1

Studying industry specific MRO literature reveals the same categorization of activities under various names; examples are Line MRO and component MRO for aviation [37, 10].

As this study focuses on the shop MRO activity for a specific removable component on an aeroplane the remainder of this section will explore the aviation MRO and remanufacturing processes of repair shops.

2-1-1 Aviation Maintenance, Repair & Overhaul and component MRO

The aeroplane aviation maintenance cycle for a plane starts before the first model of its series has been built. The hard safety requirement, which aims at ensuring *airworthiness* by aviation authorities over the world requires the development of a lifelong maintenance standard before the model can be introduced for commercial use. This programme is heavily standardized and described by the MSG-3 (Maintenance Systems Group) standard, this is also called Reliability Centred Maintenance (RCM). It is based on the criticallity rating of every single part of the plane and studied by means of a Failure Mode Effect Analysis (FMEA).[32] The standard is developed in the Maintenance Review Board (MRB). Regulatory bodies, Original Equipment Manufacturer (OEM)'s and other stakeholders form this organization when a new model is under development. In this board the OEM describes the maintenance procedures deemed required in a task-oriented form. This results in the Maintenance Planning

Documents (MPD). The MPD must be provided to every operator and describes what must be done to uphold airworthiness of the plane. With the MPD the operators compose their maintenance programmes which finally dictate the service requirement of the MRO parties the operator chooses. In contrast with the maintenance tasks, the process that an operator or MRO party designs for the execution of tasks is free for own interpretation as long as the described tasks are being executed [10].

All tasks defined are centred around the service paradigm for aviation: No system critical subsystems may ever fail during operation of the plane. Hence, much of the tasks define inspections of parts. The results of these inspections may lead to additional service activities. After all repair work has been executed, a final predetermined inspection must be executed for the respective part to be considered *serviceable*. This regulatory format and paradigm extend over the three different domains of aeroplane maintenance; airframe, engines, components. The next paragraphs provide a brief explanation of these limitations and characteristics per category:

Airframe The airframe may be considered the actual plane as it cannot be partitioned for repair. Operating a flight will be impossible without the actual frame. This means the time spent off the line, where passengers are carried, is seen as direct loss and thus should be minimized. Operators schedule time windows in their flight schedule where the plane is off-line for maintenance. The airframe is an inseparable and complex structure with many covering elements. All activity has to occur next to, or in the body of the plane, limiting the customizability of the environment. Components may have to be removed to expose the respective part of the structure. This means that a detailed planning must be prepared to have all required tasks executed before the time window elapses. The task sets vary and certain inspections works may lead to additional work. This makes each visit a unique project of a set of predefined activities. Failure to make the due time of the service window leads to severe economic losses [10].

Engine services The power plants of a plane are considered the most complex separable component of an aeroplane, it hence is treated as a separate branch within the components that can be treated "*off-wing*". At time of service the engine is removed from the airframe and can be treated in a specialized facility. In commercial business the engine is replaced by a serviceable one to allow the plane to continue service after the "*swap*". The engine forms an assembly out of sub-assemblies (assy's) that are separated for their service. The assy's require a wide variety of treatments making each engine service instant a unique project of a set of predefined activities. The time window for engines is less stringent than an airframe as the engine does not uniquely belong to the airframe, hence another serviceable engine may be fitted. However, arranging a specific engine on short notice is very costly and should be avoided [10].

Component services All separable parts of the plane not belonging to the engine are grouped in the category components. Components can be replaced on the "*line*" and are then treated at their respective work centres on any location. The works for a component are not planned further than the line service execution. A component does not belong to a specific airframe. This offers flexibility for its maintenance process. When size and weight permits, components can be shipped to external, specialized service centres. This may be the OEM of the component or an independent MRO provider [10]. In the service facility the component receives the required service dictated by the Component Maintenance Manual (CMM), which is part of the MPD. As components are swapped as LRU and usually part of a rotation pool, penalties for individual delays are not charged, instead a "*tardiness*" score of a multitude of repairs is kept over a predefined timeframe. These minimum scores are part of the service contracts offered in the pool participation [11, 10].

Shop MRO process

Within the context explained in the previous section, the MRO activities in a component shop will be detailed out additionally.

Every part has its own service cycle and must be removed or treated during a plane's service visit or on the line before it is due. This could be measured in stress-cycles, flight hours or regular time. Operators maintenance departments schedule the service visits of planes and the planned activities for each visit but works on individual components are not specified for or planned in advance. Specialized component shops receive components from a multitude of independent operators or their respective MRO organizations. These suboptimizations on different levels cause a stochastic arrival pattern of components at the repair shop.

A component often arrives without a specific requirement mentioned, hence at initial inspection, the component is evaluated for its service requirement. The tests that match the service requirement shall be defined before testing as various tests may be possible. The exact works will only be known after the testing has occurred at the executing MRO organization. The test results combined with the initial inspection will provide enough information to determine the work scope of service. With the scope defined, the first actual time requirement for repair can be determined. The time required influences the total throughput time of the component. The work scope also determines the routing through the shop; this is the physical path the component and/or subcomponents follow to receive their treatment. This may include a parts exchange with rotables, that could be treated as SRU's.

The CMM prescribes what activities need to be tested and when. Some repairs may have to be checked before the final component is assembled together. A final test must be executed before certification is done and the component may be regarded as *serviceable* again. The certification includes all test reports that came with the shop visit, this includes possible external routings. After certification the component may be shipped.

The distinguishable steps for the shop visit are listed below and depicted in Figure 2-2:

1. component arrival at shop
2. initial inspection of the component and test definition
3. testing
4. work scope determination
5. component disassembly
6. repair routing
7. component assembly
8. final check of activity

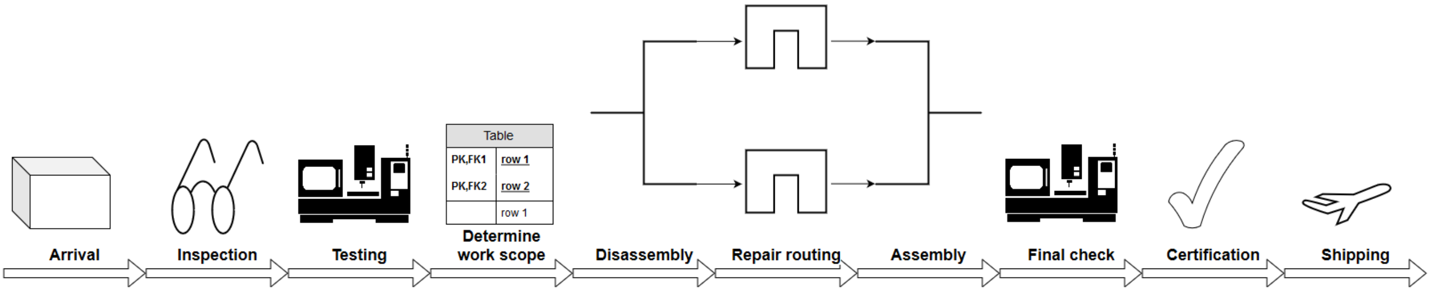


Figure 2-2: A generic aviation MRO shop flow process

9. certification
10. shipping of component

The throughput time of a component is rather variable as the set of activities required are completely dependent on the state of the component. Maintenance and repair work could entail simple check or a full replacement of a system critical part and combination hereof, the activity combinations expand over component complexity. The only situation wherein the full work scope is predefined, is when a component is decided to receive an "*overhaul*" before any testing has been done. For an *overhaul* all steps that must be executed are defined by the CMM. While the component throughtput time may show high variance, the aeroplane manufacturers do keep a "maximum" throughput time for the component groups in general. These are not mandatory to keep but do form a benchmark in general shop performance.

The aviation shop process in MRO has been described within the context of the aviation MRO itself. Several scholars have studied aviation MRO shop processes from a remanufacturing perspective. To evaluate their similarities, remanufacturing will be covered in the next section.

2-1-2 Remanufacturing

Remanufacturing emerged as a research field in the late nineties after several scholars hailed its proven potential for many industries from an economic and ecologic perspective [1, 38]. The principle of restoring an old used tool to usable form might be just as old as the fabrication of tools itself, but these publications marked the start of this subject as a research field.

Remanufacturing concerns the activity to return a part into "as good as new" state after it has spent a useful application[1]. Other than a component in a MRO cycle, a component that is in a closed-loop lifecycle by remanufacturing is not necessarily part of the maintenance system. The life cycles of a part in a remanufacturing loop could be completely independent from each other, whereas a component in an MRO cycle will pass some coordinating entity at some point. Any product conforming to the *properties of remanufacturability* presented in chapter 1-2 could be in a *remanufacturing* closed-loop life-cycle. The actual remanufacturing process has been separated from the entire supply chain for a detailed process study of the in-shop activity.

Part of the activities of MRO is the *remanufacturing* of parts. The remanufacturability of aeroplane parts is high when considering Lund's prerequisites for successful remanufacturing of a product: [38]

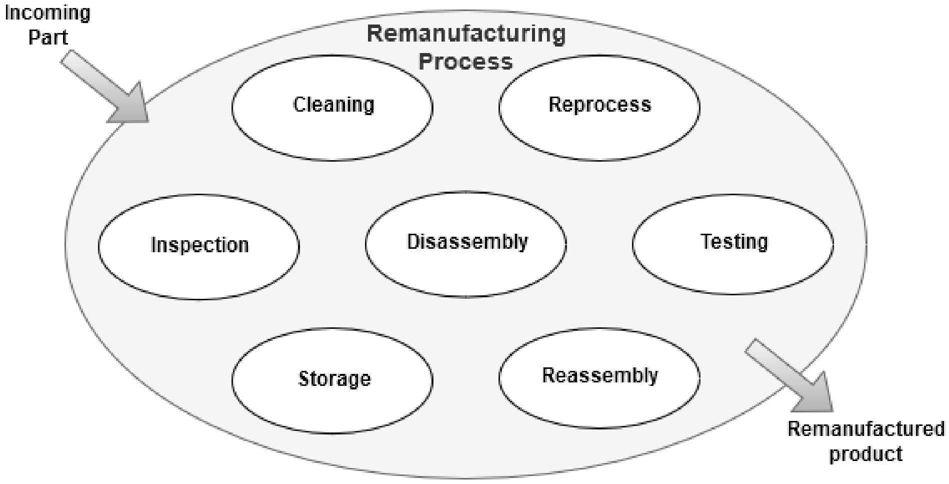


Figure 2-3: The generic remanufacturing process [39]

- it must be durable goods
- it fails in functionally
- it is standardized and parts are interchangeable
- the remaining value added is high
- it is not costly to obtain compared to value that is added
- the build technology is stable
- the customer is aware of the remanufactured product being available

The remanufacturing process

Analysis of multiple remanufacturing processes reveal a generic set of activities that should be performed for a solid remanufacturing process [1, 39]:

1. disassembly
2. cleaning
3. inspection
4. reconditioning
5. reassembly
6. final testing

Later in-depth characterization reveals additional steps and an undetermined order, leading to the collection of process elements with a yet to be determined order for a generic remanufacturing process as given in Figure 2-3 [39].

Remanufacturing as an MRO activity

An evaluation of the key differences between MRO and normal manufacturing presented by McLaughlin and Durazo-Cardenas reveals that the in-shop characteristics of the MRO and the in-shop characteristics of the remanufacturing process presented in chapter 1-3 are similar. Table 2-1 provides a structured overview of the key process properties identified. Short comparison leads to believe that remanufacturing and overhaul are the same in essence of their shop process. Much of the remanufacturing research presented describes an MRO process [4, 30, 5]. Hence remanufacturing will be considered a subset of MRO activities.

Even though a generic remanufacturing process is less stringently defined than an aviation component MRO process, the main process steps of a MRO process are present in a remanufacturing process. With the matching key characteristics mentioned earlier, it is assumed that MRO is a special form of remanufacturing. To futher ensure that shop MRO activities in aviation and remanufacturing do have the same process properties. The existance of a generic MRO process description of a single component group's shop process will be explored in the upcoming section.

Characteristic	Normal Manufacturing [40]	Shop MRO [40]	Remanufacturing [1, 41]
Process-main type	Multiple component input one product output	One main input same component is output	As MRO activity
Input requirements	Clearly defined and repeatable	Defined at outset of process	As MRO activity
Process-routing	Clearly defined per product	Depending on input state of component	As MRO activity
Work content	Fixed for each repetition. defined in Standard Operation Procedure	Depending on input state of component	As MRO activity
Tacit knowledge	Integrated in Standard Operation Procedure	Applied depending on input state of component	As MRO activity
Output tolerances	Defined by design requirements	Defined by operational requirements	As MRO activity
Output	Product created from components	Product created from initial product	As MRO activity
Work systems	Standardized and defined	Depending on input state of component	As MRO activity

Table 2-1: Key characteristics of in-shop processes of MRO activity and remanufacturing activity

2-1-3 The generic MRO process

The previous sections explored element characteristics of a generic MRO process and found the union of remanufacturing process knowledge and MRO process knowledge. These general characterizations and elements for the generic MRO process presented in this section.

Characteristics

An MRO process performs services on parts to restore or ensure the functioning of the part in accordance with a predefined standard. Assuming the part as an entity over its entire lifetime and not its service life, the functional status of the element can be regarded as the the deviance from this standard in both a positive and negative way. A negative deviance renders the part unserviceable and will require the MRO process to achieve serviceable status again. From this point of view the MRO process can be seen as a quality restoration process and has been proposed in exploratory research [42]. The requirements for a particular MRO service visit must thereforee be determined. As this principle concerns a measurement of difference an additional point measures the relative quality increase of the process. This first principle of the generic MRO process contains two task related elements; the initial quality evaluation and the final quality evaluation. The ability to add non-standardized value (no Standard Operating Procedure) is a quality driver for an MRO process.

RCM forms a solid basis for asset availability, as it ensures the serviceability of an asset as a functional system. However, that does not mean it can be regarded as a maintenance requirement planning, as failure preventing inspections build up the RCM paradigm. This results in an unknown service requirement for a part in a subsystem at any given point in time. Academia describe how information systems could greatly improve this uncertainty [10, 43] and individual examples of practice have been recorded, but the MRO industry itself still reports large variance in service demand. Additional to the stochastic process of service demand, the exact work scope of each service is subject to variance. The abbreviation MRO already covers a variety of work scopes and component properties influence the exact order of stages and routing in the process. thereforee, an overall generic fixed order of process elements cannot be stated. Multilateral relations can be stated between several elements.

Manual labour is used extensively in all process steps within the MRO process. The complexity of the handling and the actual work cause low incentives for dedicated machines to automate process steps. Automation schemes or frameworks have been tested for inseparable components for surface treatments [42] and show promising results. Several studies indicate that for complex assembled products, the product design needs to accommodate for automated handling during remanufacturing or repair [39].

Process elements

For the generic MRO process, occurrences of MRO processes and the generic remanufacturing process have been studied. For the generic MRO process three main stages can be distinguished for the main routing:

1. pre-routing
2. shop routing
3. post-routing

pre-routing The pre-routing prepares the part and plans the routing of the process. It must contain the *initial test* and the *work scope determination* for any shop routing to be planned. The term *initial test* could be divided into multiple sub-elements such as but not limited to; simple inspection, test-runs, etc. The essence of the *initial test* is that information on the current state of the part is extracted. This information forms the basis of the *work scope*. Henceforth, the *initial test* will always prevail the determination of *work scope*. The pre-routing could contain additional elements; disassembly and cleaning. These do not always

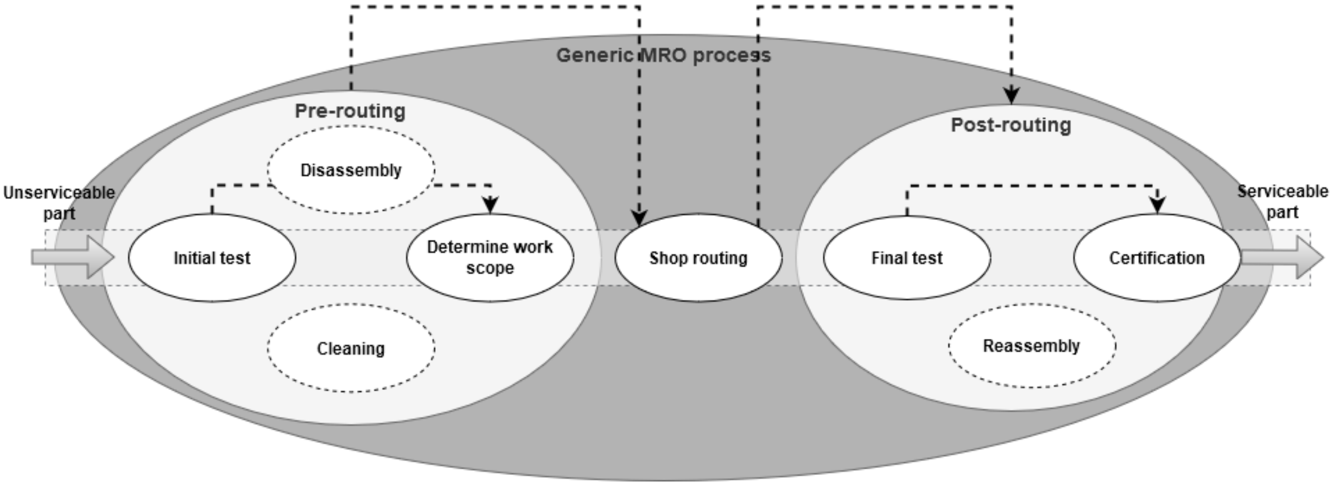


Figure 2-4: The generic MRO process

occur and their positions in the pre-routing show to be variable. They are included in the generic process as both processes could produce information for the *determination of work scope*.

shop routing The shop routing contains all tasks and shop visits where the required work is done for the service visit. This could contain multiple steps and must be detailed out with specific part characteristics.

post-routing With the service tasks executed, the post-routing closes down the MRO process service visit. Post-routing must contain the *final test* and *certification*. The *certification* must be the final step before a part's status updates from unserviceable to serviceable. The test results of the *final test* are to be used in the certification process. The difference between the *initial test* results and the *final test* results make up the value added by the shop routing. Additionally, the post-processing could contain a *reassembly* step where different sub-systems are joined to form the complete part. Regulation may require individual testing of sub-systems before *reassembly*, hence this step cannot be fixed in the sequence. In the case of multiple final tests these may be required before and after reassembly.

The different main stages and individual process steps are depicted schematically in Figure 2-4. The central horizontal strip entails the mandatory process elements in their specific order. The additional elements have been placed "hovering" in their respective main stages.

Flow properties

In the generic MRO process, parts pass through and towards the process with generic characteristics. With an asset being part of some sort of production system, down-time is highly undesirable. This limits the maximum time that is available for a part to pass through an MRO process. The time limit is ultimately an agreement between the asset operating party and the MRO process executor and could be subject to standards.

Demand for the process and the exact workload are both subject to variance. Interorganizational information exchange and state planning/tracking abilities form barriers for good insight in the arrival of jobs at the process. Hence, the arrival of jobs is must be assumed to be stochastic. The intermittent patterns have been categorized by Syntetos: [44]

- Intermittent demand, which appears randomly with many time periods having no demand
- Erratic demand, highly variable erraticness relating to demand size rather than demand per unit time period
- Slow moving demand, random occurences with long periods of no demand
- Lumpy demand, long periods with no demand, highly variable

A relation between quality deviance and work scope size of an arriving job has been described qualitatively but could not be proven quantitatively. Additionally, its direct relation to processing times could only be determined for individual processes. So far, a generic description has not been found [42]. This adds an additional dimension of variance to the total workload presented to the process. Additional characteristics are distinguishable for individual parts or part groups, these must be detailed out when a specific MRO process design is being developed.

2-2 Process control and production control for component MRO

With the characteristics and properties of the generic MRO process, design methods for control can be explored to fit the generic process. To explore design methods for control, first the criteria for control have been developed to determine control area and the subject of control.[27] This section will explore the definitions of performance criteria and control for the generic process.

A control function is a comparative element that compares a form of measurement signal with a reference value ("the target") and an actuating element that enables the alteration of the property of the signal measured. Good control performance is the adequate correction of deviance measured from the reference.[25] Section 2-1-3 defines the component MRO process to be a quality restoring process constrained by tight time requirements for cycle time of the component. This follows from the specific function of the component MRO process in the component supply chain. A distinction is made between *process control layer*, that enables the functionality of the component MRO process and *production control layer*, that enables the functionality of throughput and cycle time, which adds to the logistic performance in the supply chain. This distinction has been made in earlier design studies [42, 27]. To identify the mechanisms required for quality control and logistic control, the two issues are explored separately in this section. As several scholars stress the interaction of the two [27, 42, 45] a special section in this chapter will be dedicated to the interaction between the process control layer and the production control layer.

2-2-1 Performance in the component MROprocess

Process performance should evaluate the fitness of the entire process for the required service. This fitness gives meaning to the existence of the process. Section 2-1-3 describes the the

	Logistic Performance	Logistic Costs
External	*make-to-order production:* delivery time delivery date deviation delivery reliability	price
	make-to-stock production: service level	
Internal	throughput time due date deviation due date reliability	inventory utilization costs of delays

Table 2-2: internal and external KPIs for logistic objectives as stated by Wiendahl [46]

nature of the MRO process to be the restoration of quality of an asset. This means that the process performs, if it succeeds in restoring the components measured properties into the specified reference bounds. Failure to restore the respective quality property would result into rework. Additionally, the maximum of throughput time can be considered as a quality score for the process [13, 45]. Throughput time is however influenced by the production control and will therefore be assessed on that level. The quality increasing potential of the process is not directly controlled by the production control. Production control has an influence on the circumstances wherewith the process executed. This can be of influence for the final quality of the process, but is not directly related [45]. The scope of this study does not extend to the performance measurements of the final process that can not be controlled by the production control directly, hence performance control of the component MRO process will not be contemplated on further.

2-2-2 Defining performance in production control

For an make-to-order environment internal and external Key Performance Indicator (KPI) have been stated for *logistic performance* and *logistic costs* by Wiendahl. Table 2-2 provides an overview [46]. The SFPC enables performance ambitions for the process by realizing the desired output value or behaviour of the KPI reading. A definition on each follows:

- Logistic performance
  - *cycle time* or throughput time: the amount of time of between the order release and the end of processing.
  - *due date deviation* DDD: the amount of deviance of the planned due date and the actual due date of an item. This could be measured in absolute delay time units or relative to the original throughput time
  - *due date reliability* DDR: the chance of an item being delivered before the due date passes.
- Logistic Costs

- *Inventory* WIP: the amount of "unfinished" work in the system. This is usually expressed in a number of jobs
- *Utilization* U: The fraction of the total amount of production time available compared to the total amount actually produced.
- *cost of delays*: A monetary unit that is a sum of all the costs that follow from a specific delay.

As there is no such thing as a generic SFPC system for any production. It is important to state that an production control system should be designed to promote certain system behaviour, by assigning priority to the logistic objectives. The priority selection should reflect the operations strategy of the organization [13].

Within the subject of production, SFPC is part of the production control system. Production control is preoccupied with fulfilling the goods flow requirement on the shop floor to fulfil the organization's logistic demand [21]. This demand emerges from the production planning that is usually made to follow some kind of external demand. To achieve the planned production, the production load must not exceed the production capacity available. To achieve efficient production the capacity must not greatly exceed the load. Proper manufacturing control actively manages the mirroring of load and capacity.[45, 27]

2-2-3 Dynamics of the production system

The behaviour of the logistic KPIs cycle time and throughput rate (a form of utilization) are described in their relation to the Work in Process (WIP) by the Logistic Operating Curves as depicted in Figure 2-5 [45]. The curve's nature shows to be universal for systems with a logistic function and depicts three distinct zones for the operational state for the respective system: underload; transitional and overload operation. It can be seen in the diagram that once an operation is overloaded, cycle times only increase. This will eventually jeopardize due date reliability (DDR) and due date deviaction (DDD), which can result in additional cost of delays [27]. With the WIP level the balance between system capacity and system load can be actuated.

Hopp and Spearman find that by reducing system variability in a linear system the transitional zone reduces to zero and a *critical* WIP level appears that separates the underloaded zone (with a positive constant) to the overloaded zone (with a straight horizontal line)[45] and cycle time only starts increasing after the critical WIP level has been reached as depicted in Figure 2-5. This is the basis for many operational excellence strategies developed over the years.

The input and processes in a production environment exhibit variability. This variability could be inherent to the respective input or process, or caused by poor execution or design of the production process. Planning for the stochastic nature of production must thereforee be integrated into the SFPC, to prevent overloading of the system beyond the stage that DDR and DDD will increase beyond their respective goals. Hopp and Spearman recognize three fundamental buffering methods that can cope with the variability in the process flow for any given production environment: [45]

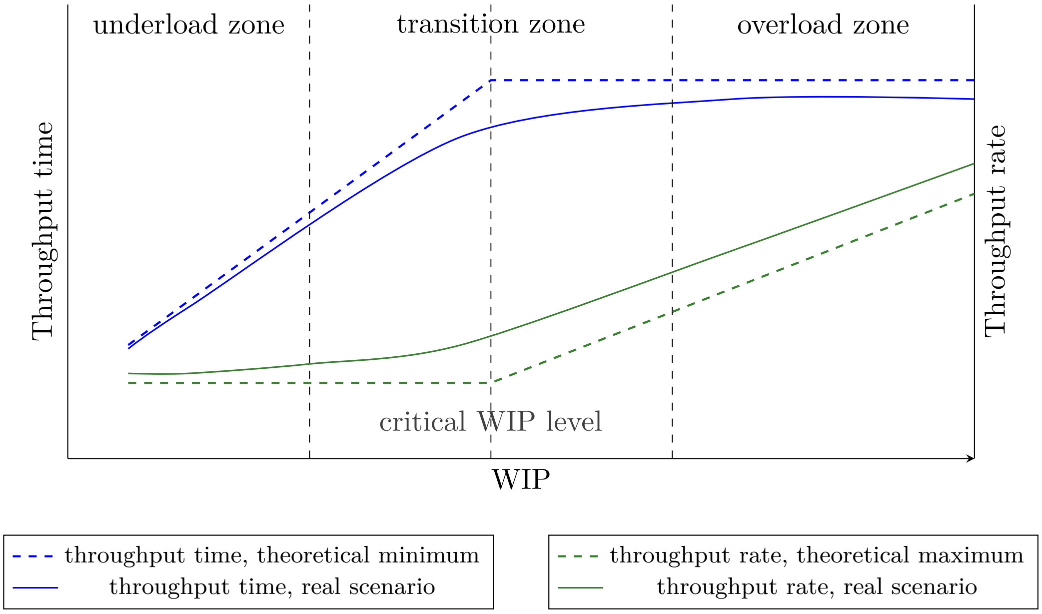


Figure 2-5: Universal logistic curves [27, 45]

- **Inventory** Sufficient inventory ensures the ability to satisfy a request made: a stock of ready-to-deliver products instantly available to the requesting party.
- **Capacity** Sufficient capacity ensures the ability to satisfy a request made by having capacity ready.
- **Time** Sufficient time ensures the ability to satisfy a request is not required instantly but after a determined amount of time.

These buffers will require resources that can not be scheduled for production and the process properties and organization strategy determine what combination of buffers can be applied and should be specified when drawing up the process design [45]. Proper application will ensure stable process operations with regard to the process variability.

The resistance against variability factors has been separated by Jodlbauwer into internal and external changing factors. The resistance against changing environmental parameters of the process is called *robustness*. The resistance against internal changing parameters is called *stability*. Evaluated SFPC systems score differently on both properties and hence both should be considered as control system design parameters.[47]

The fundamental buffers may be considered "planning" for variability in the process. However, when the process runs, the process may show increased variability beyond the passive stability provided by the fundamental buffer quantities. That means action is required to prevent the process from reaching unacceptable performance. To remain *"in control"* requires a functionality that can detect a certain value to be outside the desired *control limits* which causes an *"out of control"* situation and adjust the control parameters to bring the respective performance parameter back to its desired value [45, 21]. The combination of active and passive variability control make up the core of the SFPC [45].

2-2-4 Key design characteristics for production control

Key characteristics have been studied and described by many scholars. Lödding collects five characteristics to form the foundation for his manufacturing control configuration.[27]

- manufacturing principle
- type of production
- part flow
- number of variants
- material flow complexity
- fluctuations of capacity

These characteristics must be determined in order to design the SFPC system. A short explanation of the criteria and their evaluation follows:

Manufacturing principles

The manufacturing principle concerns the spacial structuring of the different work stations and how capacities are organized around them. For manufacturing processes five principles are widely recognized in manufacturing [13, 48].

- workbench principle
- on-site principle
- job shop principle
- flow principle
- cellular principle

Evaluation of existing literature on remanufacturing and component MRO reveals all principles except the *on-site* principle to find application in component MRO.

Workbench principle is the use of a single position for the work piece where the means and materials are moved about. An operator executes a series of tasks on the piece to increase efficiency.[13] This principle is predominantly used for assembly and disassembly operations with manual labour and relatively simple tooling.[27, 48]

On-site principle uses a single position where the work piece is centred where means and materials are moved to for process execution. The work piece is usually very large and the production series tend to be very small. This form of MRO operations for capital assets, but on the line-maintenance type of operations. [27, 10]

Job shop principle sorts workstations relative to their function principle. Work pieces are moved from different function areas, usually in batches, to finally form a completed product.[25]

Flow principle the counterpart of the job shop principle is the flow shop, where workstations are structured after their sequential order of the production process of a work piece. This is the often referred to production or assembly line. A process constructed along this principle often comprises many minor, simple operations and is therefore a good candidate for automation. [27]

Cellular principle a combination of the job shop and flow shop is the cellular principle. Shorter flow lines produce different variants or sub-parts for an overarching production structure.

Type of production

The production type is the second criterion for manufacturing control and comprises the quantity and frequency of a specific production run. Section 2-1-1 concludes that in component MRO each component receives a specific work scope and that the MRO organization is bound to cycle time limits. This means that the sizes of production are generally small but could be high in repetitions if the annual throughput is higher. With this criterion four types are recognized: [27]

- one-time production - impossible
- single or small series production - number of repetitions < 12
- serial production - number of repetitions < 24
- mass production - continuous series with dedicated lines

The very nature of MRO rules out *one-time* style production, as components are thought to pass through the MRO process numerous times. Within component MRO, components are separated into component groups that are assigned to service shops. Hence a shop does not work with separate production runs, but single piece components as part of the portfolio of the respective service centre. This means a component MRO will be in continuous production, of single products, with high repetitions. None of the categories describes this type of production adequately.

Part flow

The part flow comprises the mode wherewith work pieces are transported between the various workstations in the process environment. Two modes can be distinguished: Lot-wise transportation and one-piece flow.

Lot-wise transportation also known as batch transportation moves a fixed quantity of work pieces (a lot) between work stations. Work on the lot can only commence at the successive station if the entire lot has been completed by the prevailing station. This introduces an increased amount of cycle time for individual work pieces, that consists of waiting time. This is considered highly undesirable as the proportion of value added time for a workpiece is desired to be as high as possible. One-piece flow allows for direct continuation of the sequence of a single work piece. Hence it receives increased attention in many operational excellence methods. However, the extra waiting time by inventory forms a buffer for variability in processing time and could therefore in some cases be desirable. [45]

One-piece flow moves a work piece directly to the successive workstation as work has been completed by the prevailing station. This means that theoretically a production line can be fully utilized with one work piece being processed at every station in the line. This is regardless of the manufacturing type of the process. [27]

Number of variants

The number of variants relates to the different product types in a product series. In component MRO this relates to the spectrum of components that are being processed in the service. In a MRO component process even a single component can already deliver a spectrum of work scopes. The number of variants relates strongly with the complexity required for the process control [42]. From a process point of view an MRO process should have mechanisms that allow for the flexibility of work scope and different components. Earlier research by Haak has shown that reducing the amount of variants on a line enables simpler process control and may be economically feasible if a certain annual demand is reached.

The number of variants directly influences the variability in the production input and should therefore be considered in the design decision for the SFPC system. A higher number of variants increases the need for a more complex system [27, 45]. Here, a quantification of number of variants has not been postulated in literature so far. In the relation to the SFPC system, this design criterion relates closely to complexity of the different variants, as more complex products in general show to require more complex SFPC systems to enable satisfactory.

Material flow complexity

As number of variants in a production the complexity of material flow has a substantial impact on the sustainability of a production control method. [27]

The simplest of material flow has one successor and one predecessor with no back flows included. This is also called a linear arrangement. The complexity increases as the number of flow options increase through the system and the occurrences of back flows. The increased number of options allow for increased variability in routing for the different parts. This could be desirable as some products or services require complex material flows, but will require more input from the production control system to reach performance goals [45]. The goal of a process lay-out design is to minimize the complexity of flow to obtain uniform throughput [27].

Fluctuations of capacity

The final criterion is the treatment of fluctuation of capacity requirement. A production system will have a limit of the amount of throughput that can be realized with the means available. Section 2-2-3 describes how the balance between the capacity and the load of the system contributes to the performance objectives of the system. Fluctuation of load is predominantly caused by the variability of orders and the variability of load in the orders. This fluctuation can be controlled by either adjusting the capacity to the load or adjusting the load to the capacity available. The flexibility of both options determines the final strategy for capacity fluctuation treatment.

2-3 Information in process and control design

Both the design and operations of an MRO process requires different types and amounts of information. With a collection of studies regarding remanufacturing and MRO stressing the value of information and the problematic nature accompanied with the lack hereof, [43] information structures that enable the process must be identified. Additionally, entire MRO supply chains require information systems formalized through the entire chain to enable full MRO cycle control [22]. This section seeks to structure and classify the information in relation to the system and the occurrence of this information in the design process. A distinction is made between *control information*, which is required for control system operation and the *control system design information*, which is required to formulate a solid control system design. Additionally, within control information, *process driving information* and *production control enabling information* are recognized. This is the information required for the respective process control structure and the production control structure.

2-3-1 Process driving information

The generic MRO process presented in section 2-1-3 presents possible process activities and routings of a component in an MRO process. These activities are provided by their physical logistic input and output, being the component. However, with the MRO process concluded as a quality restoring process, information on quality should be included in the input-output relations between the process steps. For remanufacturing Kurilova present a classification for information that drive remanufacturing of a component in a closed-loop process.[43] These can be subdivided into two categories: one representing component series specific information, which is state independent and one representing information for one particular component, which is state dependent:[21]

- **State independent**
  - **Manufacturing specifications** - instructions on manufacturing
  - **Service specifications** - instructions on repair and maintenance
- **State dependent**
  - **Product design specifications** - description of the physical product as an object

  - **Original product quality assurance** - service records and original product state
  - **Component quality** - description of current state of component
  - **Remanufactured product quality assurance** - description of final state of component

State independent information will enable the process to set up, making it *control system design information*. It contains information that is required to design the MRO process and can be used to explore possible quality deviance. During operation this information should be considered the reference database that is required to conclude quality deviance against. This may appear static, but can change over time as components receive updates and tasks requirements develop over their lifetimes.[10] State dependent information will enable the setup of a specific MRO service of a specific component. The collection of this information represents the current quality standard of the component and is thereforee essential for the determination of the work scope of a service visit [43, 10]. Hence it is considered *process driving information*.

The classes of information should be part of the process design. What level of qualities required in this information structure is process and component dependent. An entity of a component that is subject of service must be described in all information categories in order to for the process to function. [43]

The lack of properly engraving this information stream and origin in the MRO and remanufacturing supply chain has been stated to cause troublesome operation of the process.[4] What qualities exactly should be described in

2-3-2 Production control enabling information

The essence of a control system is the ability to anticipate on signals obtained in the system that is to be controlled.[25] The signal for information being used to control the specific control area is dependent on the working principle of the control system. As assessing all applicable control systems for the control problems under study is out of scope, the exact control information options will not be studied further. However, it should be noted that process information and control information do influence one another both in the planning and control element of production control. Hence the control information of the suggested design shall be studied in relation to the process information structure [27]. This will be covered in the design presentation section.

2-3-3 Information quality

Quality of information is essential to information driven systems. The value of the right information is recognized in both production control and process design. With many factors influencing the quality of information, such as process variability [27, 49, 45]. Several categorizations have been made to classify information quality. A separation in dimensions for general feedback and feed forward information system design and operation has been proposed by Busert:[50]

- Granularity
- Actuality
- Accuracy

Granularity Information can be rated on a level of resolution. Granularity of control information and design information ideally has a maximum degree within its domain, however it may be expected that for proper functioning of a control system or design process a sufficient level must be determined. Additionally, obtaining high levels of granularity may come with additional challenges. It must also be realized that granularity of information may change over time due to the development of the process or due to processing of an object in a process.

Actuality Information occurrence and its reception at its required system input is not immediate. Within process control delays can be caused by techniques of measurement, information transfer or implementation delays.[51] Especially feedback data include the dynamics of the measured system and is hence related to a specific moment in the defined context.[50] Additionally for process design it must be realized that some information comes available only after a certain stage in the design process or implementation of the final design. This relates to the time dependent granularity mentioned in the previous paragraph [49]. Techniques to increase the actuality of information should be considered before accepting outdated information for both design and control purposes. [50]

Accuracy When a piece of information is synthesized, a certain amount of uncertainty must be taken into account. The description of accuracy can be rated different value systems such as standard statistical modelling for absolute numbers or fuzzy logic for qualitative descriptions.[50]

2-3-4 The influence of information quality on production and process design

By introducing quality assessment for information in the design process more informed decision could be made on process and control features. This assessement proofs vital for the mass customization of works seen in Industry 4.0 [50]

The ability to relate the quality to a moment in time in the design process also enables the development of an operations improvement strategy may quality information improvement be expected. This is however constrained by the practical limitations of the particular control problem [50]. A particular limitation is the timeframe within the design process wherewith a decision must be made. The information dimensions can exhibit different behaviour over the course of the design process. Knowledge of this behaviour or the absence hereof could have implications for process robustness and stability. This will finally influence the logistic objectives of the process once in operation.

Hence information in process control and production control should be assessed for their compatibility in the respective control system, making information quality and its behaviour over time a design criterion for the design of an MRO process.

2-4 Process and production control design

To structure the development of the design a framework will be developed with the generic design criteria that have been found so far. This section explores categories and properties of elements in frameworks that claim to be suitable for the design of control for the sub problems of the control problem. The evaluation of the particular design solutions or described system elements will not be covered as literature presents plenty of comparable studies for whole and element wise design solutions for both process design and production design.

2-4-1 Process control design

The process control design framework should enable the development of the process control layer of the component MRO process. Literature on process design prescribes the use of a process mapping in two stages to form a graphical overview of the process under development. First an activity-on-arrow description of the process steps including the first estimations of processing time. Second an activity-on-node description of the activity-on-arrow description is developed. This should resemble the logistical flow associated with the process [13]. Form this point modern techniques such as the Value Stream Mapping (VSM) by Rother and Sook can be used to increase the detail [52].

- basic process design must be defined before any layer can be added
- how are process steps defined?
- what is basic process information for production control design? (use slack)

In addition, a simplified capacity analysis calculates the required means for the desired output without accounting for exact production system dynamics. The analysis reveals basic information on what type of capacity constraints are to be expected.[45, 52] This type of "initial analysis" combined with the process design has been suggested in several studies in MRO production design.[42, 12]

2-4-2 Production control design

The process control design sets up the structure of the process for the specific process function.[25] The production control system orchestrates the logistical aspect of the production process. It therefore engages in planning and control all the way to shop floor level, hence the production control and SFPC system are considered the same unit.

The SFPC system has been split into elements that will be given form by the design sequence. The remainder of this section will first describe the elements and hereafter describe a design sequence proposed by literature.

Design elements for production control

The criteria influence the design elements for the SFPC. To exert control Lödding states a manufacturing control model consisting of four tasks that make up the manufacturing control system: [27]

- Order generation
- Order release
- Sequencing
- Capacity control

Order generation A client order does not entail the full logistic job preparation that is required to execute the job. The order generation process ensures a client order is transformed into a internal job order. This includes but is not limited to production planning, material withdrawals etc. This task is a planning task and hence should be seen as the reference state for process performance. this concept is also referred to as the aggregate production planning by various scholars [21]. The method or order generation must consist of three characteristics:

- **Type of trigger** The generation of an order is dependent on the production type of an organization.
- **Scope** The generation can be done for several layers of the product structure.
- **Trigger logic** The generation of the order occurs due to some form of logic for a specific time.

Order release An order release is a specific signal that prompts the actual release of the order to the production floor. The planned requirements from the order generation are hereafter reserved for the specific order. The release influences WIP and all WIP related entities.

- **Criteria** The conditions that must be met for release
- **Degree of detail** A release can be made for a specific operation of a production sequence or for the entire operation.
- **Trigger logic** The decision for release is to be made in some form of decision structure.

Sequencing During order generation a sequence of jobs is planned for production. However, this planning may or may not be achievable at a later point in time when production has commenced. Sequencing allows for final control in the order of execution of an order at a work centre instead of the initial planning that occurs earlier in the process.

Capacity control The beginning of this section explains how variability of the production process calls for adjustments in process parameters to ensure the planned performance goals are met. Capacity control assigns capacity to form actual output from the production input.

The control element is classified in three characteristics:

- **Criterion** the characteristic for controlling capacities
- **Degree of detail** to which level of detail the control will extend
- **Trigger logic** in what way may adjustments be initiated

The criteria build on the following two principles:

- planned output orientation principle
- Capacity bottleneck principle

The planned output principle triggers on deviation of the planned output, being the result of customer demand. The planned output can either be too high, resulting in stock of finished products, or be too low, resulting in delay of orders. Controlling capacity on planned output will us the planned output as a target reference. This supports higher initial schedule reliability.

Capacity control should always be performed with awareness of the current bottleneck mechanism in the respective production process. If the control policy is not aligned with the bottleneck mechanism, the capacity adjustment can not control the process dynamics as the mechanism determines the entire process capacity.

Within MRO services, the functioning of the overlying supply chain will largely influence what chose to make.

Element structure The interrelation of the four tasks are depicted in Figure 2-6 and how they relate to the control variables and how these translate to the logistic objectives of an organization.

The SFPC design sequence

For the configuration of the SFPC system Lödding proposes a fixed sequence to define the design elements of production control.

1. Order generation method
2. Order release method
3. Sequencing rule for the work centres
4. Capacity control method

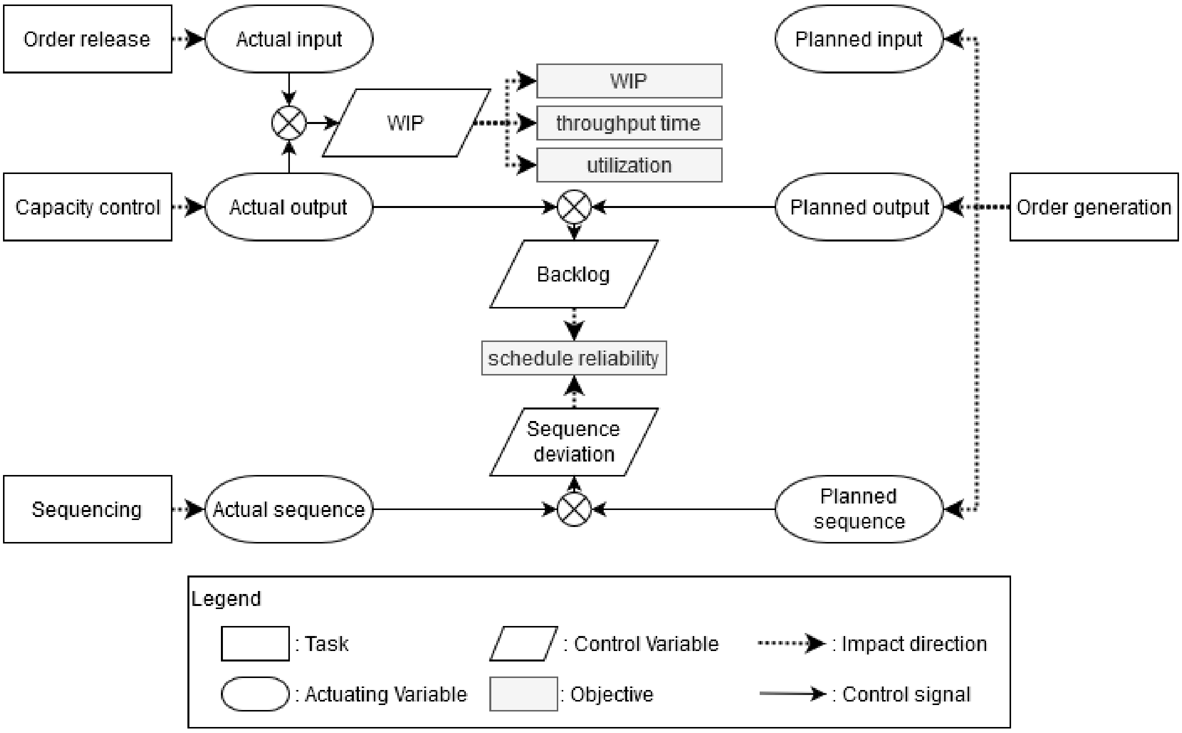


Figure 2-6: The elements in manufacturing control model and system performance, adjusted from Lödding [27]

Order generation method must cover the three characteristics stated for order generation in the prevailing section. Three criteria of the production environment should at least be studied to conclude a suitable method for order generation:

- Predictability of demand
- Planning necessity
- Suitable generation of scope.

The predictability of demand rates the quality of information on demand as prescribed in section 2-3-3. At the moment of designing the process lacks operational data and must therefore make use of other estimators if process data can not be mined else where. Here the predictability of demand in a component supply chain is linked to the failure mechanisms of a part [53]. Additionally, the ability of the information transmission structure between the asset operator and the MRO organization is of major influence, as described in section 1-3.

Planning necessity covers the importance of estimating the requirements of customers in the supply chain if a make-to-stock type of production is used and describes the consequences for an incorrectly estimated production. In a component supply chain, the correct planning of intermediate Serviceable (SE) components to balance production and demand for component pools has been stressed to combat cannibalization of parts and penalties for in ability to deliver components. The impact of these factors was caused by the criticallity and part value. [12]

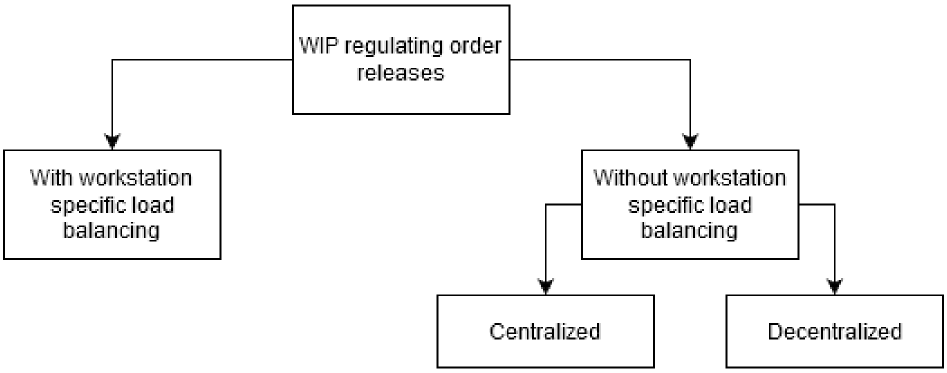


Figure 2-7: WIP regulating classes [27]

Suitable generation of scope determines the ability to generate a scope by review of the order and distinguishes a multi-stage order and single stage order as described in the prevailing section. By the very nature of the MRO process, that must generate its own workscope in the process itself, this means that an MRO process will produce a single stage process by default.

Order release method is selected by finding a suitable method class. Three main categories are described:

- Immediate order release
- Due date based order release
- WIP regulating order release

Immediate order release is not only a class but a full method as such. It offers no control possibilities as an order immediately passes through the stage in the production process without being altered.

Due date based methods specify specific stages of the production to time instance in the future. This could simply be the release in relation to the due date of the order, but can also entail specifications for suborders. Proper capacity planning is required for the due date based methods. These techniques are vulnerable to the stochastic nature of the production environment.

WIP regulating release methods are aimed at connecting the production input to the production output. The regulation of WIP has shown to directly impact a range of logistic performance KPI's in section 2-2-3. WIP regulation is specifically useful when capacity planning and due date planning is cumbersome or too inaccurate for the specified logistic performance goals. The WIP regulating techniques are subdivided into additional subclasses depicted in Figure 2-7 It should be noted that several methods within the regulating class can be combined to form one release policy. These will not be described further in this section as it surpasses the scope of the selection process.

A vast range of order release options are described in literature for the characteristics of the component and processes that may occur in the MRO process. As these have been thoroughly described by multiple scholars including their applicability, these will not be described in this study. The method is limited to the selection of class for a order release method. After a class has been found, a suitable method can be found in literature for the specific design case.

Sequencing rules for work stations form a final adjustment feature to further optimize for the logistic objective; schedule reliability, service level or output rate. Four criteria are to be assessed for the applicability of a rule for the target work centre.

A rule can only support one logistic objective as only one rule can be set as prime sequencing policy for the entire process.

Second the impact of a sequence on a specific workstation is to be determined, as different rules have various impacts in combination with other production setup properties.

Thirdly, the possibility of implementation of the rule must be assessed. Based on information quality at hand, work force ability and/or computational ability will influence to what extent this a rule can be implemented.

The final criterion assesses the extensiveness of general quality of the order schedule. Sequencing functions as an active control measure to correct for impact on the production schedule caused by variance in the production process. The schedule quality will relate to the necessity to readjust the planned sequence in order to reach the logistic performance goals.

Capacity control method is partially constrained by the operation environment of the process. The main issue here is the degree of flexibility in capacity adjustment that the environment offers. This extends to overload flexibility as, by adjusting load on the system, capacity utilization can also be controlled. Three main categories are distinguished:

- capacity flexibility available
- no capacity flexibility
- temporary capacity flexibility

With capacity flexibility available at any time, the most important criterion in the method is the type of trigger that will be used to adjust the capacity of the system. Would the capacity be temporary the extend and time of the temporary availability become more important. Additionally, a model is required for the adjustment as for when to change the capacity and what relation to the supply chain this may have. Earlier studies in the MRO environment have shown the benefits of controlling capacity from a supply chain perspective.[12]

2-4-3 Robust design

Robust design as a design method has been introduced by Taguchi for the improvement of quality of manufactured products by designing the product and its process for stable quality results. The design method utilizes the minimization of impact of stochastic properties in the production process without having to eliminate them, as these are assumed to be unfeasible to control. This results in a design that is inherently stable for its quality over the entire production output, due to "minimum sensitivity to variations in uncontrollable factors"[54]

The Taguchi design sequence is made out of three stages:

1. System design
2. Parameter design
3. Tolerance design

System design comprises the designing of the concept and function of the design solution. It is described as the composing the "right combination" of methods and physical means to satisfy the planned performance of the design.

Parameter design comprises the analysis of the response of the design to the uncontrollable stochastic variables that occur in the system. With the analysis results, parameters can be chosen to make the final design performance less dependent on the stochastic variables. This stage is considered the essence of the Taguchi approach and is also known as *robustification*.

Tolerance design is the final step in the approach that is used would the parameters designed in the previous stage be insufficient for overall design performance within planned specifications. By setting tolerances for the respective quality dimensions, the overall performance of the design can be increased further at the cost of additional constraints to the production process.

Use of robust design in process and production design

Robust design was originally used for product design and the process that would manufacture the products, but has seen much wider application in design including parameter design for control systems as controller robustness is a desired property for any control system. [55, 56]

2-5 An MRO process Shop Floor Planning and Control design framework

The theory analysis is concluded with the presentation of the experimental framework for the design of a SFPC system for a component MRO process. The framework will be based on the design sequence for manufacturing control by Lödding with the characterizations of the generic MRO process, the characterizations of information and the characterization of manufacturing control. To increase control system robustness, robustification of the initial control parameters will be added after the *Robust design* method proposed by Taguchi. The remainder of this section will describe the steps in detail as depicted in the overview in Figure 2-8

Step 1: *Logistic objectives*

Determining the logistic objectives for an MRO process is part of the operations strategy of the organization that wishes to implement the process.[13] The development of the strategy should include the setting of the logistic objective of the process that must be designed to match the strategy. The objectives do not have to be determined in the framework's variable but must be transformable so the design is constrained enough.

Step 2: *Logistic process model*

A component that is to move through an MRO process needs to pass through a sequential set of tasks. The exact sequence can be derived from the generic MRO process model presented in section 2-1-3. The overview of the process should be presented in a task-oriented graph. It must be noted that if the graph does not resemble the lay-out of flow, an additional graph must be made to visualize this. An example could be the case of back flows occurring in the sequence. Task oriented process representation will not show how this additional complexity must be accounted for in the control system. With the full functioning of the logistical process represented, the context of the surrounding supply chain must be connected to the model.

Step 3: *Process information structure*

The process information structure should visualize the different information layers that play a role in the operation of the MRO process. This is separated in two substeps:

Process information: sources, connections Information transfer from the specific tasks defined in the logistic model of the process should be visualized in the model overview. Here a distinction is made between process controlling information and process driving information. Process controlling information is not directly part of the SFPC. It controls the quality restoration process, the inherent property of the MRO process. Manufacturing control could make use of this information in the SFPC, but is not strictly required. The relation between the process control information and manufacturing control information will be analysed for the configuration of the SFPC, which is done later in the framework. The process information structure can be added to the logistic process scheme to relate the evaluation of the information along with the logistic process.

Supply chain information: sources, connections It may occur that some process information emerges outside the shop process. To enable possible integration of the shop process with the entire supply chain, the origin of this information in the supply chain must be determined. Knowledge of the overarching supply chain influences design options for process control and SFPC system design [57, 22]. As a full end-to-end analysis of the supply chain is out of scope, only the information transgressing from the overarching chain to the shop process will be considered, which includes the identification of the source and its position in the chain.

Step 4: *Information quality characterization*

With information mapped and integrated in the process logistic overview, the process and control information can be characterized after the dimensions proposed in section 2-3-3.

Step 5: *configuration of SFPC system*

With the full characterization of the MRO process the configuration of the SFPC system can be done in accordance with the sequence proposed by Lödding presented in 2-4-2. This sequence consists of the four steps:

- Step 5.1: Selection of order generation method
- Step 5.2: Selection of order release method
- Step 5.3: Selection of sequencing methods
- Step 5.4: Selection of capacity control system

The result of this step is the definition of elements for the production control system design for the MRO process. The control elements can be added to the graphical representation already developed, preferably distinguishable from the process driving information.

Step 6: *Production control information structure*

With the preliminary design of the production control defined, the control system must be detailed out further to complete the design. The design cycle of step 5 defines the elements and mechanisms for control. Step 6 determines the information requirement of the control functions for proper functioning and how these relate to the physical flow and process control. To obtain this overview, information links are added tot the graphical overview of the entire process.

Additionally, the information quality required for the information flows of production control must be defined. Step 5 explores the limits of quality function of the process and when hen properly executed should produce a feasible setup. However, the exact definition of quality requirement has not been defined. Hence, this step defines the requirement further. These quality requirements should be grouped for the respective control element.

Step 7: *Robustification*

With the preliminary design from the first step, the control parameters for the SFPC system can be designed in accordance with the Taguchi parameter design method to utilize information quality in control information additionally.

Should it turn out that after robustification the system still under-performs, alterations in the information structure might enable satisfactory performance. This means the design process iterates over the steps 3 to 6 once more to obtain a new design proposition. The final design should have the process tasks with its driving information structure and its control structure clearly distinguishable in a graphical representation.

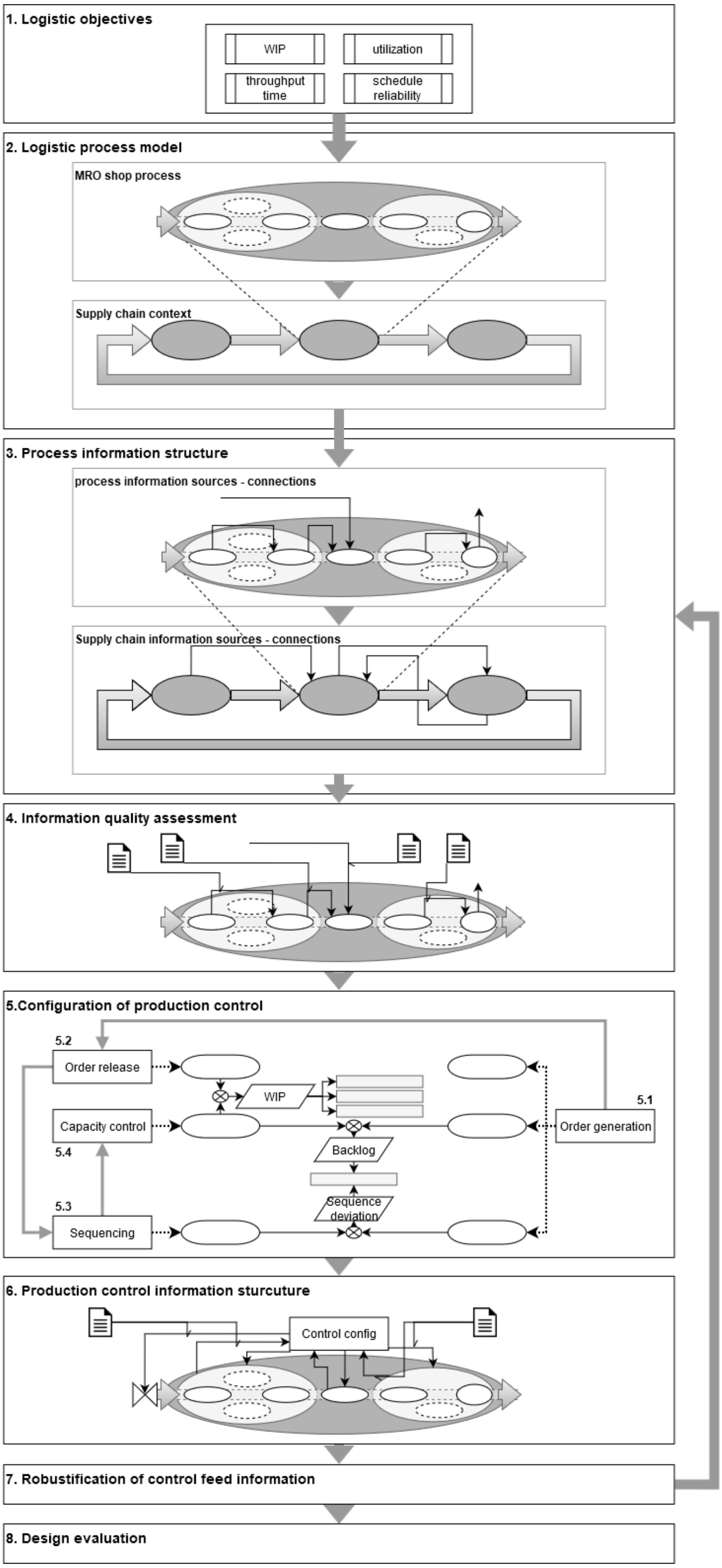


Figure 2-8: The experimental MRO process control design framework

2-6 Chapter summary

This section summarizes the past chapter by answering the research questions stated at the introduction of this chapter. Section 2-1 answers the first question:

What is a generic MRO process design according to literature?

The generic MRO process is a quality restoration process with the ability to evaluate quality increase of the process for its component of service, which has a variable work scope. This variance causes variable throughput times of components, yet a maximum of throughput time maintained. In addition can be stated that the inflow of orders is erratic by nature. In the special case of aviation MRO can be added that tasks are predefined routing options are rigid and developed by institutionalized authorities.

Section 2-2 and Section 2-3 develop the answer for the second question:

What criteria are essential for a solid MRO production control design?

The production control contributes directly to the process performance by means of its logistic performance. therefore it can not be seen separately form its process context and the component supply chain that the process is part of. The logistic performance is defined by the prime logistic performance objective that is the result of the overarching supply chain. The component quality state and the information requirement to determine the this state must result from this realization. Finally the general characteristics of production control must defined.

Section 2-4 explores the elements of production control to answer the third question:

What are elements of a production control system?

Four elements in production control are distinguished.

1. order generation
2. order release
3. sequencing
4. capacity control

Order generation accepts a client order develops this into an order for the shop floor. This element is also called aggregate production planning as it in a global sense plans the activity on shop floor level. Order release occurs when production may start working on an order. From this point on the order is on the shop floor. Sequencing structures the order of working at a work centre to promote a particular logistic objective. Capacity control regulates the amount of capacity assigned to a work centre under a load on a short term. The final three named elements directly control entities on the shop floor and are therefore the SFPC, however can not be designed separately from the other control element.

Section 2-4-2 evaluates the design sequence for production control, which answers the fourth question:

How is a production control system designed?

The control elements are selected in decending order of the list answering the thrid question on the basis of selection criteria that match the logistic performance requirement and the process design.

Section 2-3 evaluates the information in process and control design to answer the fith question:

How can the role of information in the greenfield design of the MRO process be defined?

Information is an integrated part of the MRO process and control design, denoted as process driving information and control enabling information. Both have a quality requirement that must be attained for the process and control to be effective.

Section 2-5 sythesizes a framework for the design of a production control system for MRO by answers of the previously answered questions. With the sixth question being:

What framework from literature for an MRO process shop floor planning and control can be stated?

A step wise framework is developed as depicted in Figure 2-8.

With the questions answered and a framework developed this report continues with the description of the test case where the framework will be used to design a production control system for a real MRO process.

Chapter 3

A case study on Shop Floor Planning and Control design

The framework developed in chapter 2 will be applied to the selected case at KLM Engineering & Maintenance (E&M). The development must answer the next research question:

- *What is an MRO process SFPC design for the Liquid Cooling MRO process considering the process criteria for general MRO Shop Floor Planning and Control?*

A short introduction of the Liquid Cooling (LC) capability and its component is given in Section 3-1. A summary of the application is descibed in Section 3-2. An in-detail design study of every step is enclosed in the appendix B. The final design is presented in Section 3-3 with its properties and graphical representations.

3-1 The Liquid Cooling capability at E&M

For this study the *"Liquid Cooling"* capability has been selected, a system developed for the Boeing 787 "Dreamliner" series, whereof the first model was introduced in September 2011 [58]. The LC system provides cooling throughout the planes hull for the Environmental Control System (ECS), which entails passenger air conditioning, cargo refrigeration and utility cooling. It consists of an extensive glycol filled piping network with pumps, valves, sensors and heat exchangers. Cooling capacity is provided by two types of cooling units: Supplemental Cooling Unit (SCU) and Cargo Refrigeration Unit (CRU). The cooling units function by a electrical driven, closed refrigeration cycle, as seen in a home or office air conditioning system. Both types are integrated units, which means that aggregate control signal, power, in- and output flows are supplied to the unit and that compressor operation, drive motor control and other utilities are operated by the internal control systems of the unit. The LC system is unique for modern commercial aeroplane models and little experience exists within the aviation industry with the use of electrical driven refrigeration cycles for the ECS [59]

A business case has been drafted with the operational strategy for the new LC capability. Here is defined that the capability should perform all services for the SCU and CRU. Additionally, means have been proposed. Following its approval, the preparations of means have commenced. The services for the units is complex due to the variety of sub-systems that make up the units and the lack of experience with the technology. With an approximate size of 1 m^3 and weight of about 150 kg, they require special handling in a shop environment where components are usually of liftable size.

The business case covers the component shop that is tasked with the Maintenance, Repair & Overhaul (MRO) services that the capability will provide. This means the higher supply chain is not part of the design described. Hence, this environment matches the prerequisites for applicability of the experimental framework.

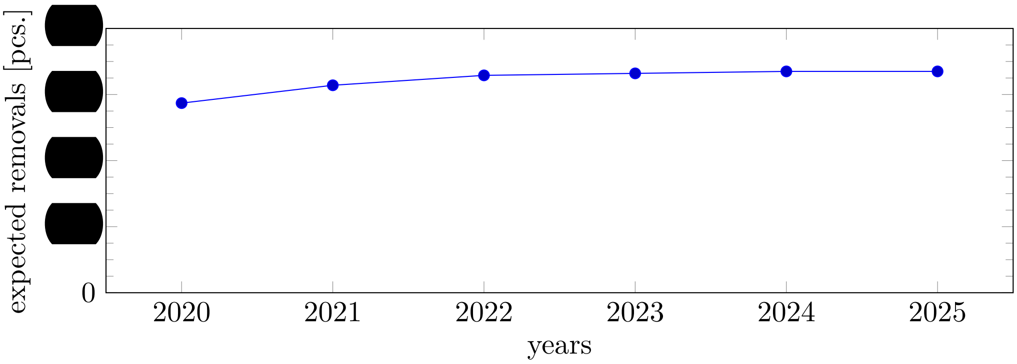


Figure 3-1: Expected demand for of LC unit MRO E&M

3-2 Application of the framework

For the execution of the framework studies for each individual step have been conducted, these have been enclosed in appendix B. The findings of the studies are presented here in the section in the form of abstracts with graphs and tables for the respective steps.

3-2-1 *Step 1: The logistic objectives*

The logistic objectives for the process have been expressed in the business case developed. The analysis of the logistic objectives is presented in the appendix B-1.

The design scope in the business case is set for the entire end-to-end MRO component process. However, the logistic objectives are set for the shop internally to solidify the performance objective within the design scope of the control system under development here. The yearly production objective mentioned are set related to the expected demand as mentioned in Figure 3-1. The aim for throughput time of the shop process for any MRO service on an LC unit has been set to [redacted] and is the result of Boeing's Product Support and Assurance Agreement (PSAA), other supply chain activities and E&M's own operations strategy. The performance of the shop will be measured in with a value called *On-time performance*, which is the fraction of orders with a throughput time equal or less than the target throughput time.

Additionally, the case prescribes the means of production wherewith the throughput must be realized and the production principle, that are covered in 2-2-4. These restrictions have implications on for the process design, as will be shown in step 2 and 5.

- Throughput time: [redacted]
- Main Key Performance Indicator (KPI): On-time performance (OTP)

3-2-2 *Step 2: The logistic process model*

The logistic process model has been composed of the information provided by the business case, the Component Maintenance Manual (CMM) and expert opinion. This was partially presented by the capability development team and partially from own research. The full analysis is presented in appendix B-3.

The analysis concludes the following task sequence matching the generic MRO process options:

1. Initial test
2. Work scope determination
3. Shop routing
4. Final test
5. Certification

Figure 3-2 provides a process oriented overview with the stages in sequential order.

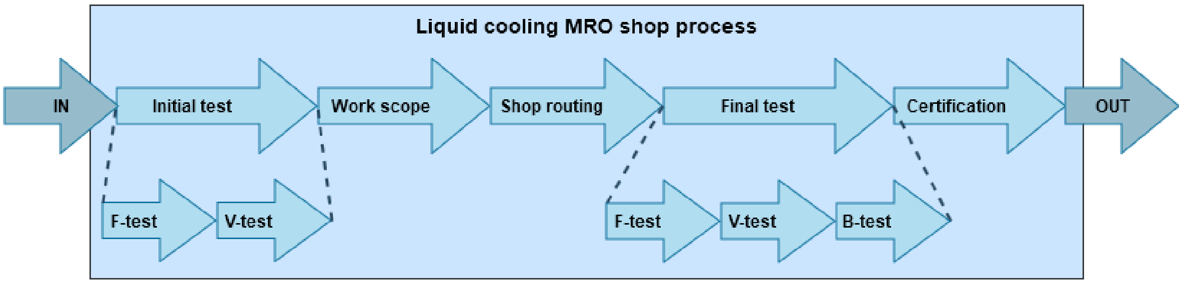


Figure 3-2: The process scheme of the LC capability

F-test denotes the functional test, where the component is connected to a machine that runs a fully automatic functional test of the component features.

V-test denotes the vacuum chamber test. Here the gas circuit sealing is evaluated with a proofing gas and manually operated sniffer device in a vacuum drawn confinement.

B-test denotes the electrical bonding test, where good electrical connection of all critical electricity connections is evaluated with manually performed measurements.

Process layout and basic logistic design properties

In addition to the specification for the process steps. The business case provides directives on the mobilization of resources. It separates test activity and repair activity in two (virtual) cells. Personnel and machinery is assigned to a cell. Figure 3-3 and Table 3-1 provide an overview of the basic process design. The process overview utilizes a combination of the process visualization techniques Value Stream Mapping (VSM) and swim lane.

The VSM technique provides a structured material flow and property oriented overview of the process under study [52]. The swim lane technique provides an overview of decisions and information of the process and how these are distributed over the different entities present in the system [60]. Combining both techniques provides a clear overview of how different information relates to subprocesses and how the information structure influences the logistical component of the process. The combination of these techniques has successfully been implemented in studies within process information relations. [42, 57]

A simplified capacity analysis with the resources mobilized, shows that the production process is mainly restricted by manpower. The bottleneck is formed by the number of repair operators assigned to the repair cell. Additional it could be concluded that the time calculated for the test operator is sensitive to the production schedule ineffectiveness and ineffectiveness due to multitasking. The execution of the simplified analysis has been presented in Appendix B-2 with and Table B-3.

- Labour constrained production process
- Little margin between capacity potential and required annual output
- process bottleneck is the number of manhours deployed to the repair cell

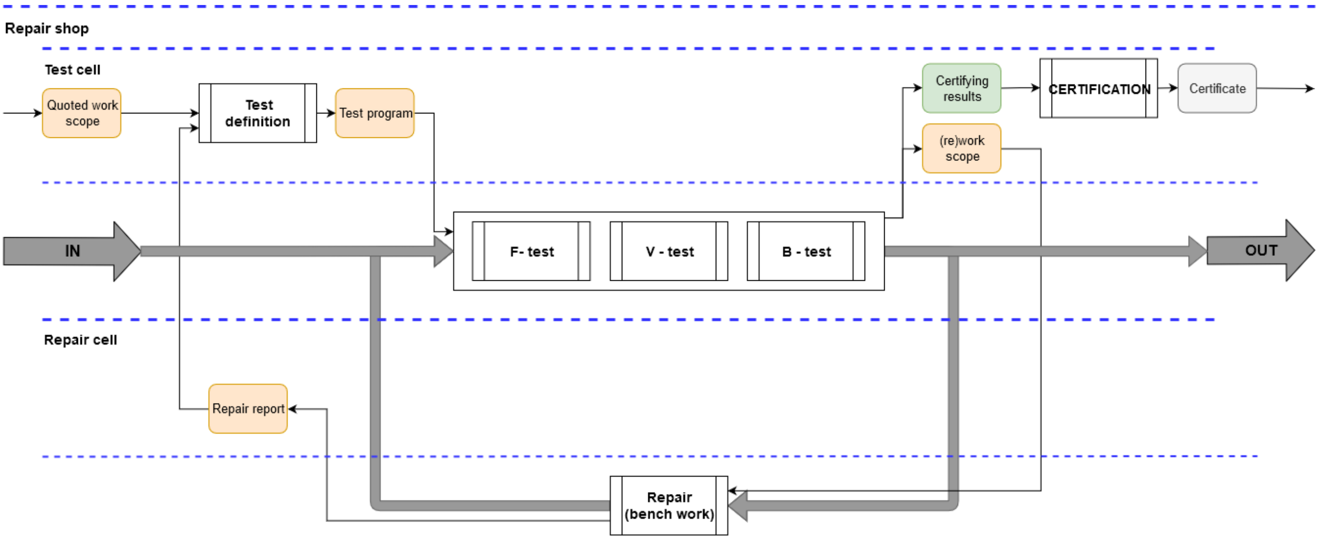


Figure 3-3: The VSM-i process scheme of the logistic shop process

Process stage	Cell	Operators	Machines	Total manual time [hrs]	Machine time [hrs]
F-test	test cell	[redacted]	[redacted]	[redacted]	[redacted]
V-test			[redacted]	[redacted]	[redacted]
B-test			-	[redacted]	
work scope			-	[redacted]	
certification			-	[redacted]	
repair	repair cell	[redacted]	-	[redacted]	

Table 3-1: Basic process design data for the LC process at E&M

The supply chain context

The shop component MRO process fits into the MRO component supply chain that is managed by E&M as depicted in Figure 1-2. Part of this supply chain is an external party that can perform the exact same services as the MRO component shop under design however, is not preferred due to pour performance by the party. The decision to outsource is made internally by the component shop management. This access to extra capacity will be covered in step 5.

- A (non-preferred) outsourcing capacity option

3-2-3 *Step 3: The process information structure*

With the logistic model of the process visualized, the drive information is added by means of the information model. The analysis of the information structure is separated into two classes with one class subdivided into two layers. The transgressing information structure, where information from outside the shop environment enters or leaves the shop and the internal information structure, that drives the internal logistical process of the shop MRO process. Both together will form the entire information requirement to drive the process and are a result of the design information structure, that enables the whole design process. The remainder of this section will describe the three different structures.

Design information structure

The design information of the current stage comprises of three basic classes:

- Business case
- Component Maintenance Manual
- Basic logistic properties

The business case sets requirements from an operation tactics perspective, these have been developed with a strategical goal in mind in cooperation with the shop. The CMM that sets requirements for tasks that must be executed by the process. This has been provided to E&M by the Original Equipment Manufacturer (OEM) after an application process. The basic logistic properties of several process steps are developed by the capability design team. It includes processing time analysis with touch time and machine time included, found by expert estimates made by the team and consulting test machine manufacturers.

Process information structure

The process information model for the LC capability at E&M has been analysed in accordance with its two layers described by the framework presented in chapter 2-5. A full analysis is enclosed in Appendix B-3-3 and a summary is presented in this section.

The drive information consists of a sequential set of processes that control physical process steps or are the result of a process step. Separating the elements over their function and the transgressing and internal scope results in the following listing of elements:

- Transgressing
  - CMM standard (reference element)
  - Quoted work scope (state dependent input-output element)
  - certificate (state dependent input-output element)
- Internal
  - controlling elements
    - work scope
    - final test program
    - approval
    - rework scope
  - input-output elements
    - pre-test results
    - repair report
    - final test results

The full process logistic model is presented in Figure B-1. The information model presented allows for the analysis of influences of process information on process logistics. This will assist in finding the right Shop Floor Planning and Control (SFPC) system to control the logistics of the process in step 5.

3-2-4 *Step 4: The information quality characterization*

The information model is completed by characterizing the information relative to their influence on the logistic process. Both models have been studied in accordance with the information quality dimensions and qualitative values have been assigned. The full analysis has been enclosed in appendix B-3-3 and its conclusions are presented here for the respective models.

Design information structure

It is concluded from Table B-5 that the information on restrictions into the process design are quite well defined, but the most influential means do have a low quality. The presumed bottleneck controlling processing time is based on an expert estimate. The estimate has been in the field of yet unknown technology to the design environment and is hence subject to be variable.

Process driving information

It is concluded from Table B-1 and Figure B-8 in appendix B-4 that the process for every component start with a large likely hood for lack of information. The lack of information translates through the process and the process design is composed to correct for this lack of information. The bottleneck for the process design is directly affected by the initial lack of information. Not until right before the bottleneck step can the information be completed.

Implications

The initial lack evolves to uncertainty in the main bottleneck of the process in respect with production time required. The lack of information has a substantial impact on the process from a design perspective (long term capacity requirement) and control perspective (short term capacity scheduling) on the bottleneck step of the process. Proving the need for a control system that is resistant towards changing workload, but also the incorrect configuration of mean expected loads. To visualize these implication the drive information model from Figure B-8 has been converted to a VSM-i format.

3-2-5 *Step 5: Configuration of the SFPC system*

The configuration of the production control system has been executed with the proposed framework. An analysis has been performed by studying literature for the respective elements and the process characteristics. These analyses have been enclosed in appendix B-4. This section describes the selected solution for the respective elements and briefly explains its working principle and features of importance.

Step 5.1: Order generation method

For the selection of an order generation method, the three earlier mentioned criteria are evaluated: predictability of demand; planning necessity; suitability of scope.

The predictability of demand is found to be poor by the theoretic analysis and the analysis of the production information. The planning necessity of the process is low due to the large fraction of manual work by the operator with simple hand tools. As each sequential process step is defined by the prevailing step, the scope generation for the process is restricted to a single stage scope. Additionally, to the three main criteria the high requirement on system utilization for desired output, the CONstant Work In Process (CONWIP) mechanism is found most suitable for the order generation method.

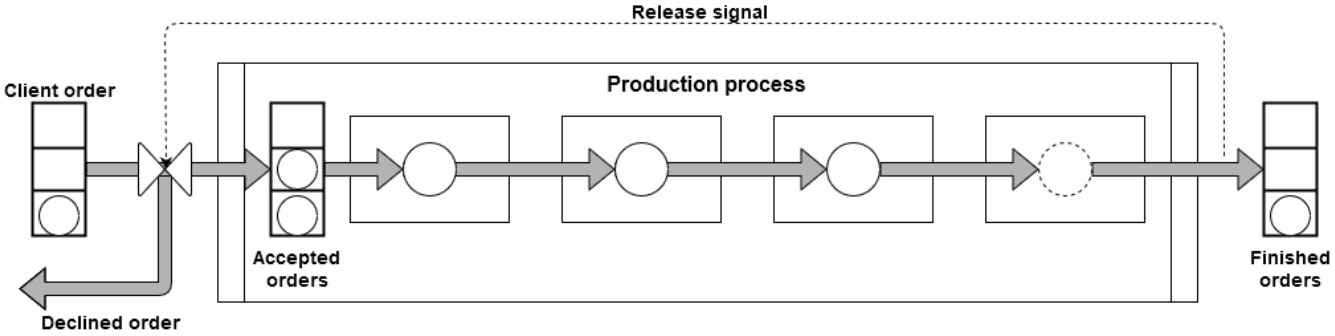


Figure 3-4: CONWIP control for order generation

The CONWIP mechanism is a form of *pull* system that regulates the amount of work in the system with a Work in Process (WIP) cap.[61] Orders are accepted into the production process until the maximum of WIP has been reached. Any new arriving orders are buffered or declined in one way or another. Only when a processed order leaves the production process, a new order is generated an allowed into the production process. Figure 3-4 provides a schematic overview of the principle.

Order release by CONWIP method is especially rigid against variation in processing time over the different stations or even jobs, as it does not control by properties of individual stations in the system, but rather the system boundary. This makes it more suitable for systems with standard back flow occurrences than other pure *pull* systems.[61]

The number of orders a system can accommodate varies per system type. It has been suggested that in a make-to-order system the absolute maximum of orders would be the amount that would just clear the due date of the last order to be processed.

$$N_{max} = \text{MAX}\{WIP_{sys} + WIP_q\}, \quad \text{for:} \quad \frac{WIP_{sys} + WIP_q}{\frac{1}{T_B}} > T_{due} \tag{3-1}$$

With the assumption stated in Eq. (3-1) parameters T_{due} and T_B show to be the control parameters that define the set point N_{max} being the load limit of the system. Therefor this control function is configured by the parameters:

- Norm bottleneck processing time T_B
- Maximum of throughput time T_{due}

Step 5.2: Order release method

For order release methods several classes have been defined in Section 2-4-2. First the main class and possible subclass is selected from the general process characteristics, internal and external variability and due date reliability as objective. Hereafter a method is selected based on specific characteristics, clear labour restricted bottleneck, high utilization requirement and complex material flow due to standard loop.

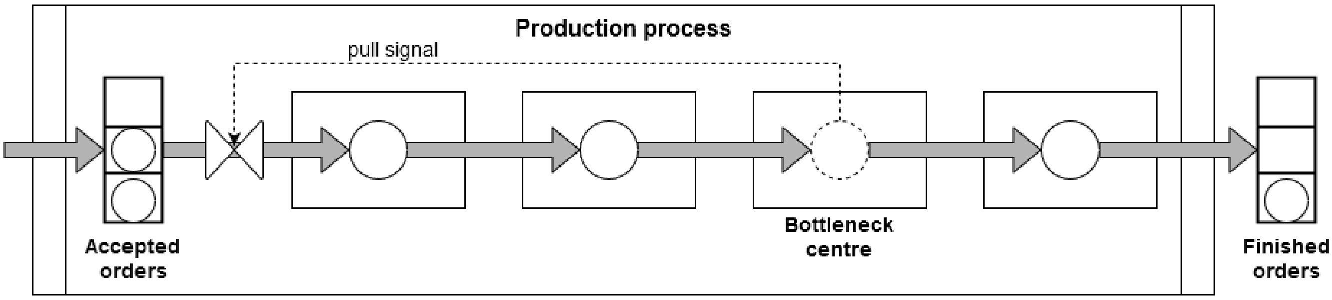


Figure 3-5: Bottleneck control without safety buffer for order release

Based on the general system characteristics and their resulting requirements; robustness and due date reliability, the use of the WIP regulating class has been selected. These methods show good resistance against errors and deviations and have shown to result in perform better in predictability of throughput times. With the specific characteristics show *bottleneck control* to be suitable for obtaining high utilization of the bottleneck process. The Drum-Buffer-Rope (DBR) system is specifically aimed at obtaining this high utilization. [62]

The DBR system recognizes that the production rate of a system cannot exceed the production rate of the bottleneck sub process. Hence it subordinates the entire production to the pace of the bottleneck. This means the orders are released by the pace of bottleneck processing. This could be a timed interval, but also a trigger event, that indicates decreasing bottleneck utility. The system "pulls" the released order towards the bottleneck process at it its production pace. After the bottleneck the order is left to pass through the remainder of the system at the pace of the subsequent stations. This illustrated in the Figure 3-5. A time buffer of partially processed items is installed before the bottleneck station to prevent it from running idle. This means possible system variability is reduced by deliberately extend the total throughput time to gain higher utility potential.

However, the prime logistic objective of the LC was to obtain delivery reliability for the short contract time. The additional time buffer counters this goal and it has therefore been decided to not implement the buffer, but to only keep the accepted order buffer at the beginning of the process.

Additionally, the part of the overloading protection property of the DBR system vanishes if the bottleneck resource is part of a loop function in the routing as it does not add a maximum on production load [27]. A maximum of production load has been added as an additional condition to the control function of the release method. The scope of this condition is the production system without the buffer of accepted orders at the beginning of the process. The release condition then become the "vacancy" trigger and the load state satisfying its limit condition.

$$WIP_{repair} < N_{man,repair} \quad \text{and} \quad WIP_{loop} < N_{limit} \tag{3-2}$$

Step 5.3: Sequencing rules

Sequencing rules are applied to official queue points in the process design. Sequencing rules are an active measure to control deviations of the production schedule. The policies assigned to the respective queues must be selected with the four criteria stated in Section 2-4-2. The first criterion concerns the prime logistic target of the entire process, which was earlier determined to be high due date reliability. The other criteria must be evaluated for the respective queues where the policy shall be implemented. There are three official queue positions in the process; the accepted orders buffer, the test station buffer and the repair station buffer.

Accepted order buffer The order buffer holds the orders that have been generated upon acceptance of the client order. The throughput time of the shop is of a fixed time period and serves the MRO component supply chain who must in turn be reliable in due dates. As the logistical process of the supply chain causes deviations in the total MRO Turn-Around-Time (TAT) of components, a rule that promotes the due date reliability of the entire supply chain is desirable to implement. As the date of arrival at the MRO centre is kept with the LC unit, a due date-based sequence can be implemented, satisfying the third criterion. The necessity of readjusting the order schedule has been suggested in several studies as the time taken for the components to reach the centre is of stochastic nature. Readjusting the order schedule after due date has been suggested counter the variance in logistical time. [57]

The Earliest Due-Date (EDD) policy belongs to the class of sequencing rules that promotes due date reliability by processing the orders having the earliest due date first.[27] The EDD shows to perform specifically well in the remanufacturing environment over other due date reliability promoting policies. [14, 26, 18]

Test station The queue in the test station collects both untested and repaired components requiring testing. Components that arrive for initial testing are only released into the queue by trigger of the bottleneck. Components leaving the repair station arrive in stochastic nature, since repair time is variable for the respective components. The bottleneck control method should promote high utility of the bottleneck process, but the absence of a safety time buffer prior to that station, exposes the station to variance of the test station sequence, this stresses the necessity of sequencing and here fore satisfies the fourth criterion. By prioritizing the orders released by the bottleneck control over the repaired orders, the time safety buffer is moved to the total order buffer of the process. This policy is called Extended Work in Next Queue (XWINQ). It promotes the DBR method from bottleneck control to impact the next station, which is the bottleneck station. By its specific impact on its successive station the second criterion has been satisfied. The applicability is ensured by the documentation that is required to accompany all components in the shop.

The XWINQ policy belongs to the class of sequencing rules that promotes increased output of the process by affecting the work load of specific stations in the process.[27] The policy prioritizes orders in such a way that the utilization rate of a successive station is affected. The exact influence is determined by the specific way of prioritizing and is determined for the respective queues where it is applied. In this case the component status of repair is the control input variable. The policy is used effectively to handle flow complexity specific areas of a production process. [27]

Repair station The repair station receives components from the test station paced by bottleneck control system. As no safety buffer is kept before the station a queue will sporadically

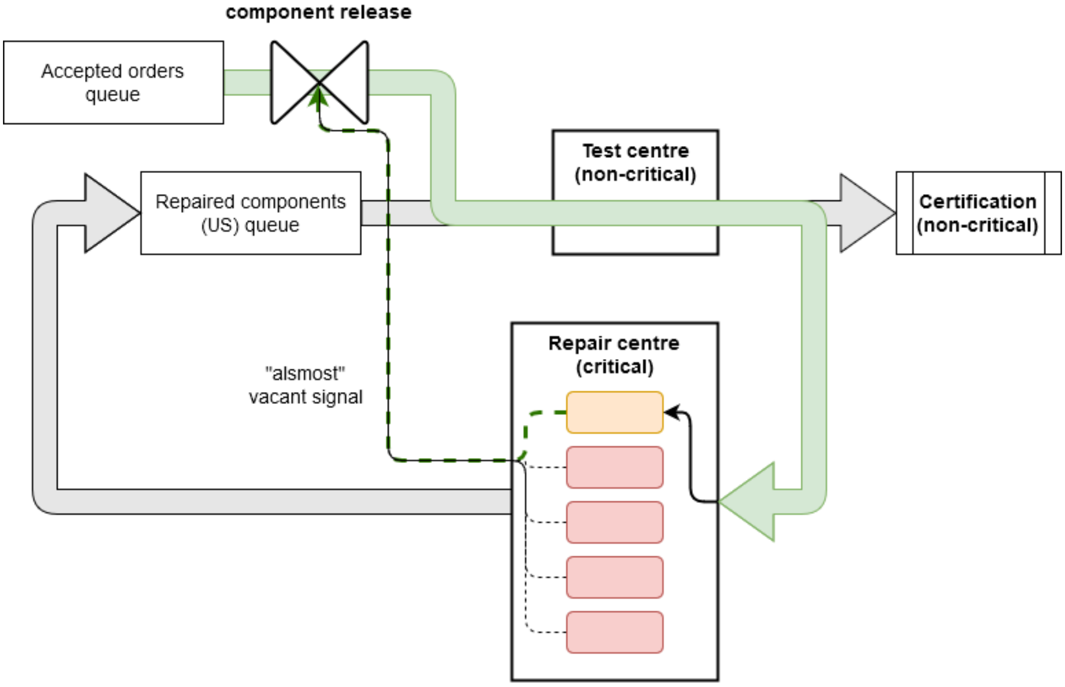


Figure 3-6: Sequencing for bottleneck control with XWINQ rule

form when the timing of release has not been correct. Being the bottleneck station, the repair station does not have to consider its impact on the successive stations. Hence a simple First-in-first-out (FIFO) policy suffice for this queue.

The FIFO rule is the most intuitive sequencing rule available.[27] It belongs to the class that promotes due date reliability, by keeping the throughput times of orders short. Orders arrive at the queue and are picked up in order of arrival. The rule is found to perform well in the DBR production method, but has limited ability to buffer system variance since it is not affected by due date slack or the original production schedule. [14, 18]

The sequencing rules have been implemented to serve the main purpose of the process; due date reliability. One exception is for the production sequence in the test cell. It has been chosen to integrate the sequencing function of the test cell with the bottleneck control to promote bottleneck performance, its working principle has been depicted in Figure 3-6.

Step 5.4: Capacity control method

Capacity control assigns the final means to the planned output to produce the actual output. The ability to assign capacity to the load is fully dependent on the production environment, that provides a certain degree of flexibility for capacity change.

Analysing the amount of resources deployed reveals the process to be strained and no capacity increase can be expected to be available other than to outsource an entire order. This mechanism has partially been described in the order generation process where orders are accepted or outsourced on the basis of likelihood of making their due date (*"performance"*. Since no other options for capacity control are available without having to make unrealistic assumptions on

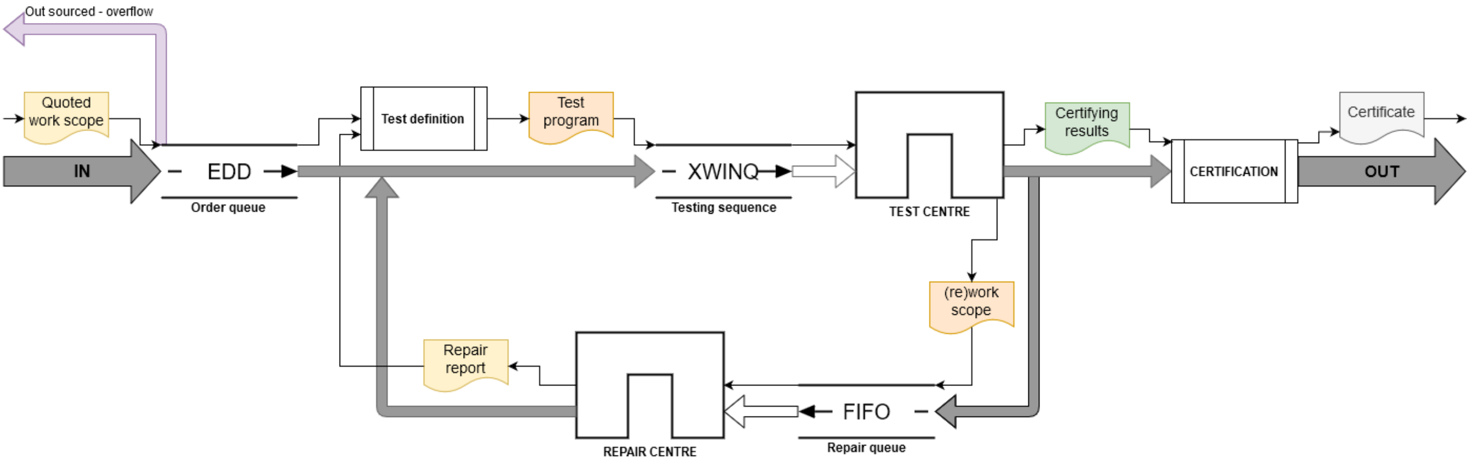


Figure 3-7: The controlled production process overview in VSM configuration with control elements added.

productivity of operators, the outsourcing option is developed further. The capacity change is characterized by three subjects; the criteria for adjustment, scope of adjustment and trigger logic.

The prime logistic target of the LC process is due date reliability and is measured by the OTP. This measurement considers late orders; hence the risk of lateness should be mitigated by the capacity adjustment in the system. The probability of lateness is affected by two influences: sum of accepted orders and the capacity available within the available production time of the respective orders. Both are values stochastic of nature. Therefore, the criterion for capacity adjustment is the probability of lateness of accepted orders not yet fully finished.

As the decision to outsource is taken upon order arrival from the client. Work scope details are not available other than delivered by the client. Due to the generic MRO process characteristics and specific capacities deployed for the LC process, the only option is to entirely outsource the service of the component.

The trigger logic for outsourcing relates to the probability of lateness of an order, being the criterion for capacity change. In the current system, an estimate is made for the amount of bottleneck capacity. This norm value is then used to calculate the estimated bottleneck load given the number of prevailing orders in the system and the amount of bottleneck capacity available over the contract time of the component that must be decide on. Would the system not be able to produce the required man hours in the contract time of the respective component, the risk of lateness is regarded too substantial to accept the order.

Result of the design configuration

With the complete production control configuration cycle completed, A final design can be drafted. Since information flows have yet to be identified and added, it has been chosen to visualize the process in a logistic overview with the control elements placed on their respective positions. The result is depicted in Figure 3-7.

3-2-6 *Step 6: Production control information structure*

The production control configuration has inserted elements and functions into the MRO process. The different elements have an information requirement that must be satisfied for it to function properly. Appendix B-5 describes the analysis of these information requirements by connecting the sources and sinks and characterizing the information quality required for proper functionality of the respective element. Adding the information flows and information control elements to the graphical overview Figure 3-7 in VSM-i configuration produces the overview depicted in Figure 3-8 and the information overview of Figure B-8 into the total process information network to Figure B-9

Additionally, the control system configuration shows to have set values wherewith the configuration can be tuned to achieve desired performance. For the order generation function these are contract time and norm throughput bottleneck time. For the order release function, the load limit has been determined to be the set value. Table 3-2 provides an overview. These control system tuning parameters are independent of the system state and can be adjusted by the process governance.

function	set values
order generation	contract time norm thoughput bottleneck time
order release	load limit

Table 3-2: Set values for the control configuration

3-2-7 *Step 7: Robustification of control information*

The production control information structure reveals the set values that need to be defined for the control system to operate. These set values are references that are used in comparative functions in the control elements that compare the measured system state with the reference to decide on active control adjustments.

In the case of the LC process, the system measures the load state expressed in units in the respective control boundaries and compares these to the reference. Given that the units themselves vary in resource requirement this method of calculating load is susceptible to variance. Hence the definition of workload and system load measurement are re-evaluated for more stable dimensions of measuring. Appendix B-6 provides the full analysis and its findings are presented here.

Definition of work load Workload can be defined by just its quantity with a reference value transforming this value to a load representation. This is used in the current control configuration. The load on each capacity of an order can also be identified individually and then summed for all orders in the control boundary. This would provide a "true" representation of the actual load on the system. True is written between quotation marks as the representation will be as accurate as the sum of the individual order load estimates is.

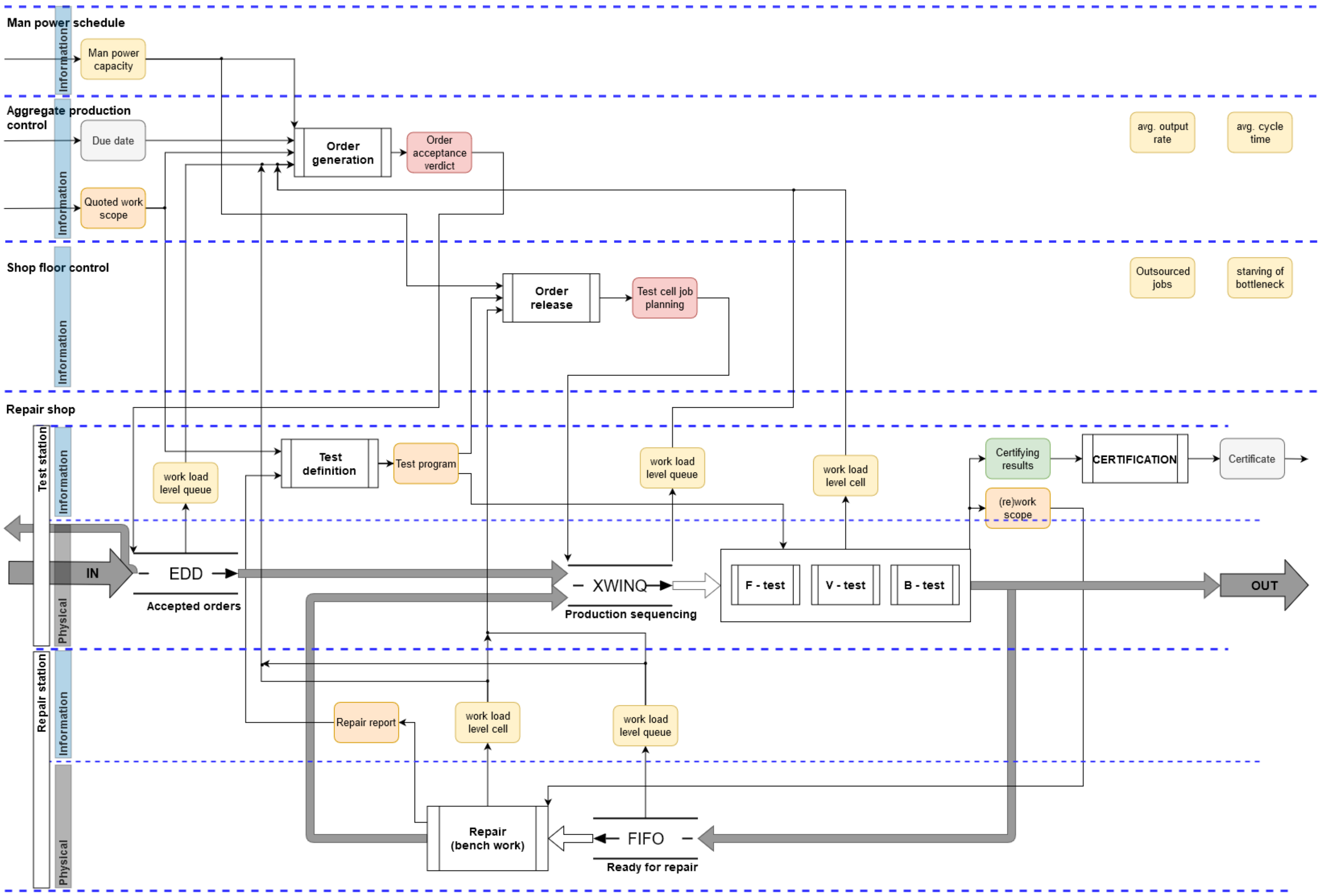


Figure 3-8: Integrated production control system for the LC process in depicted in a VSM-i scheme

Redefining system load measurement Using the CONWIP method with normalized load estimation to control load in the system shows to be susceptible to the variance of the individual workload of the total orders in system. Hence is suggested to not control the number of units in the boundary but the total sum of the individual order load estimations. This concept will be referred to as Equivalent Work in Process (EWIP).

The change of variable in control parameters has implication for the configuration. The *load limit*, used in order release, is now a function of the capacity available in the system over time and hence not a set value for the control system and the norm throughput time vanishes completely. The sequencing functions do not regulate by order load, but other variables and are therefore not affected by the change of variable. The total information overview by Figure B-9 updates to Figure B-10.

3-3 A SFPC design for the liquid cooling process

The previous section has described the application of the experimental design framework for the production control of an MRO for the LC process at E&M. This served to answer the seventh research question:

What is an MRO process SFPC design for the Liquid Cooling MRO process considering the process criteria for general MRO Shop Floor Planning and Control?

Full representations of the production process are given in Figure 3-8 in VSM-i representation and Figure B-10 in IDEF0 representation.

Given the design requirements developed and the solutions to answer to the requirements the following characteristics of the design are proposed:

- Control of WIP or EWIP for a certain limit will not allow for accumulation of work in the system (theory testing - moderator WIP-EWIP functionality)
- EWIP controlling will allow for higher performance to WIP controlling given the same resources and configuration (theory testing - comparative study: EWIP over WIP)
- With the control of WIP or EWIP the system is made robust and stable to the external variability and internal variability of the MRO process.

With the completion of the experimental control system design the evaluation of both the design and the framework could be done. Here both parameter configurations had to be evaluated.

Chapter 4

Evaluation model

The application of the framework for the Liquid Cooling (LC) Maintenance, Repair & Overhaul (MRO) process resulted in a control design with two parameter options that had to be evaluated for their functionality and performance on the design criteria. This would confirm the experimental framework to enable control system design for the named criteria. The evaluation will be constructed around the final research question:

- *What is a performance testing environment to evaluate a production design?*

This question is explored by developing a strategy for evaluation in Section 4-1. With the evaluation strategy an input-output simulation model was developed, described in Section 4-2. Validation of the model is described in Section 4-3. Finally a summary closes the chapter in Section 4-4

4-1 Logistic model evaluation strategy

In a multitude of studies of logistic processes and their control logic Discrete Event Simulation (DES) modelling is applied to compare different configurations in performance and to demonstrate the functionality of control [15, 63, 48, 64, 65] and has been advised for use of modelling complex production control and manufacturing environments [66]. This section describes the use of DES modelling for the evaluation of the proposed production control system.

4-1-1 Discrete Event Simulation modelling

Discrete Event Simulation simulates by changing a systems state over discrete time steps that lay between the events that cause the systems change. As the system state between the changes does not alter, it allows a state to be calculated as soon as the prevailing state is known. The entities that make up the system can be conceptual or physical nature and originate outside the simulation boundary or reside in the boundary only [67]. DES is used extensively for the evaluation of logistic processes and other dynamical systems not exhibiting properties dependent on differentials in continuous time.[66] By simulating the separate entities in a system, complex queuing models, mathematically unsolvable, can be solved numerically [25].

The proposed process control design actuates a logistic process where a multitude of properties can be altered, the use of DES models is used extensively in research and design for production planning and control [67]. Additionally, DES has been regarded suitable for the evaluation of designs developed with Taguchi methods [30]. Therefore, the control design will be evaluated by means of a DES model.

4-1-2 Goal of the DES and criteria for evaluation

The goal of the performance evaluation of the control system should measure to what degree the control system is able to deliver the required performance with the production system. It is important to realize that the process and its control system must therefor, be evaluated as one system, as the combination of both enables the final performance. The DES model should be built to satisfy this requirement. This section will explore these exact evaluation criteria in relation to the set of design requirements used to come to the final control configurations, and translate these to output that should be observable in the simulation. With these output requirement and the measurement strategies the controlled input can be defined. This composes a set of design requirements for the DES model itself and is listed afterwards.

Requirements: parameters observable

The design requirements of Section 3-1 for the controller subject to the evaluation are summarized:

- Prime objective: due date reliability
- Second objective: throughput maximization
- Robustness
- Stability

To measure the "added value" of the control configuration some form of measurement had to be defined to see how the control system enables the process to perform when simulated for the different configurations or absence hereof. This was done for each design requirement listed. Additionally, requirements for controllable input are explored.

Due date reliability can be measured by internal throughput time [27]. By comparing the throughput time with the contracted time, a reference value is defined for performance and non-performance. At KLM Engineering & Maintenance (E&M) this value is called On-time performance and is the fraction of orders with a throughput time shorter than the contract time. Hence, both values are adopted in the performance measurement of the DES model.

Throughput maximization This maximization is realized by ensuring high utilization of the constraining elements of a production process [62]. Therfore the bottleneck utilization could serve as a direct measure for the ability to maximize throughput. In the LC process the bottleneck process is constrained by man hours available for the repair, hence it was decided to use the fraction of time an operator has the ability to work on components of the total production time. In addition, the throughput maximization is deemed the secondary objective of this production system as the initial analyses indicated a challenging capacity constraint to meet the expected demand. Hence, the ability of the system to meet a certain demand over time is chosen as an additional reference measurement for performance, this will be measured in the throughput rate of the system.

Robustness For this paragraph the term robustness collects robustness for external disturbances and stability for internal disturbances in one term. Robustness is a concept much described in control system literature, but difficult to quantify in a measurable parameter. In production system evaluation several explanations of the concept are maintained. In the Taguchi method earlier described in Section 2-4-3 the aim of the method is to minimize the deviation of the target function. Here the target function represents some physical property of a product. For production system performance this same principle is applied to performance measures for the respective system [68]. This implies that "a production system is robust if it can remain working at a high-performance level despite the given risk". Where risks are the probabilities of events that form of disturbances that affects the respective performance measures. A distinction should be made between "high" and "optimal" performance; high performance is satisfactory performance of substantial level, but not the highest achievable with the system; optimal performance is the highest achievable performance given the system.[69] This defines measurement of robustness as the ability to attain a certain performance regardless the nature of the noise factor, on the condition that the system is not operating in its highest achievable performance.

The LC MRO process control has been designed for robustness and stability, meaning resilience to internal and external disturbances, that the operations are exposed to. These risks have shown inherent to the nature of the MRO process. This correlates with the mentioned interpretations of general robustness earlier in this paragraph and hence robustness and stability of the performance framework of the LC process will be evaluated *by the response of the target functions to induced deviations on the main input variables.* With the target function corresponding with the primary and secondary logistic targets, throughput time and bottleneck occupancy. The use of a DES simulation has shown very suitable for the evaluation of stability and robustness of controllers in discrete systems. [69, 70, 71]

Parameters controllable

Comparative studies require the control of the independent parameters to observe the dependent parameters. The independent system parameters can be of static or dynamic nature. Most yet mentioned in the previous paragraphs are static variables in terms that they do not change due to process or control system dynamics. These parameters can simply be defined prior to the simulation.

As this study intended to evaluate the controller behaviour for the performance environment the different operational zones. These are defined for different levels of Work in Process (WIP) as was stated by the logistic curves in Figure 2-5. However, WIP level is a dynamic parameter of the system and subject to actuation of control, hence controlling it externally for every configuration would result in incomparable results.

Little's law shows the dependency of WIP, arrival rate and processing time. As the arrival rate at the system is an unactuated external variable in the real environment, and processing times are assumed as static variables with stochastic properties, the simulation can utilize a controlled order arrival rate to compare system response for equal input.

DES model requirements

With the evaluation criteria defined, requirements for the input-output model can be formulated for simulation input, simulation output, simulation model.

- The model should
  - resemble a DES of the logistic process design of the parametrized LC process.
  - simulate the process on an individual order basis.
  - have both control configurations installed with a selector that toggles the desired configuration and respective settings prior to simulation.
  - simulate stochastic properties of noise factors:
    - job processing requirements
    - estimation errors
    - rework
  - track all elements simulated.
  - enable control of the stochastic arrival of single jobs
  - automatically acquire relevant data from each iteration and summarize to an output.

Input must be read from a file that can hold the input for several experiments so iterations and batches of experiments can be loaded. Equally, the output file should be able to summarize each iteration experiment for the entire batch.

4-2 Input - Output model description

The input-output model is the actual testing environment for the LC process and its control system. The DES model has been constructed in Python programming language in object oriented manner with a special DES modelling frame called SimPy. Processes in the SimPy environment are based on the standard generator functions in Python [72]. The combination of both sees much application in prototyping of manufacturing and logistical network, including their control elements [73, 74, 75]. The programming distinguished four different elements as

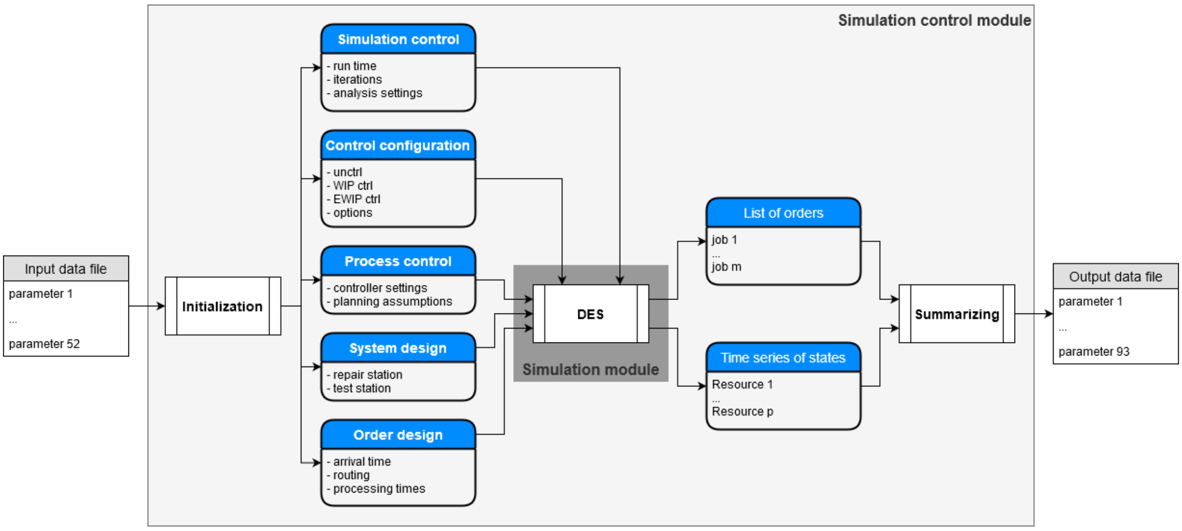


Figure 4-1: The input-output software architecture

depicted in Figure 4-1 and follows the following principle: input is read from a file by the simulation control module. The intializes the environment where the simulation process will run. When the environment is ready, the simulation is triggered. When the simulation ends, output data will be delivered to the control module, that transforms the data in to results and writes these to the output file. The remainder of this section will describe the programming of the DES and the surrounding simulation control module. Descriptions of the input and output files are enclosed in appendix C.

4-2-1 Simulation model

The simulation is centred around the individual jobs that undergo specified events in the form of processes that are created and then execute assigned processes. These assigned processes resemble the physical process steps in the production. At some point the started process finishes all assigned processes meaning the MRO order has completed its process route. Throughout this description the process that resembles an order will be referred to as a job, to prevent confusion with the processes that the "job" process is to execute. The job is passed through different entities in the simulation. These entities are instances of several classes. Figure 4-2 provides an overview of the classes and process entities in the simulation program. The object classes and four major processes or groups of processes are recognized and covered below.

Object classes

The object classes represent the physical production system and several control system entities. The classes are initialized by the simulation control module that will be covered later in this section. The classes with their methods and attributes have been described with the following pseudo-code:

```
class repair_cell(object, env, repair_men, repair_positions):
```

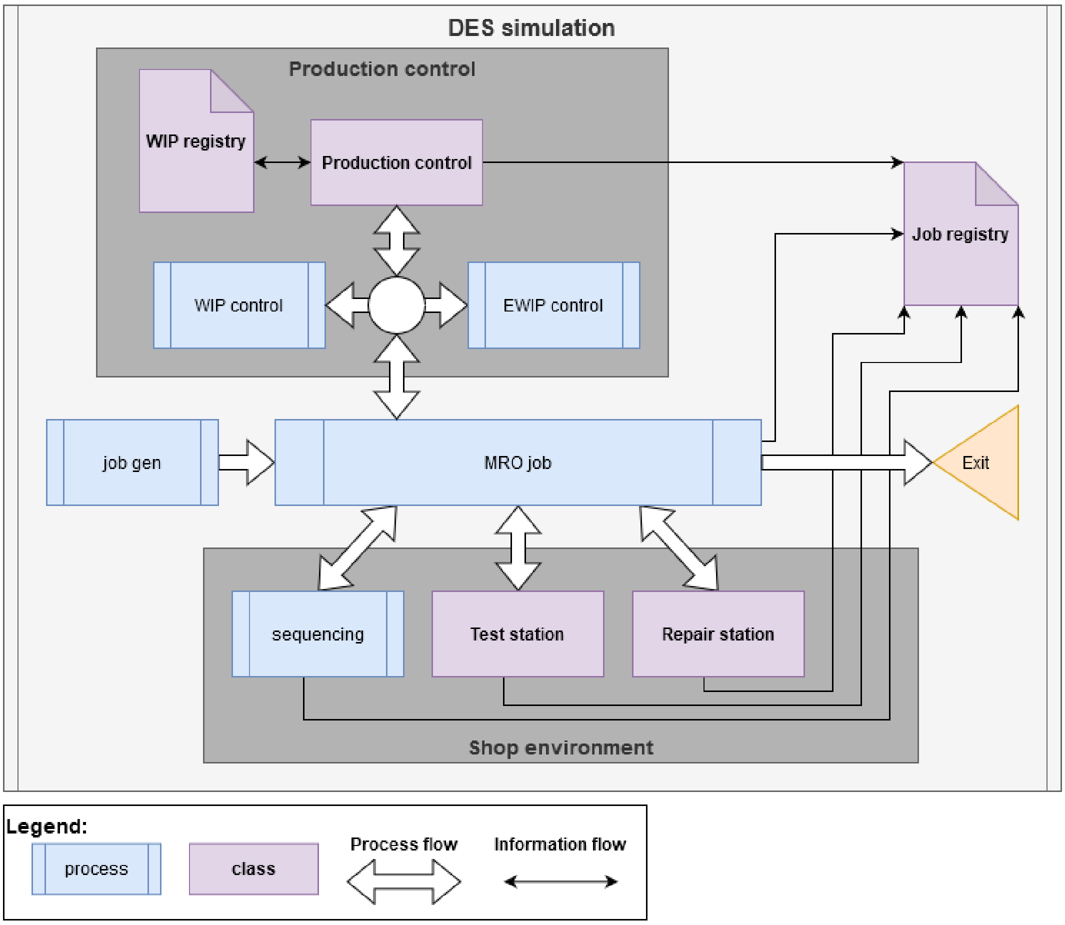


Figure 4-2: The DES object interaction relations

```
    # data
    self.repair_men = repair_men
    self.repair_positions = repair_postions

    # elements of the repair station
    self.repair_man = simpy.Resource(env, capacity=repair_men)
    self.repair_bench = simpy.Resource(env, capacity=repair_positions)


class test_cell(object, env, test_operators, test_mach_q):
    # data
    self.test_operators = test_operators
    self.test_mach_q = test_mach_q

    # capacities of the test station
    self.test_operator = simpy.PriorityResource(env, capacity=test_operators)
    self.test_machine_1 = simpy.Resource(env, capacity=test_mach_q[0]]
    self.test_machine_2 = simpy.Resource(env, capacity=test_mach_q[1]]
    self.test_machine_3 = simpy.Resource(env, capacity=test_mach_q[2]]


class production_control(object, env, norm_times, touch_times, contract_time, man_availability, machine_availability):
    # data
    self.norm_times = norm_times
    self.touch_times = touch_times
    self.contract_time = contract_time
    self.man_availability = man_availability
    self.machine_availability = machine_availability
    self.norm_test_T = sum(norm_times(0:3))     # summing the norm times of tests

    # control elements and variables
    self.sys_queue_resource = simpy.Resource(env, capacity=1)
    self.suspend_inflow = false
    self.release_trigger = env.event()


class job_registry(object):
    # definitions
    self.registry = DataFrame(keys)

    # class methods
    def add_job(my_job, t_arrival, T_test1, T_test2, T_test3, T_repair, N_passes, error, status):
        new_job = array(my_job, t_arrival, T_test1, T_test2, T_test3, T_repair, N_passes, error, status)
        self.registry = self.registry.append(new_job)

    def update_status(my_job, report):
        self.registry.at[my_job, 'status'] = report

```

```

class wip_registry(object):
    # definitions
    self.current_wip = 0
    self.direct_ewip =  array(0, 0, 0, 0)

    def add_job:
        self.current_wip = self.current_wip + 1

    def remove_job:
        self.current_wip = self.current_wip - 1

    def direct_add_job(T_test1, T_test2, T_test3, T_repair):
        self.direct_ewip = self.direct_ewip + array(T_test1, T_test2,
            T_test3, T_repair)

    def direct_remove_job(T_test1, T_test2, T_test3, T_repair):
        self.direct_ewip = self.direct_ewip - array(T_test1, T_test2,
            T_test3, T_repair)
```

Simulation of capacity Some of the classes hold special instances of classes of the Simpy package; the `simpy.Resource` and `simpy.PriorityResource` are such classes. These are shared resources that are used by the processes to create capacity congestion points and is conceptually a semaphore: it stores requests by its users in a form of an access token. This generates a queue of the processes more requests are made than units of capacity is available [72].

Job_generator process

The job generator process is the starting point of a job in the simulation. Upon initialization the process receives a set of attributes listed in Table 4-1. Upon call, it generates its next event and then generates a job with the following pseudo code and passes the job to the main register of jobs and starts the `MRO_job` process.

```
def job_generator(env, inter_arrival_time, test_time_T1, test_time_T2,
    test_time_T3, repair_time, yield_after, error_estimation, repair_cell,
     test_cell):

    while True:
    jobs_generated = 0

    while job_limit >= jobs_generated:
        # generate the next arrival time by order sampling
        inter_time = distribution_sampler(inter_arrival_time)
        yield env.timeout(inter_time)
        jobs_generated = jobs_generated + 1
        arr_time = env.now

        # generate order specific properties by random sampling
        test1_T = distribution_sampler(v-test_time)
```

attributes	type	main catergory
env	class	simulation context
job limit	int	simulation property
interarrival time	distribution	environment property
v-test time	distribution	environment property
f-test time	distribution	environment property
b-test time	distribution	environment property
repair time	distribution	environment property
yield after	distribution	environment property
estimation error	distribution	environment property
repair cell	class	shop environment
test cell	class	shop environment

Table 4-1: Attributes of the job_generator process

```
        test2_T = distribution_sampler(f-test_time)
        test3_T = distribution_sampler(b-test_time)
        repair_T = distribution_sampler(repair_time)
        passes = distribution_sampler(yield_after)
        est_error = distribution_sampler(error_estimation)

        job_registry.add_job(my_job, t_arrival, T_test1, T_test2, T_test3
            , T_repair, N_passes, error, status) # add order to orderlist
        env.process(MRO_job)
```

MRO_job process

The `MRO_job` process is the main driver of the repair simulation by routing the job to the required processes applicable for each individual case. It is called by the `job_generator` process after a job has been generated. From here it calls the relevant control module if applicable for the order generation and order release. The following pseudo code shows the activation of the controller modules. The processes `conf_wip` and `conf_ewip` denote the respective WIP and Equivalent Work in Process (EWIP) control configurations.

```
def MRO_job(env, my_job, t_arrival, T_test1, T_test2, T_test3, T_repair,
    N_passes, error, status, repair_cell, test_cell):
    priority = 0

    job_registry.update_status(my_job, 'arrived')  # update order status

    # production control for EWIP
    if ctrl_ewip = true:
        result = ewip_queue(env, my_job, T_test1, T_test2, T_test3,
            T_repair, error)
        priority = result

        if priorty == 1:
```

attributes	code name	type	main catergory
env	env	class	simulation context
job number	my_job	int	job property
arrival time	inter_arrival_time	float	job property
v-test time	test_time_T1	float	job property
f-test time	test_time_T2	float	job property
b-test time	test_time_T3	float	job property
repair time	repair_time	float	job property
yield after	N_passes	int	job property
estimation error	error_estimation	float	job property
status	status	string	job property
repair cell	repair_cell	class	shop environment
test cell	test_cell	class	shop environment

Table 4-2: Attributes of the MRO_job process

```
            job_registry.update_status(my_job, 'outsourced')  # update
                order status
            env.exit()

        else:
        wip_registry.direct_add_job(env, my_job, t_arrival, T_test1,
            T_test2, T_test3, T_repair, N_passes, error, status)

    # production control for WIP
    if ctrl_wip = true:
        result = due_date_ctrl(env, my_job, t_arrival)
        yield result
        priority = result

        if priorty == 1:
            job_registry.update_status(my_job, 'outsourced')  # update
                order status
            env.exit()

    wip_registry.add_job(env, my_job, t_arrival, T_test1, T_test2,
        T_test3, T_repair, N_passes, error, status)
    job_registry.update_status(my_job, 'released')  # update order status
...
```

It can be seen how the process is halted by the `env.exit()` command would a controller decide to outsource an order. Orders that passed through the acceptance process and awaited their release, move on to be processed in accordance with their routing. Routing of the order in the test and repair stations is handled by their respective executing processes.

```
...
    while N_passes > 0:
        #Que regulation in front of the test station where a free test
            operator is awaited
        test_man = env.sequencer(env, my_job, prio)
```

```
        yield sequencing

        #Passing to the test station
        testing = env.test_job
        yield testing

        #Passing to the repair station
        repairing = env.repair_job
        yield repairing
        N_passes = N_passes - 1

    else:
        #Que regulation in front of the test station where a free test
            operator is awaited
        test_man = env.sequencer(env, my_job, T_test1, T_test2, T_test3,
            test_cell, request_test)
        yield sequencing

        #Passing to the test station for certification
        certi_testing = env.test_job

        wip_registry.remove_job                    # remove the order
            from the WIP list
        if ctrl_ewip = true:
            wip_registry.direct_remove_job(T_test1, T_test2, T_test3,
                T_repair)
        job_registry.update_status(my_job, 'serviceable')  # update order
            status
```

The prime `while` loop represents the repair loop where the component must cycle until it reaches the number of required passes. The number of passes has been predefined upon order generation. In reality this would not be known as the order arrives. Using a controllable random sampler does enable the study of the effect of rework in the system. After the number of cycles has been completed, a final test is done the overall system WIP status is updated and the order is registered as *"serviceable"*. This point marks the end of the process in the simulation for the specific job.

Control processes

The control configuration processes for WIP and EWIP control comprise small series of processes described here. They are activated by the main `MRO_job` process.

WIP control configuration The WIP control configuration accepts orders based on the system state. An order is accepted on the basis of the norm processing times and the system filling. The process `due_date_ctrl` verifies this condition and starts the jobs release process `sys_queue`.

```
def due_date_ctrl(env, my_job, arr_time):

    #calculate expected due time for current system state
```

```
    prev_jobs = wip_registry.current_wip + production_control.sys_queue_resource.queue

    throughput_time = dot(prev_jobs*production_control.norm_times, ones(size(norm_times)))  #scalar and dot product

    if throughput_time > production_control.due_days: #condition for outsourcing
        return 1

    released = env.sys_queue(env, my_job)  #calling the order release process
    yield released
    outcome = released

    return outcome
```

Would the time required for the order exceed the time available on the contract. The order meets the condition for outsourcing. This halts the process with an exit value. Orders that are accepted are passed on to the queue of accepted orders. These are handled by the `sys_queue` process. This process monitors the system state and whilst orders are allowed to be released. If the WIP limit of the system is reached, a one-in-one out policy is implemented. This signal is provided by the `release_trigger` of `production_control`.

```
def sys_queue(env, my_job):

    req = production_control.sys_queue_resource.request()  #form a queue by applying requests
        if production_control.suspend_inflow = true:
        yield production_control.release_trigger  #release signal if WIP controlled
    yield req
    production_control.sys_queue_resource.release(req) #release the simpy resource

    return -1
```

With the order released, the process returns to the main `MRO_job` for shop processing.

EWIP configuration The EWIP control configuration accepts orders based on the system state. However in stead of a assumed norm, caluclation. the EWIP state is estimated by the "real" work load of an order and all orders in the system, including queue. This requires a slightly different control sequence.

The system filling is not bound to a fixed number, but the availability of resources. A simple comparison of the available resources in the contract period of the order under study and the requirements to complete the order reveals if the process can accommodate the order.

```
def ewip_queue(env, my_job, T_test1, T_test2, T_test3, T_repair, error):
    job_stats = array(T_test1, T_test2, T_test3, T_repair)
    if estimation_error = true:
        job_stats[3] = error #the errorenous estimate
```

```

    job_load = array(production_control.touch_times*2) + array(job_stats)

    #integrating the capacities available over the contract time in hours
    test_ManH = test_cell.test_operators * production_control.
       contract_time * production_control.man_availability
    repair_ManH = repair_cell.repair_men * production_control.
       contract_time * production_control.man_availability
    test_machH = test_cell.test_mach_q * production_control.contact_time
       * production_control.machine_availability
    repair_machH = repair_cell.positions * contact_time

    cap_ava = array(test_ManH, repair_ManH, test_machH, repair_machH)   #
       capacity available
    ewip_ahead = wip_registry.direct_ewip + job_load              #ewip
       capacity required for work ahead

    #test for acceptance
    for n in ewip_ahead:
        if cap_ava[n] > ewip_ahead[n]:
            check[n] = true
        else:
            check[n] = false

    if false in check:
        return 1    #signalling rejection

    else:
        return -1   #signalling acceptance
```

With the order released, the process returns to the main `MRO_job` for shop processing.

Shop processes

The shop process comprises 3 main processes that handle the order; `sequencer`, `test_job` and `repair_job`. Each order is assigned by the `MRO_job` process and after every completion the `MRO_job` process reported to.

Shop processing starts at the queue before the test station. Here newly released orders and repaired orders are collected in one queue that provides entry to the test station. Here the orders await the test operator to become available. Since newly released orders are on a drum beat schedule for repair, a dummy Simpy resource prioritizes newly released orders and passes the order to the test man as it comes available.

```
def sequencer(env, my_job, prio=0):
    req = production_ctrl.sequencer_resource.request(priority=prio)
    yield req

    req_test_man = test_cell.test_operator.request(priority=prio)
    yield req_test_man

    production_ctrl.sequencer_resource.release(req)
```

```
    return req_test_man
```

The process now holds the `test_man` and is passed to testing by the `MRO_job` process. The assumed routing of an order i first the vacuum chamber, then the functional test, and then the bonding test. Tests that are not required for the order are skipped. The test man performs mounting and dismouting components in machines and executes the bonding test whilst the other tests are run by the machines themselves. As the test operator must handle a multitude of assignments, priority must be assigned to the tasks to prevent deadlocks in scarce resource situations. This is realized by giving priority to all tasks that release a resource. Additionally orders that are scheduled by the drum beat need to be prioritized over "certifying" tests. This is illustrated by the following pseudo code:

```
def test_job(env, my_job, test_1_duration, test_2_duration,
   test_3_duration, test_cell
            , req_test_man, prio=0):

    test_cell.test_operator.release(req_test_man)

    if prio == -2:
        prio_mount = -1
        prio_dismount = -3
    else:
        prio_mount = 0
        prio_dismount = -2

    if test_1_duration > 0:
        req = test_cell.test_machine_1.request()    #request machine
        yield req
        test_man = test_cell.test_operator.request(priority=prio_mount)
              #request test operator
        yield test_man

        yield env.timeout(list_touch_times[0])

        test_cell.test_operator.release(test_man)
        yield env.timeout(test_1_duration)
        test_man = test_cell.test_operator.request(priority=prio_dismount
           )    #request test operator
        yield test_man

        yield env.timeout(list_touch_times[0])
        test_cell.test_operator.release(test_man)
        test_cell.test_machine_1.release(req)

    if test_2_duration > 0:
        req = test_cell.test_machine_2.request()    #request machine
        yield req
        test_man = test_cell.test_operator.request(priority=prio_mount)
              #request test operator
        yield test_man

        yield env.timeout(list_touch_times[1])
```

```
        test_cell.test_operator.release(test_man)
        yield env.timeout(new_test2_T)
        test_man = test_cell.test_operator.request(priority=prio_dismount)    #request test operator
        yield test_man

        yield env.timeout(list_touch_times[1])
        test_cell.test_operator.release(test_man)
        test_cell.test_machine_2.release(req)

    if test_3_duration > 0:
        req = test_cell.test_machine_3.request()    #request postition
        yield req
        test_man = test_cell.test_operator.request(priority=prio_dismount)    #request test operator
        yield test_man

        yield env.timeout(test_3_duration)
        test_cell.test_operator.release(test_man)
        test_cell.test_machine_3.release(req)
```

After testing the component is passed to the repair station. Would all repair operators and positions be occupied, the order waits in a queue before being served. Under repair a pre-warning is sent to production control to release a new order as a position would become available soon. The following pseudo code illustrates:

```
def repair_job(env, my_job, T_repair, repair_cell):
    req_man = repair_cell.repair_man.request()      #request repair operator
    req_bench = repair_cell.repair_bench.request()  #request repair position

    yield req_man
    yield req_bench

    if ctrl_wip: # relay upcoming vacancy to sequence
        yield env.timeout(T_repair - production_control.norm_test_T)
        if not production_control.suspend_inflow:
            production_control.release_trigger.succeed()
        yield env.timeout(production_control.norm_test_T)
    else:
        yield env.timeout(T_repair)

    # finish the repair
    repair_cell.repair_bench.release(req_bench)
    repair_cell.repair_man.release(req_man)
```

With the completion of the repair order returns to the `MRO_job` process for further handling.

Monitoring and tracking

Measurements occur in the system by monitoring the WIP state described by the lists in `wip_registry` and the SimPy resources. All SimPy resources come with methods that allows the tracking of its queue states and users at the time of calling. This monitoring is done by means of a "monkey patch" that has been set up to surround the resources and calling for a read-out of its state methods for every `request()` and `release()` that is being called. This results in a set of time series over the entire simulation. These series are passed to simulation control after the DES simulation has been completed.

All activity of an order is tracked by the `job_registry` that is called to update time spent between processes, resources and in queues. The entire list is passed to the simulation control module after the DES simulation has been completed.

4-2-2 Simulation control

The Discrete Event Simulation runs in an environment that needs to be initialized. Additionally the resulting data from the simulation needs to be summarized and stored for analysis. The simulation control module surrounds the DES environment to provide these functionalities.

Initialization The initialization process starts with the opening of the input file at appointed location. The input file contains a series of parameters that hold information how the simulation should run, and how the model should be configured. Full file description and parameter declaration is given in Table C-1 in appendix C. After read-out, the initialization is started and finally the simulation is run.

Summation and storing Upon simulation completion, the program passes an output set of data to the simulation control environment. This data is transferred to a temporary file where that awaits the final simulation run for a specific configuration. This information is then reduced to mean values and standard deviations of the individual simulation results to form one data array as provided in Table C-2 in appendix C.

4-2-3 Model verification

To ensure proper model programming and implementation of control, a verification program has been composed. It has been split into two stages. First the it is ensured the logistic behaviour the model conforms what may be expected given the design. Then the verification of the control logic has been evaluated. The verification program of the process is done by an event tracing analysis, a limit calculation and a comparison to analytical calculation. The verification of control logic has been assessed by event tracing. The verification of the control system as a whole is included in the main research report in Section 5-1

Load	station times [h]					
	Test 1	Test 2	Test 3	Repair	total orders	
	1.5	2	0.5	22	100	
Capacities	machine quantity				operators	
	Test 1	Test 2	Test 3	Repair	repair	test
	100	100	100	100	100	100

Table 4-3: Input data for unlimited capacity simulation

Logistic process event tracing

The software provides the user with output as the software processes advance through the program. By study of the output verification of the process logic can be obtained. The program has been evaluated for the different control configurations including *no control*. Herein the process logic of the software could be verified.

Limit evaluations

Two limit evaluations have been performed. One assuming infinite capacity of the system. One assuming no load exerted onto the system. Using the properties described would result in a simple predicted answer in a logistical process.

Infinite capacity causes the system to have so much capacity available that no element would ever have to wait anywhere in the production system. Components would move through just taking their prescribed deterministic processing times at the respective stations, this reduced the input load and capacities to the data given in Table 4-3 This means that the system with infinite capacity was presented with 100 orders in a time frame of 2000 hours with deterministic Interarrival Time (IAT). The experiment was repeated for a range of arrival times starting at 10 hours, decreasing with steps of 0.5 hours until 2 hours IAT. The average throughput time of the processed jobs is given in Figure 4-4.

Table 4-4 showed how regardless of IAT between jobs, no jobs experienced any delay other than its bare processing time. Meaning that the flow logic of the DES model operates as intended.

Minimized load of orders of orders assigns a capacity requirement equal to zero for all loads of the order. This would result in the order, when arriving at a station to directly pass through the station without any delay. This would result in an average throughput time of close to zero. As only the simulation calculation would require time for the order to pass through and hence again the input reduced to the load and capacities given in Table 4-5. The system with normal capacity was presented with 100 orders that arrived with a deterministic IAT. For computational reasons a value of zero was not submitted, yet a very small value could be entered. The experiment was repeated for a range of arrival times starting at 10 hours, decreasing with steps of 0.5 hours until 2 hours IAT. The average throughput time of the processed jobs is given in Figure 4-6.

IAT [hrs]	Avg. cycle time [hrs]	std cycle time
10	29	0
9.5	29	0
9	29	0
8.5	29	0
8	29	0
7.5	29	0
7	29	0
6.5	29	0
6	29	0
5.5	29	0
5	29	0
4.5	29	0
4	29	0
3.5	29	0
3	29	0
2.5	29	0
2	29	0

Table 4-4: Average throughput times for infinite capacities

Load	station times [h]					
	Test 1	Test 2	Test 3	Repair	total orders	
	1.00E-06	1.00E-06	1.00E-06	1.00E-06	100	
Capacities	Machine quantity				operators	
	Test 1	Test 2	Test 3	Repair	repair	test
	1	1	1	5	5	1

Table 4-5: Input data for unlimited capacity simulation, observe the non-zero, yet very small processing times

IAT [hr]	Avg. cycle time [hr]	std cycle time
10	1.50E-05	1.60E-24
9.5	1.50E-05	1.60E-24
9	1.50E-05	1.60E-24
8.5	1.50E-05	1.61E-24
8	1.50E-05	1.61E-24
7.5	1.50E-05	1.60E-24
7	1.50E-05	1.60E-24
6.5	1.50E-05	1.60E-24
6	1.50E-05	1.60E-24
5.5	1.50E-05	1.60E-24
5	1.50E-05	1.60E-24
4.5	1.50E-05	1.60E-24
4	1.50E-05	1.60E-24
3.5	1.50E-05	1.60E-24
3	1.50E-05	1.60E-24
2.5	1.50E-05	1.60E-24
2	1.50E-05	1.60E-24

Table 4-6: Average throughput times for orders with no loads

The lack of load showed the expected response as can be seen in Figure 4-6. The throughput time remains infinitely small, indicating that no other delays are caused in the model during the logistic process other than the assigned processing time in stations.

Input-output bounds The bounds prescribe that regardless the type of delay that is caused by the logistic system, an order must come pass through as time approaches infinity. This has been applied in the practical sense by limiting the number of orders presented to the system and setting a very large simulation run time. The bounds are studied for the scenario with apparent unlimited capacity and the minimization of orders and depicted in Figure 4-3 and Figure 4-4 respectively. It can be seen that all orders presented to the system pass and leave the system over time. In Figure 4-3 can be seen that over decreasing arrival time, the maximum level of WIP increases. This is to be expected as the total processing time of the components in the system does not change, as concluded from Table 4-4, therefor a higher rate will cause more orders to arrive over the same processing time. When no load is exerted on the system by the orders, every order passes through the system instantly. This can be seen in the time series given in Figure 4-4, where the maximum WIP level does not exceed one. Every order arriving leaves the system before the sequential order arrives.

With the graphical analysis of the WIP bounds and all orders leaving the system, it can be concluded that the DES model upholds the basic logistic logic of orders as intended upon programming.

Combining the results of the different verification tests, it is assumed that the DES programming does perform the model functions as designed.

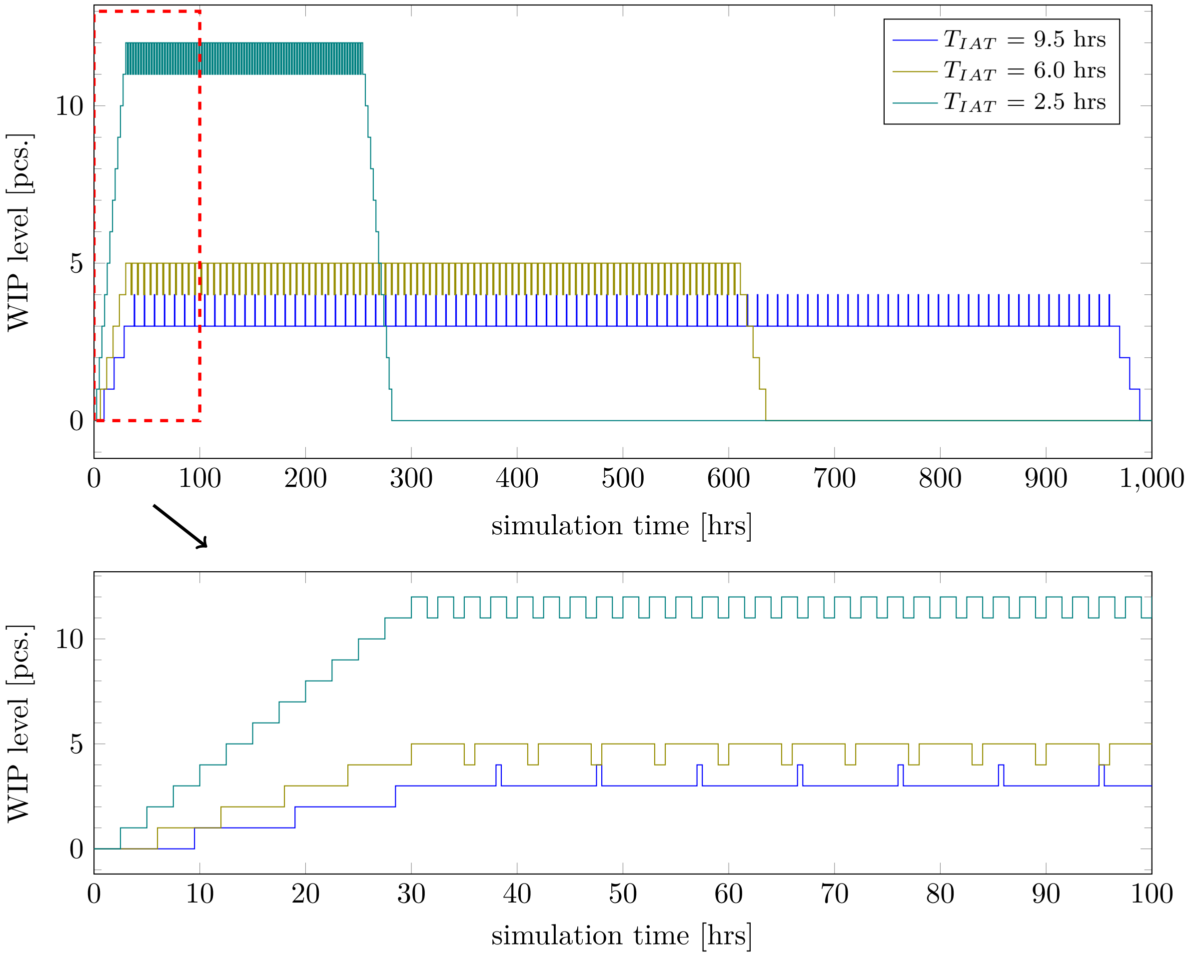


Figure 4-3: Time series of WIP for different IAT for unlimited capacity, showing a zoom of the red rectangle in the lower panel.

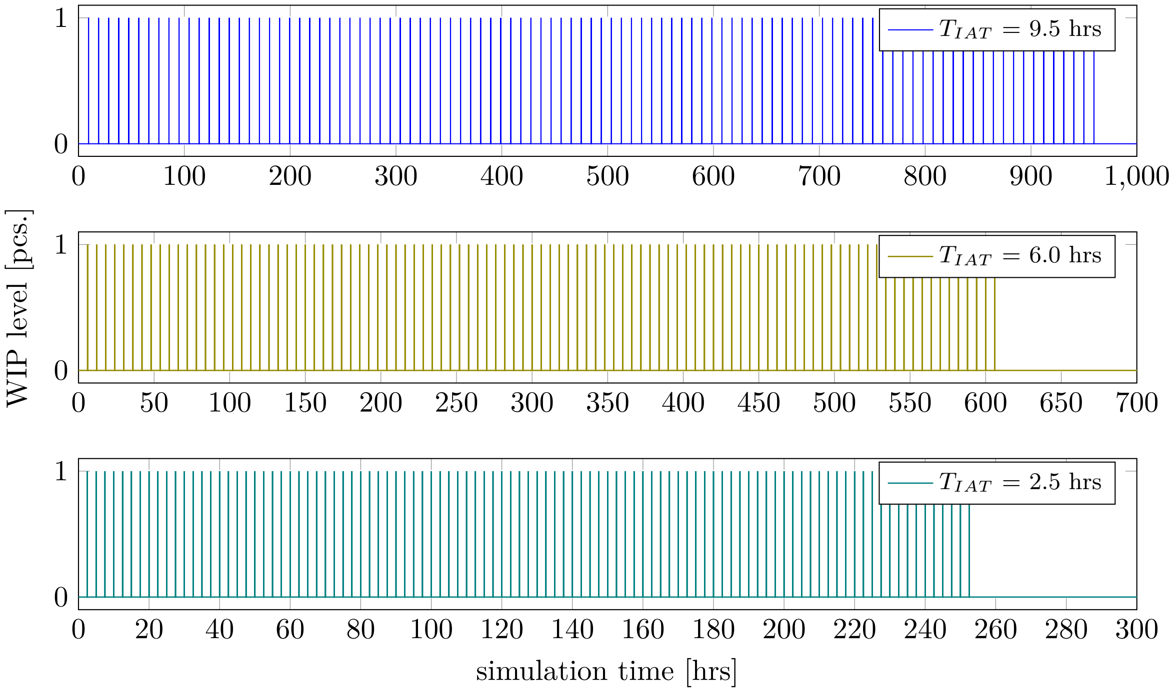


Figure 4-4: Time series of WIP for different IAT for orders with no load

4-3 Model validation

From the verification was concluded that the DES programming executes the designed functions for the logistic process that comprises the case study. To perform valid experiments with the DES model the prerequisites for valid results need to be studied, this was done with the model validation. This comprises evaluating the simulated results with some reference that strengthens the likelihood of the DES model being representative for the phenomenon studied, given its input data. This was done in the following sequence:

First, this required a valid input data set. Second, the validation of the run time of one simulation and the number of iterations had to be determined for the set. The run time length should ensure that final values and transient periods that may occur during the simulation can be identified so the behaviour under study can be isolated and the number of iteration of the experiments ensures that the correct level of certainty can be reached for significant conclusions. Finally, the results of the input data set, number of iterations and run time length would have to show valid for the simulated environment.

Standard input data set

The virtual environment behaviour is the result of the model input and the programmed software dynamics. The DES software builds a virtual environment from the data input. This requires the input to be representative for the behaviour of the actual element or entity that is should describe. In the input file the categories; process control, system design and order design, make up the virtual environment, the remaining parameters controlled the software or had to be determined by experimentation.

parameter	value	unit
test machine availability	[redacted]	-
repair position availability	[redacted]	-
manhour availability	[redacted]	-
time per day	[redacted]	hrs.
due days	[redacted]	hrs.

Table 4-7: Standard input for planning assumptions

The parameters that made up the virtual environment are specified in the standard input data set, facilitating the manipulation of the system by dependent parameters. Some of this information had been determined already. Table B-5 is seen that some parameters had been defined by the Component Maintenance Manual, business case, machine manuals or expert estimate.

The system design, norm times of the process control and default routing of the order design had been defined by the business case as seen in Table 3-1 and laid the foundation of the current configuration design. For the planning assumptions in the process control the performance environment of the organization has been studied. E&M keeps statistics on the availability and productivity of assets (including manpower) for their operations in its enterprise resource system SAP. Table 4-7 provides an overview of the obtained data.

The remaining elements of the order design parameters characterized the order sizes. This was the very information considered unknown in the design process. To simulate the stochastic behaviour of these attributes, estimates were made with expert knowledge to define these parameters. Each attribute is shortly described hereafter by there respective groups; test, repair, interarrival time and a summary is given by Table 4-8. Additionally, all of the input parameters are summed in table Table D-1 in appendix D.

Testing orders The tests are executed by automated machinery with a pre-defined test programs. This means that with rather great certainty the processing time for the tests can be defined on an hours scale if the test is deemed appropriate. It was decided to model this behaviour by means of a binomial distribution. Expert knowledge estimated every test to be executed with **80% over the total of orders**, independently distributed over the orders.

Repair orders The repair order distributions are all distributions affecting actual repair activity time and comprises the repair time, "yield after passes" and estimation error. Estimating the repair time for the LC component was shown particularly difficult as the component is an assembly of subsystems that E&M does not have broad experience with. A repair time estimate of most tasks had been composed to estimate a mean repair time. In the absence of any more information on the distribution a **uniform distribution** can be used to model the stochastic behaviour [76]. The minimum and maximum of the distribution were subject of study and have been determined for the experiments. For the validation the estimated deterministic mean value of **22 hours** was chosen. With similar reasoning yield and error estimates are modelled as **uniform distributions** and were set to their deterministic mean

		shape parameters	
order attribute	distribution type	a	b
v-test	binomial	0.8	
f-test	binomial	0.8	
b-test	binomial	0.8	
repair	uniform	22	22
yield after passes	uniform integer	1	1
error	uniform	0	0
interarrival time	uniform	6	6

Table 4-8: Standard input for distributions of order assumptions

value of **1 times** (one full repair cycle) and **0 hours** (no errors assumed by default), respectively, for the validation. Additionally, it should be noted that repair yield only can be integers as a repair order is inseparable, therefore the uniform distribution is of integer type.

Interarrival time The time between arrival of orders determines the demand pattern the simulated system is subjected to. By the expected demand foreseen in the business case, depicted in Figure 3-1 the mean minimum and maximum of interarrival rate was be determined and translated to interarrival times. The distribution type of the interarrival time relates directly to the cause of the demand for a particular service and in the case of MRO components is related to the mechanism that decides on removal [10]. Based on the best of expert knowledge available erratic demand as described in Section 2-1-3 is assumed and by the framework of Lipton et al. a **uniform distribution** was selected. With the mean expected minimum of interarrival time, the default input was set to a deterministic value of **6 hours**. This value would be subject to change for many experiments.

Run time length

To evaluate proper run time length and transient behaviour the WIP level over simulation time for the standard input in single simulations were studied. Table 4-9 shows the input data for 4 simulation experiments in addition to standard input data in Table D-1. The block width of the uniform distribution of the IAT is chosen arbitrary as by Little's law the IAT mean value determines a converging final state and not the variance of the stochast [77]. The width was set to 8 hours, with the exception of the scenario of 2.5 hours IAT, where a block width of 8 would result in negative values for the IAT, hence the widest value possible was 5 hours.

Figure 4-5 depicts the various WIP levels over the entire simulation time. It shows the IAT of 2.5 hrs to result in a diverging system state. A IAT of 5 hours and longer will cause the system to reach finite average. The time of filling for the system must be considered here before staring the data analysis. With the zoomed graph in Figure 4-5 a graphical analysis is made and an off-set time for measurement start is set at **200 hours**. This off-set would be valid only for IAT values under the studied **10 hours** Interarrival Time. Given the planned IAT used in the evaluation studies this interval was considered sufficient.

run time	t_{inter}	distribution block width
6000	10	8
6000	7.5	8
6000	5	8
6000	2.5	5

Table 4-9: Input parameters for run time experiment

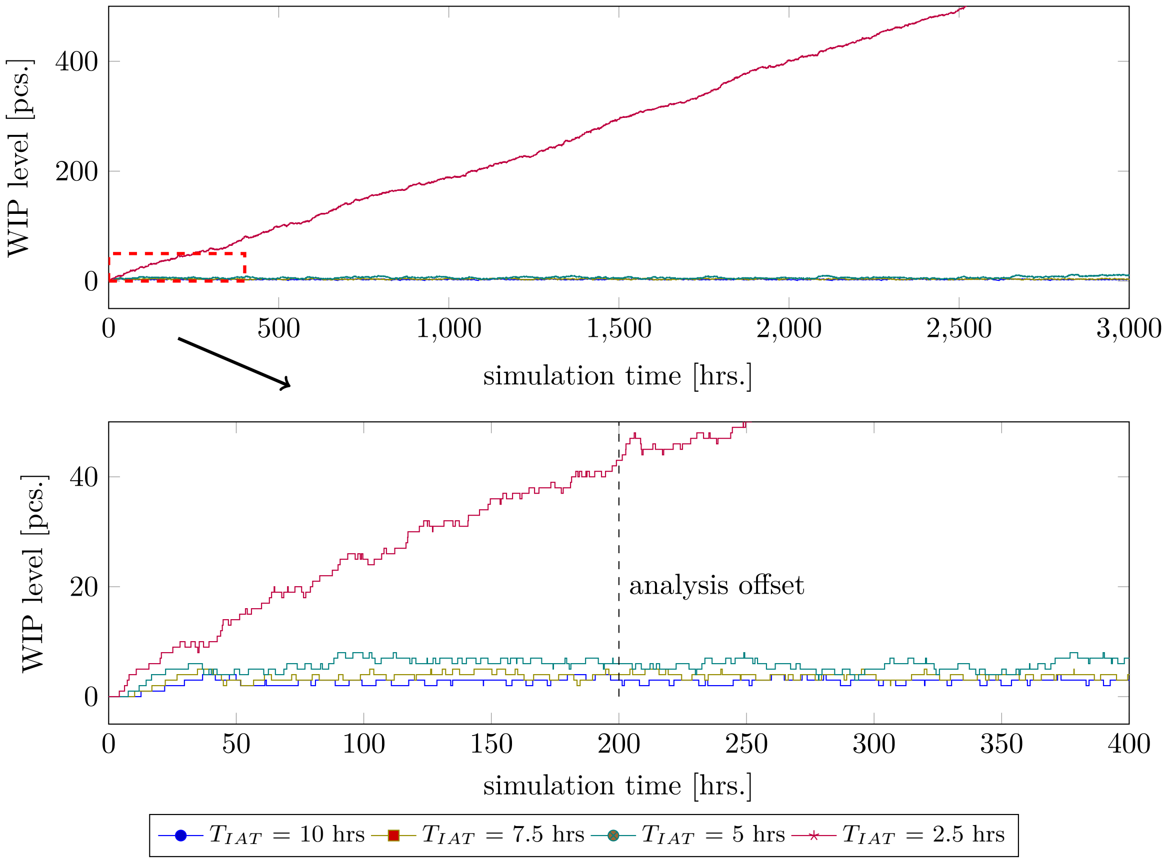


Figure 4-5: Time series of WIP for different IAT, with a close-up of initial transient zone shown in the lower panel

parameter	iterations	t_{inter}	block width
$c_{avg.CT}$	50	4	0
$c_{avg.WIP}$	150	7	2
	300		4
	500		6
	750		8
	1000		

Table 4-10: Input data and parameters for iteration experiment

Number of iterations

The number of iterations of an experiment determined the size of the standard error of the final average of an output parameter. In convergent systems, the final value of a output parameter can be determined over the increasing number of samples added tot the data set, where one sample point is generated per iteration. Ideally the number of samples is infinitely large, as this would make the standard error approach the standard deviation of the value. However, due to the limited amount of computing power and time, an infinite data set could not be generated. In addition, the number of iterations required to obtain a satisfactory significance was easily quantified.

The two important output parameters for this research were the average WIP level in system and the average throughput time, these were studied for their final value. The final value was estimated by modelling the coefficient of variance (or relative strandard deviance) defined by Eq. (4-1)of the respective output parameter over the number of iterations.

In the verification experiments the IAT of jobs showed to have substantial impact on system stability. It was therefore assumed that IAT is the prime influencing factor of the final system state. The series were repeated for two inter arrival times with each five distribution widths of a uniform distribution. Table 4-10 provides an overview. The choice of tested IAT was based on the verification experiments were a high IAT showed a low variance of the average value and a low inter arrival time showed a high variance of the average value.

$$c_{var} = \frac{\sigma}{\mu} \tag{4-1}$$

The coefficient of variance is plotted for average WIP level and thoughput time in Figure 4-6 and Figure 4-6 respectively. Two clusters of curves are distinguishable, separated over the IAT, with the configurations with the shortest IAT showing the highest coefficient of variance. Additionally, it can be seen that the block size of the uniform distribution shows of minor influences on the coefficient of the respective output parameters compared to the variation in IAT.

Comparing the coefficients of average WIP level and throughput time revealed that throughput time was most affected by the number of iterations and starts at a higher coefficient. Iterations cannot be run for single output variables, hence the sample size needed to be increase until of the parameters of interest the would reach the desired level of accuracy and certainty. As of this, the parameter average throughput time will be modelled to predict its

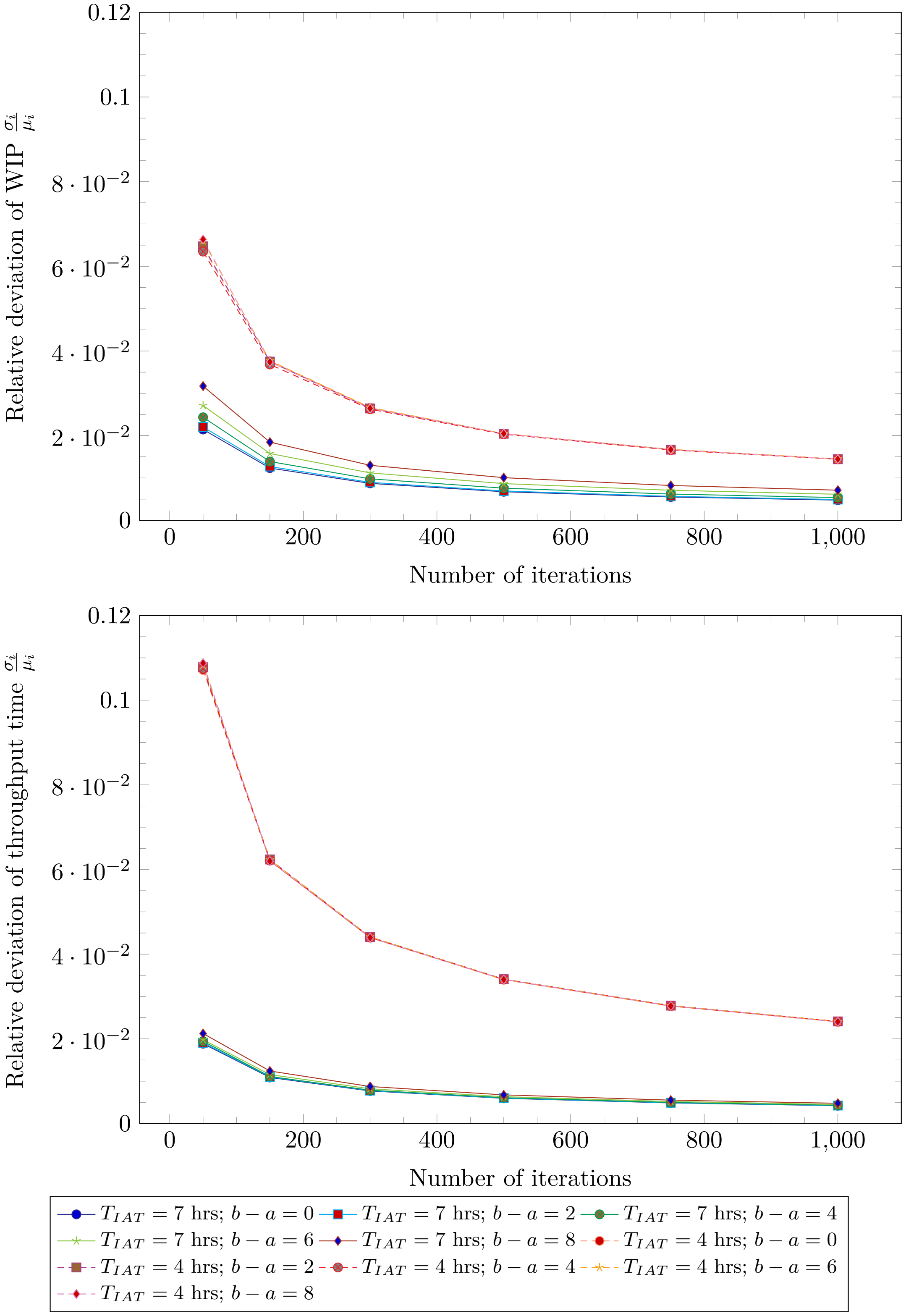


Figure 4-6: Relative deviance of WIP and throughput time over number of iterations for various uniform distributions, unif(a,b)

final value. The data set with IAT 4 hours and block distribution width of 8 hours. The shape of the curve was modelled as a power function given in Eq. (4-2).

$$f(x) = a(x-\tau)^b + c \tag{4-2}$$

Solving of the coefficients was been done with a Ordinary Least Squares (OLS) solver package of the Scipy library in the Python environment. Table 4-12 provides the resulting coefficients by the solver. With a squared sum of residuals of $5.8e-10$, this is considered a good fit. Figure 4-7 depicts the curve and resulting modelled fit. As the final value of coefficient of variance approaches zero, it was decided to pick the number of iterations directly from the graph. The majority of decrease can be seen after 400 iterations, that produces a coefficient of variance of 0.04 approximately. After 400 the number of iterations required to reduce 0.02 additionally was 2.5 as large. This was deemed very costly. The confidence intervals for several levels are given by Table 4-11. With an interval size of 0.66% of the mean sample size at confidence level $\alpha = 0.001$ the number of iterations is deemed sufficient for significant conclusions. Hence, **400 iterations** with a coefficient of variance of 0.04 was decided to be a decent trade-off between capacity and level of significance.

significance α	interval normalized $\frac{c_{int}}{\mu}$
0.001	0.006582
0.005	0.005614
0.01	0.005152

Table 4-11: Confidence intervals for IAT 4 hrs. and uniform width 8 at 400 iterations

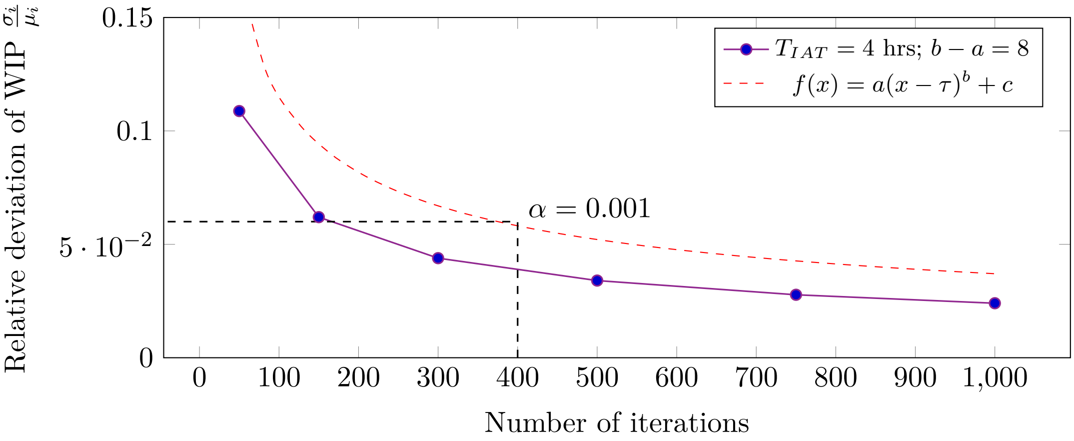


Figure 4-7: Experimental curve and power model for the solved parameters

a	b	c	τ	squared sum of residuals
6.6e-01	-4.7e-01	-1.7e-03	4.9	5.8e-10

Table 4-12: Power function coefficients of OLS fit and squard residual sum

Model validity

Ideally, the model output could be held against process data from the case under study, however as such detailed operational data was not yet available for the case's process, alternative ways had to be found to study the representativeness of the model for a MRO process environment. Literature describes behaviour, universal for production systems on numerous dimensions, validated in industry [27]. A comparison of model behaviour with the validated universal models could be used. Additionally, a live comparable system can be studied and compared to model results. This would require a process with the same characteristics for the generic MRO process and production control as stated in Section 2-1-3 and the case specific characteristics developed in Section 3-1. Both validation methods were applied and are described below.

Comparison to theory Earlier studies of the logistic curves in Section 2-2-3 relate the average WIP level to the throughput time of the system. From numerous studies regarding average WIP and throughput time is concluded that in any uncontrolled logistical system an exponential relation between throughput time and average WIP exists. Plotting the experimental data gathered in the verification on a logarithmic scale yields the graph depicted in Figure 4-8. Every data point corresponds with the incremental arrival rate of orders used in the input data set. It shows how throughput time increases exponentially with the average WIP level in the system after a sequential stable and transitional interval. This supports the proposition of the model being valid for a generic production system simulation according to the earlier mentioned logistic curves in Figure 2-5. In addition it can be seen that the WIP controlling configurations never reach the exponential growth of throughput time as their advance is limited by the maximum of average WIP imposed by the controller.

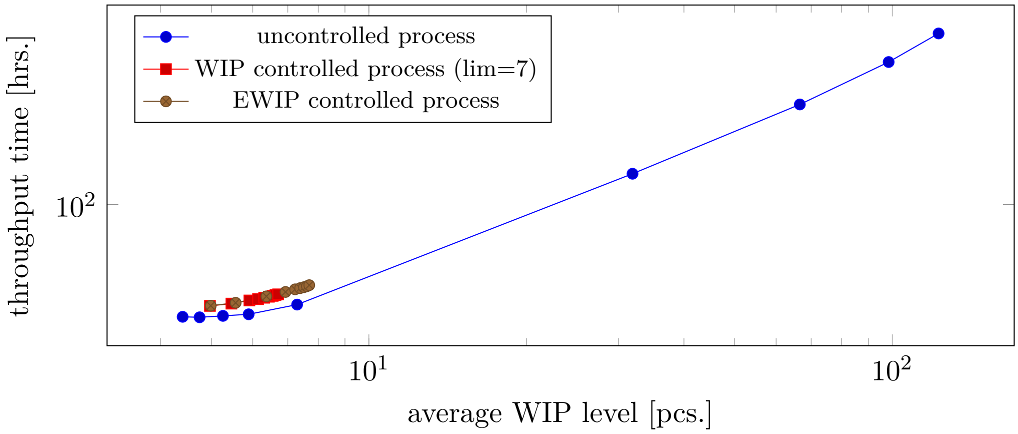


Figure 4-8: Throughput times of the control configurations over average WIP level

Real environment case The comparison to a similar system proved difficult. An attempt was made to find a MRO process with similar characteristics as the case under study, however, it was found that shop floors that do not have an official production control system implemented usually have a form of informal control regime that is difficult to model of characterize with the developed DES model.

4-4 Chapter summary

This chapter described the development of the evaluation environment that should answer the eight research question:

What is a performance testing environment to evaluate a production design?

The controller and parameter designs are evaluated for their logistical performance properties and their special ability for stability for internal detractors and robustness to external detractors. Evaluation of the logistic performance of a system was done by constructing a DES simulation model, with the python programming language and a special simulation package SimPy. The input-output model is coded in object oriented from and consists of a control module and a simulation module. The model was verified for proper functionality for all control configurations, including the option for no control. Expert knowledge has composed a data set that could not be validated for the planned application. As this was a greenfield design and no operational data was available to validate. The system did however show valid production system behaviour as described by literature. This means the a comparative study could be performed for the performance and system stability and robustness of the different control configurations.

Chapter 5

Evaluation experiments

With completion of the test environment, the proposed control configurations could be evaluated to study the ability of the design framework to produce production control designs that match the design requirements of the process as stated in Section 4-1-2. The evaluation of the designs was separated into the verification of the the control function and the verification of special design features. This chapter consists of three main sections. First the verification experiments are described in Section 5-1. Second, the experiment results are presented in Section 5-2. Finally, interpretations of the results are made and implications realized in Section 5-3. Here, also the implications for the Liquid Cooling (LC) process and the design framework in general will be considered.

5-1 Controller verification experiments

This section concretizes the evaluation strategy to experimental input for the evaluation criteria. It is important to ensure the design of the experiments enables unbiased comparison of the output. For this specific evaluation over a range of input must be studied to identify the behaviour and make significant comparisons. For this situation all criteria relate directly to the effect of the Work in Process level in the process. The evaluation experiments are described after their listing:

- Control function evaluation
  - Logistic objectives
  - Work in Process (WIP) control setting
- Feature evaluation
  - Robustness
  - Stability

Evaluation: Logistic objectives

The experiment studied the throughput time and throughput rate of the system over the range of interarrival times for the different control configurations (no control included). The range of interarrival time was taken somewhat smaller and centered around the transistion operational zone that appeared to occur between 5 to 4 hours interarrival time in the validation experiments. An overview of the intervals is depicted in Table 5-1. Unspecified parameters make use of the standard input data set given in Table D-1.

experimental interarrival times [hrs.]								
6.5	6.0	5.5	5.0	4.5	4.0	3.5	3.0	2.5

Table 5-1: Range of interarrival times for experimentation

Evaluation: WIP controller setting

This experiment evaluated the functionality of the control setting parameters for the WIP limit. By default this value was set to 7, but will be studied over a range of settings for the experimental inter arrivals range. The experimental range is given by Table 5-2. The remainder of parameters is set by the standard input data set given in Table D-1. As only the WIP controller has been fitted with such feature, only this configuration will be studied.

WIP limits [pcs.]				
5	6	7	8	9

Table 5-2: Range of WIP limits for the control setting functionality experiment

Evaluation: Robustness

The two main external uncertain factors appointed by literature are demand and work scope. Hence two experiments are conducted with both system configurations and the range of interarrival times. One adding variance to the arrival rate and one adding variance to the work scope of orders. This is done by increasing the respective coefficients of variance for the parameters under study over the experiment series. The coefficient of variance was chosen as it offers good comparability with other parameter variation [45]. Table 5-3 shows the range of coefficients used for both experiments. Table D-1 has been used for the remaining parameters. The range of interarrival times used in a series is given by table Table 5-1.

Coefficient of variance $\frac{\sigma}{\mu}$					
0	0.04	0.08	0.12	0.16	0.2

Table 5-3: Range of coefficients of variance

Evaluation: Stability

To evaluate the stability of both controllers the effects of errors in the planning estimates are studied for both control configurations. Due to the different working principles of the controllers, errors were introduced in the system in different ways, but will be rooted in an incorrect assumption on the incoming orders.

For the WIP control configuration the assumed order time is set under the systems design in the form of a norm time. The error is applied in terms of deviations from the true mean repair time of the incoming orders. Table 5-4 shows the error coefficient used.

The Equivalent Work in Process (EWIP) control configuration estimates the repair time required of every arriving order. The error of the estimation is modelled as a uniformly distributed probability with a coefficient of variance of $c_{var} = 0.12$ with a shift of mean value of all estimations equal to the fractions presented in Table 5-4. The width of the The other parameters for both experiments are set in accordance with the standard input data set in Table D-1. With the exception of the estimation error option, which is toggled on for these experiments.

Mean deviation by error				
-0.25	-0.1	0	0.1	0.25

Table 5-4: Deviation of the real mean as fractions of the set mean

5-2 Experiment results

Logistic objectives

Figure 5-1 shows the WIP level for the increasing interarrival time for the standard run time and iterations with the respective significant intervals given in Table 5-5 for the confidence level of $\alpha_c = 0.001$. The average WIP level is showed on a logarithmic axis as the uncontrolled process increases exponentially after the interarrival time drops below 4.5 hours. This diverging behaviour is also seen in Table 5-5 for the uncontrolled system. In both controlled configurations, the average WIP in the system exhibits asymptotic behaviour. In WIP controlled configuration the maximum average stays below the 7 orders level, which the controller is set to do. The EWIP control configuration allows for slightly yet significantly higher averages and is not bound by the hard limit of 7 orders. Additionally, before under loaded zone, the uncontrolled process exhibits a significant lower average WIP level compared to both its controlled counterparts.

The primary logistic objective for the system is due date reliability. Hence the throughput time was studied over a decreasing order interarrival time for the control configurations, as depicted in Figure 5-2. Table 5-6 shows the associated confidence intervals of the data with a level of $\alpha_c = 0.001$. Not all data points of the uncontrolled process are pictured. After 4.5 hours interarrival time of orders the throughput time rises unbound. This can also be seen in the table where, for the uncontrolled system where the confidence interval grows explosively. Both controlled systems rise to their respective asymptote over the decreasing interarrival

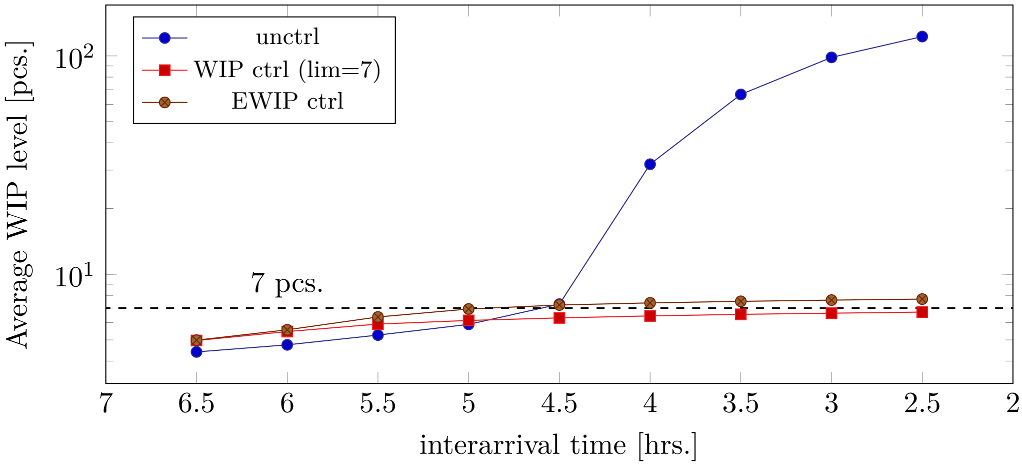


Figure 5-1: Average WIP levels of the control configurations over inter arrival time

	unctrl [pcs.]		WIP ctrl [pcs.]		EWIP ctrl [pcs.]	
IAT [hr.]	c_l	c_r	c_l	c_r	c_l	c_r
6.5	4.388	4.424	4.964	4.974	4.981	4.991
6	4.732	4.763	5.456	5.466	5.557	5.571
5.5	5.242	5.281	5.906	5.916	6.363	6.377
5	5.872	5.911	6.135	6.145	6.922	6.936
4.5	7.265	7.318	6.303	6.313	7.222	7.232
4	31.52	32.283	6.436	6.446	7.385	7.395
3.5	65.712	67.504	6.544	6.554	7.507	7.517
3	97.161	99.754	6.625	6.635	7.605	7.615
2.5	121.202	124.108	6.702	6.712	7.688	7.698

Table 5-5: Critical boundaries for $\alpha_c = 0.001$ and for the average WIP level in the control configurations

time. All systems cause additional delay on the minimum average of processing time required for orders (26 hours).

With regard to the secondary logistic objective, the influence of decreasing interarrival time on the bottleneck occupancy was for the control configurations was evaluated. Figure 5-3 shows the occupancy of the entire system in relation to the interarrival time of orders for the different control configurations with Table 5-7 showing the significance intervals for the data at a $\alpha_c = 0.001$ level.

All system configurations show increasing occupancy over the interarrival time decrease. The uncontrolled configuration shows a stronger increase and then more or less stabilizes over the interval 4.5 - 4 hours inter arrival time. After 4 hours additional increase is observed, with a final stabilization below 3 hours interarrival time. Both the controlled configurations show a more asymptotic behaviour for over interarrival time decrease. All configurations show significant difference from 6 hours of interarrival time and lower at a level of $\alpha_c = 0.001$.

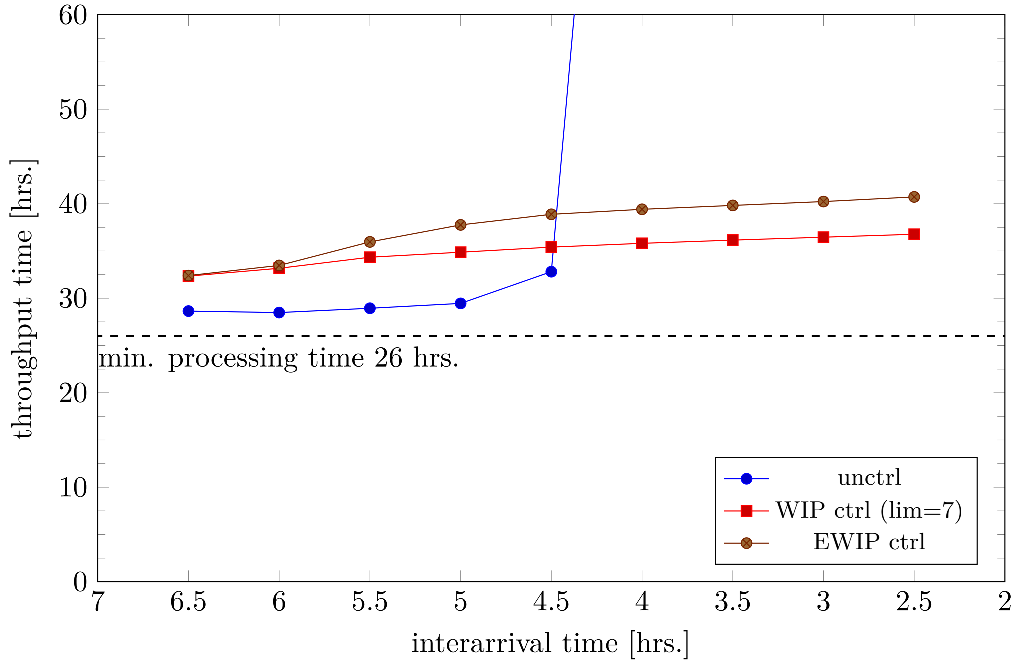


Figure 5-2: Average throughput times of the control configurations over order interarrival time

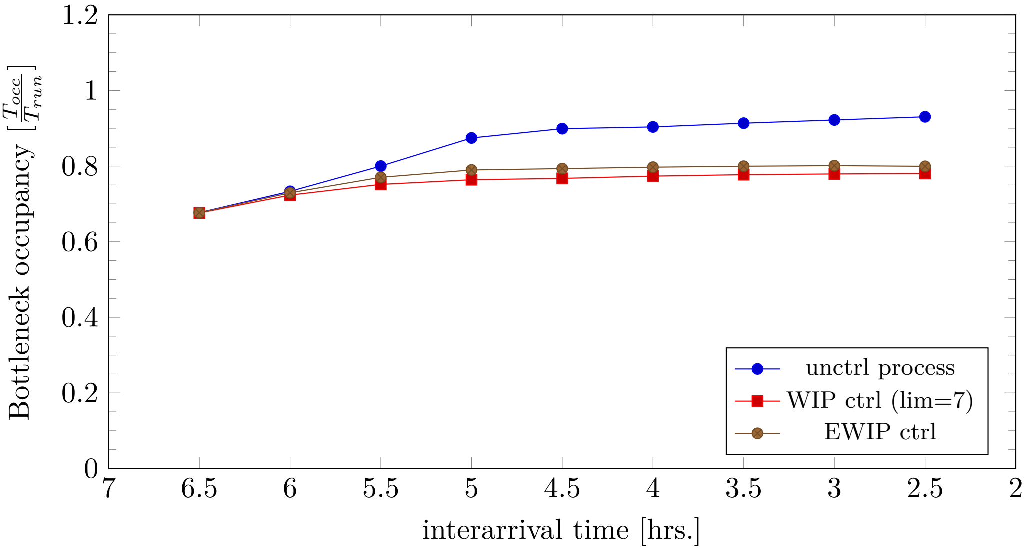


Figure 5-3: Bottleneck occupancies of the control configurations over interarrival time

	unctrl [hr.]		WIP ctrl [hr.]		EWIP ctrl [hr.]	
IAT [hr.]	c_l	c_r	c_l	c_r	c_l	c_r
6.5	28.557	28.72	32.3	32.38	32.36	32.44
6	28.413	28.556	33.126	33.214	33.423	33.517
5.5	28.861	29.016	34.292	34.388	35.901	36.019
5	29.369	29.535	34.821	34.919	37.696	37.824
4.5	32.686	32.931	35.359	35.461	38.816	38.944
4	138.982	142.376	35.758	35.862	39.344	39.476
3.5	299.837	308.389	36.097	36.203	39.752	39.888
3	480.325	494.903	36.405	36.515	40.16	40.3
2.5	660.125	680.143	36.715	36.825	40.65	40.79

Table 5-6: Critical boundaries for $\alpha_c = 0.001$ and for throughput time of the control configurations

	unctrl		WIP ctrl		EWIP ctrl	
IAT [hr.]	c_l	c_r	c_l	c_r	c_l	c_r
6.5	0.66	0.694	0.67	0.682	0.671	0.682
6	0.717	0.75	0.717	0.729	0.723	0.735
5.5	0.783	0.817	0.745	0.758	0.764	0.777
5	0.857	0.892	0.757	0.771	0.783	0.796
4.5	0.882	0.915	0.76	0.775	0.786	0.8
4	0.887	0.92	0.766	0.781	0.79	0.804
3.5	0.897	0.93	0.77	0.784	0.793	0.807
3	0.906	0.938	0.772	0.786	0.794	0.808
2.5	0.915	0.946	0.774	0.787	0.792	0.806

Table 5-7: Critical boundaries for $\alpha_c = 0.001$ and for bottleneck occupancy of the control configurations

WIP controller setting

Repeating the experiment series of changing interarrvial time for the WIP control configuration over a range of WIP limits reveals the influence of the limit setting on the production system dynamics.

The graph in Figure 5-2 shows the throughput time for the control system setting of and the normalized differences between the adjacent series results in relation to the one-sided critical boundary of the significance level. Small variation in throughput time is observed in the region 6.5 to 5 hours of interarrival time. At 4.5 and lower the difference between the series becomes significant.

Figure 5-5 shows the bottleneck occupancy in for the different limits. All series show a asymptotic behaviour with the lowest limit realizing the lowest occupancy ranking up with the limit values until the limit reaches 7. After this point no significant difference can be concluded at the confidence level of $\alpha_c = 0.001$.

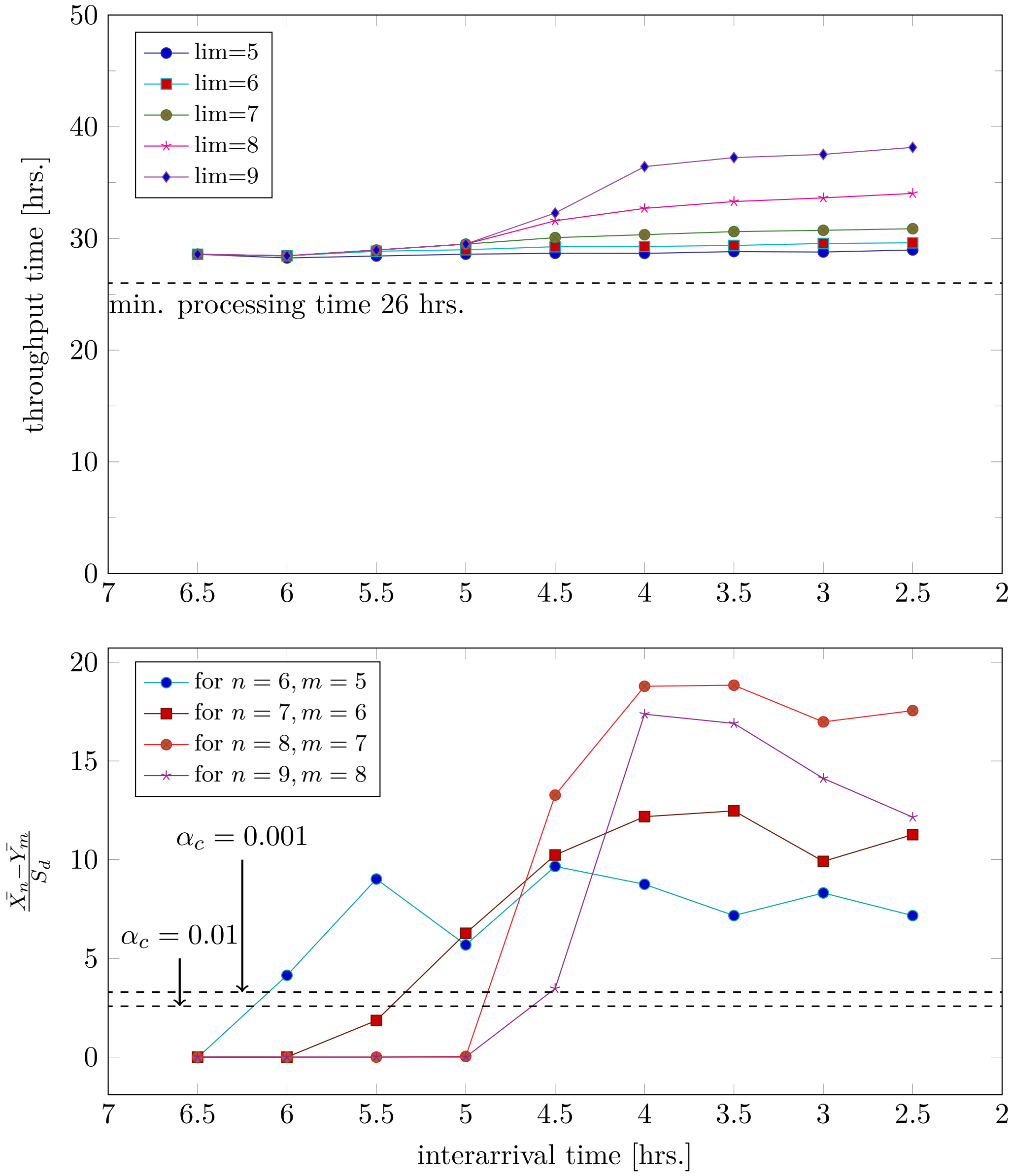


Figure 5-4: Throughput times and single sided levels of significant difference for WIP control configurations over various WIP limits

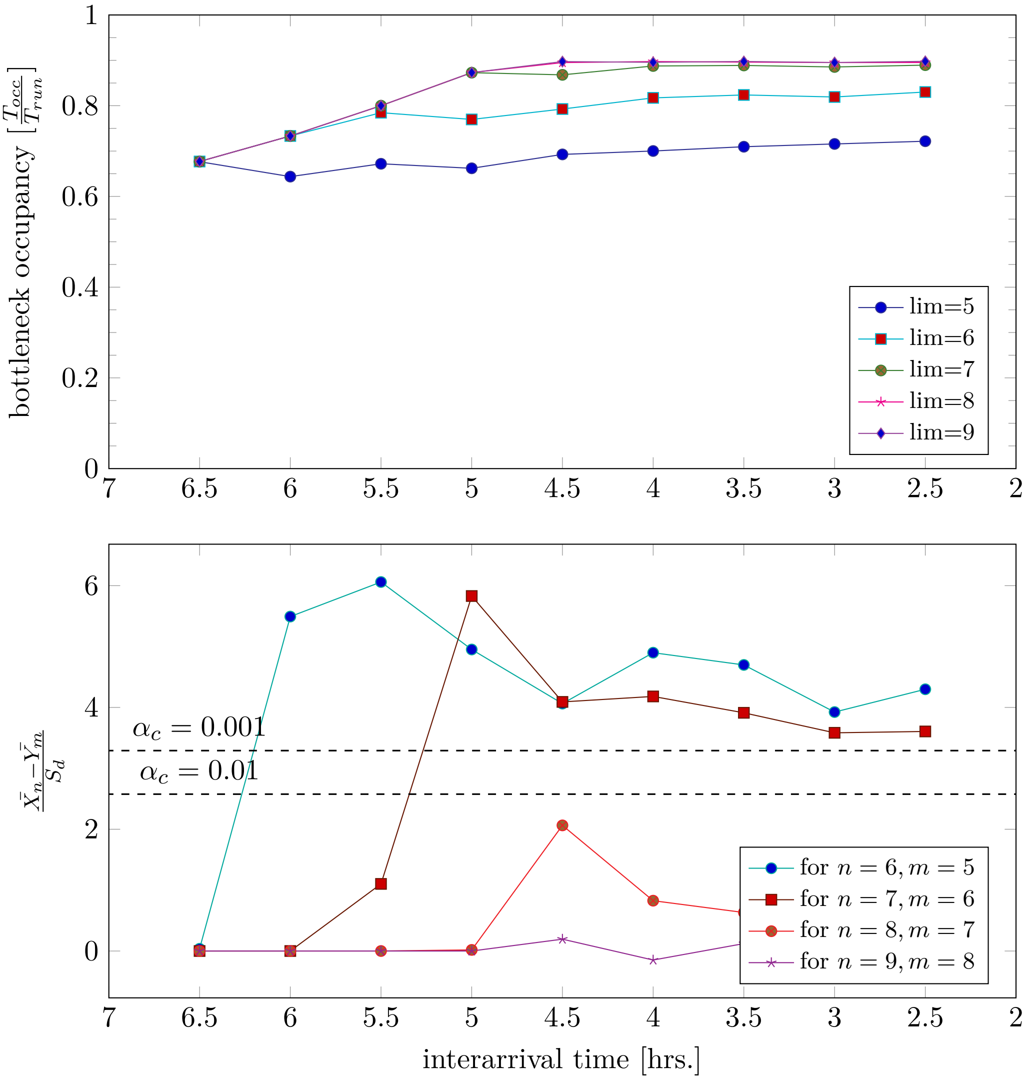


Figure 5-5: Bottleneck occupancy and single sided level of significance of the normalized difference for the WIP control configuration over various WIP limits

Robustness

Robustness was evaluated by observing performance of of the controller configurations with the interarrival time series under the influence of increasing variance in repair processing time (representing the work scope). The effect is studied for each configuration separately.

WIP control configuration Figure 5-6 shows the throughput time for the experiment series with different levels of repair time variance for the WIP control configuration. The series show to be clustered starting at 6.5 hours and increasing with decreasing steepness curve until 3.5 hours of interarrival time. Up until value of the interval the cluster is structured, meaning that for each interarrival time value, the values of throughput time are sorted from least variance to highest variance in increasing order of throughput time. Evaluating the normalized differences between the adjacent series reveals the difference between the series are significant for a level of $\alpha_c = 0.01$. After the 3.5 arrival interval the upper three variance series drop as one cluster steeply to the starting level. The remaining two show a similar clutered drop after 3 hours of inter arrival time. Within the sub clusters the distance between the series remains significant. Only the control series continues the increase of interarrival time.

Figure 5-9 shows the bottleneck occupancy for the experiment series. The series shows the same clustered behaviour as the throughput time values, but inversed. The highest variance results in the lowest occupancy and vice versa. The sudden behaviour of the subclusters at the end of the interarrival time range is also seen. Analysing the significant distance between the adjacent series reveals that the series are different for a significance level of $\alpha_c = 0.01$.

EWIP control configuration Figure 5-8 shows the throughput time for the experiment series with different levels of repair time variance for the WIP control configuration. The series appear ordered in a cluster with the highest variance showing the highest throughput times and the absence of work scope variance the lowest throughput times. The difference between the adjacent series appears significant at level of $\alpha_c = 0.001$, with the exception of coefficient of variance 0.4 and 0.5 for 6.5 hours of interarrival time. over the interval 5.5 to 4 hours the whole cluster appears to inverse the ordering and than change back to original after 4 hours interarrival time and then diverges as interarrival time decreases further.

Figure 5-9 shows the bottleneck occupancy for the experiment series. Yet again the series are clustered in order of variance level with the highest occupancy realized for the the least variance. The cluster follows a curved path downward over the decrease of interarrival time and diverges significantly for the level of $\alpha_c = 0.001$ over the trajectory.

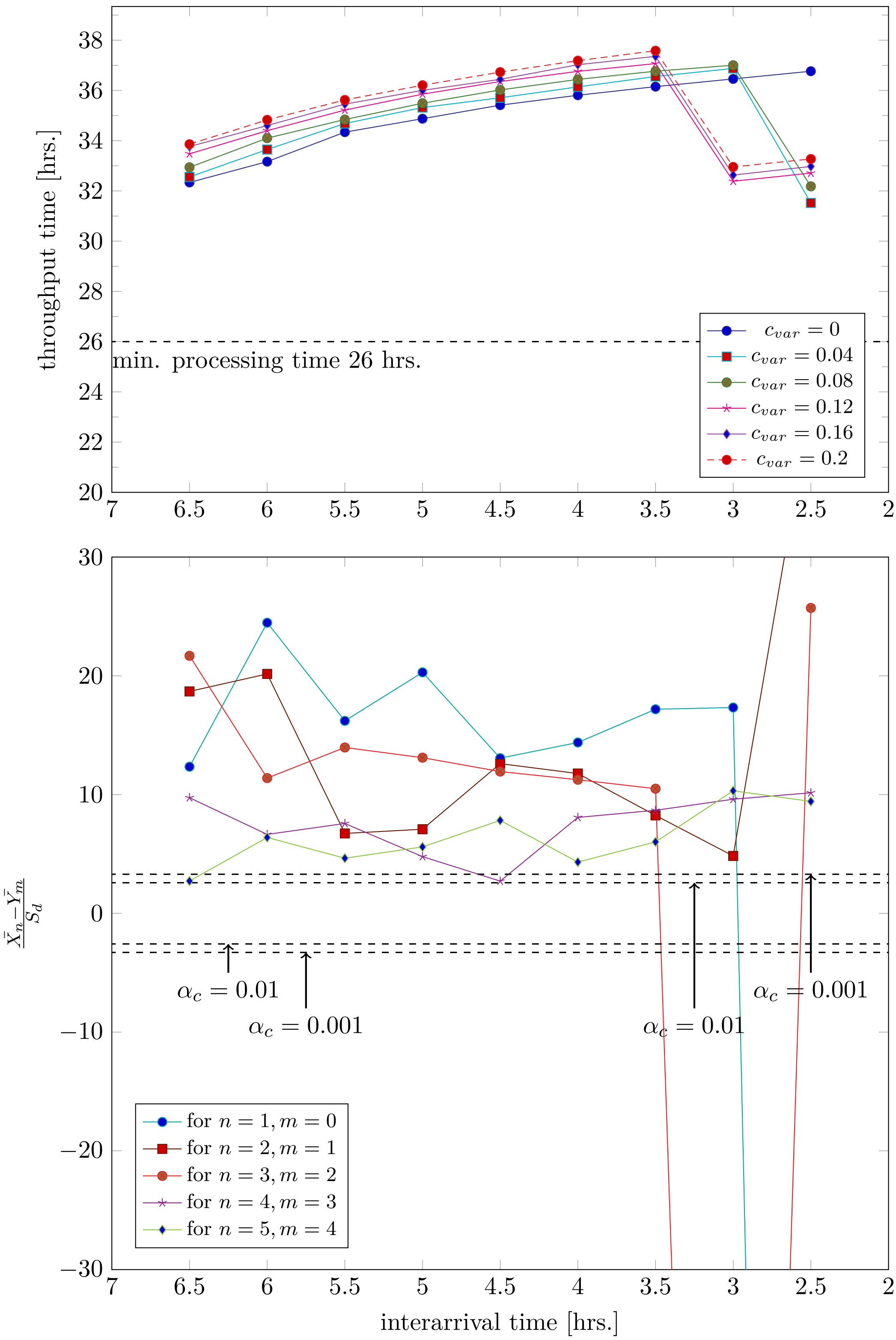


Figure 5-6: Throughput times and single sided level of significance of the normalized difference of the WIP control for work scope variance with $WIP_{lim} = 7$

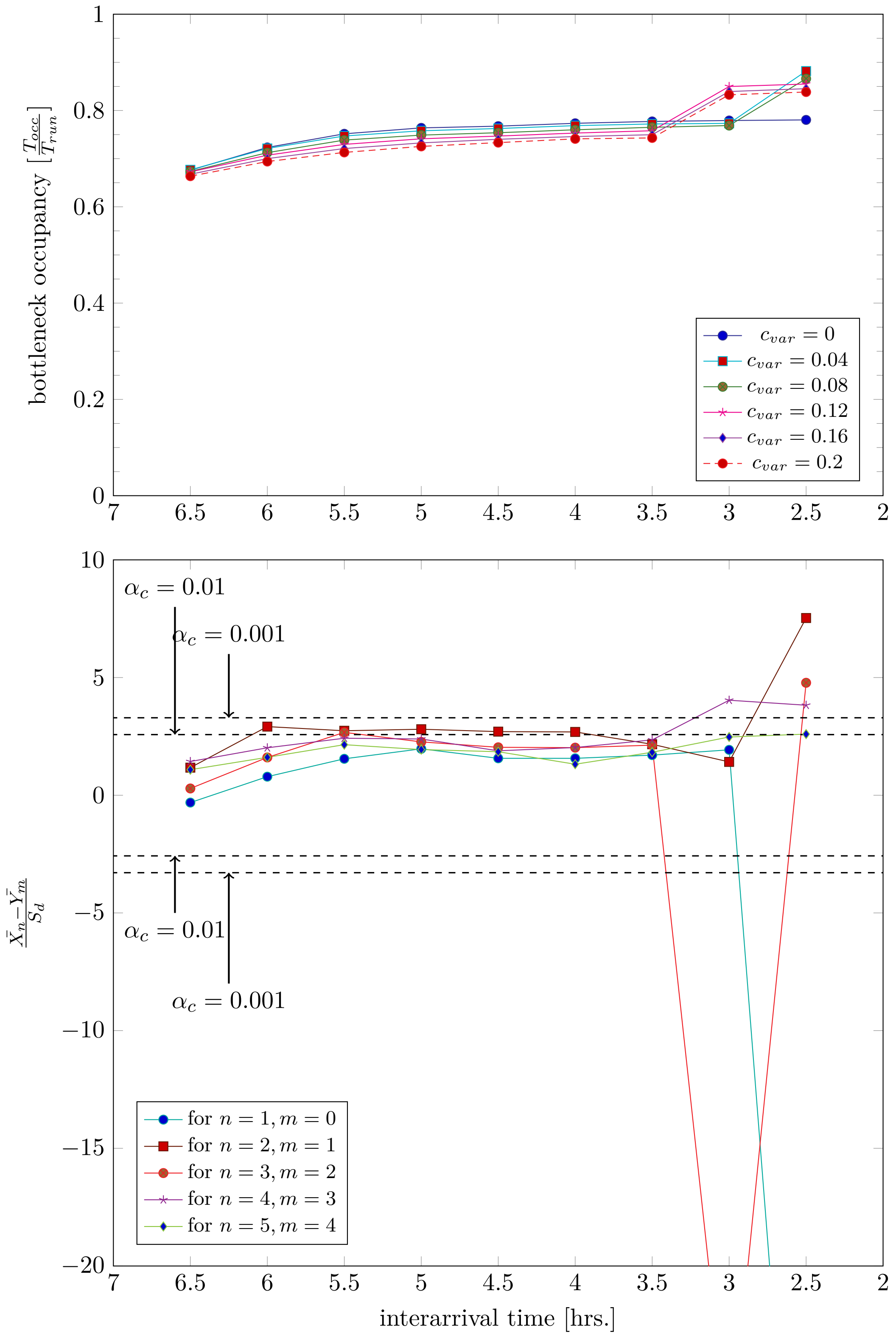


Figure 5-7: Bottleneck occupancy and single sided level of significance of the normalized difference of the WIP control for work scope variance with $WIP_{lim} = 7$

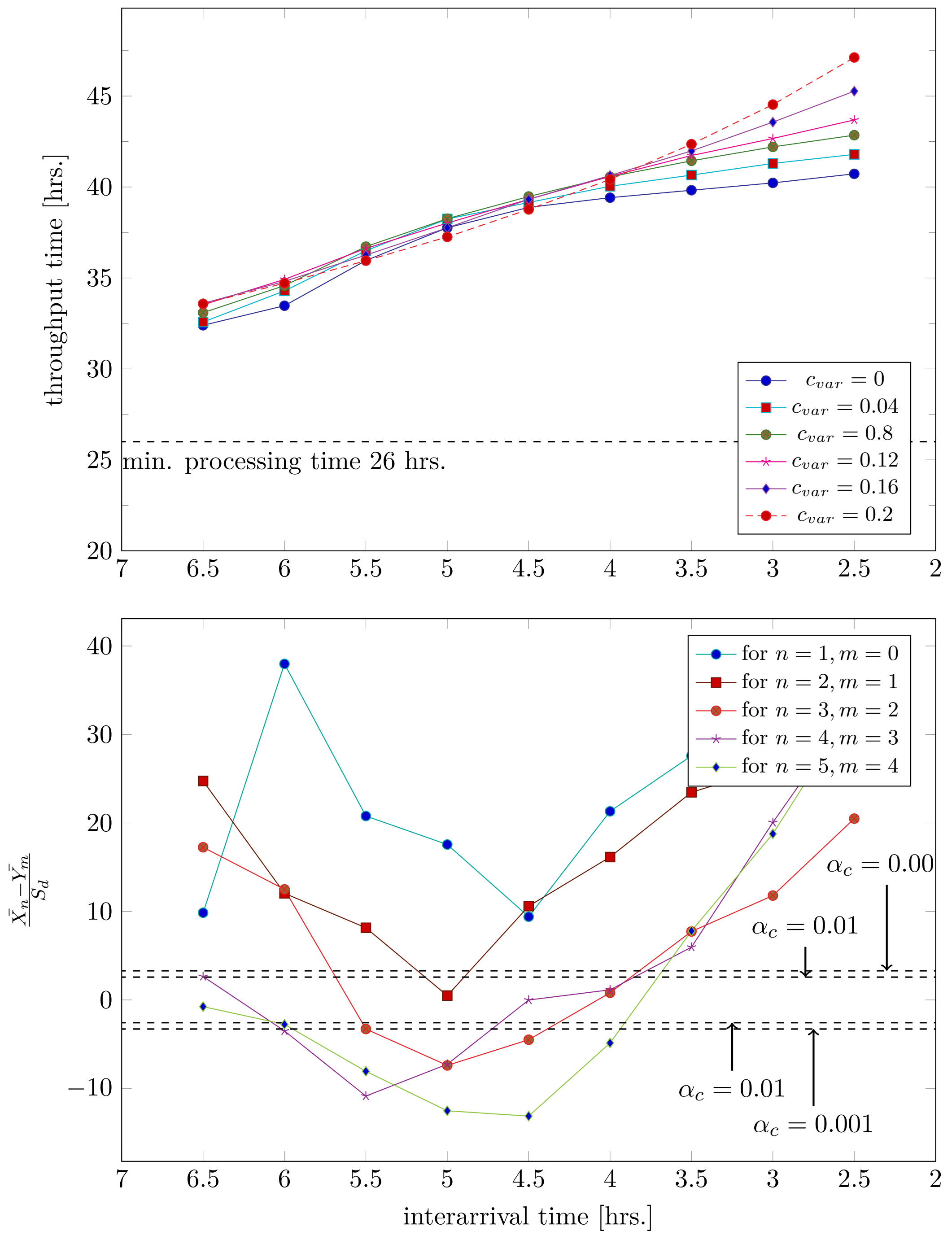


Figure 5-8: Throughput times and single sided level of significance of the normalized difference of the EWIP control for work scope variance

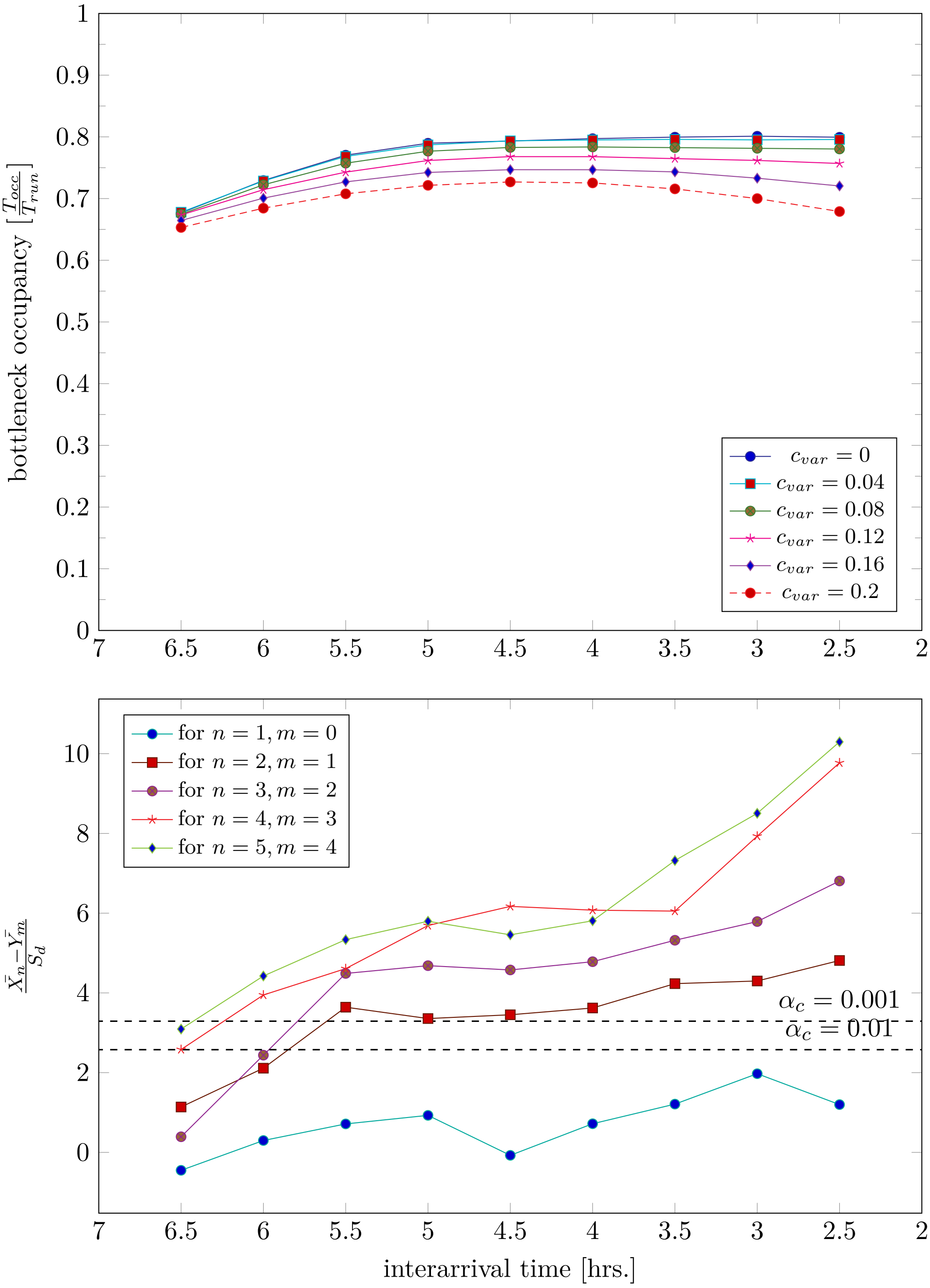


Figure 5-9: Bottleneck occupancy and single sided level of significance of the normalized difference of the WIP control for work scope variance with $WIP_{lim} = 7$

Stability

Robustness was evaluated by observing performance of of the controller configurations with the interarrival time series under the influence of increasing variance in repair processing time(representing the work scope). The effect is studied for each configuration separately.

WIP control configuration Figure 5-10 shows the throughput times for the experiment series with different coefficients of error on the mean repair time assumption for the WIP control configuration set with a WIP limit of 7. The different series show a structured cluster where a shorter assumed mean time results in higher throughput times and longer assumed means in shorter throughput times. Evaluating the adjacent significant differences between the series reveals that for a level of $\alpha_c = 0.001$ for lower assumed mean the difference with the no assumption error results in a significant difference after 5.5 hours inter arrival time and lower. It is remarkable to see that there is no significant difference between the lower assumed mean series. An erroneous higher assumed processing time is significant for an error coefficient of $c_{err} = 0.25$ after 6.5 hours of interarrival time. With the series of $c_{err} = 0.1$ showing no difference with the scenario without assumed error.

Figure 5-11 shows the bottleneck occupancies for the experiment series. An erroneous mean shorter than the real mean results in a high occupancy rate for the bottleneck station. As with throughput time, the both series with a smaller assumed mean score no significant difference between them but are both significantly different from the standard scenario with a confidence level of $\alpha_c = 0.001$ after 5.5 hours of interarrival time. For the higher erroneously assumed mean series no significant difference is seen for $c_{err} = 0.1$. The higher error shows significant difference 6 interarrival time and lower.

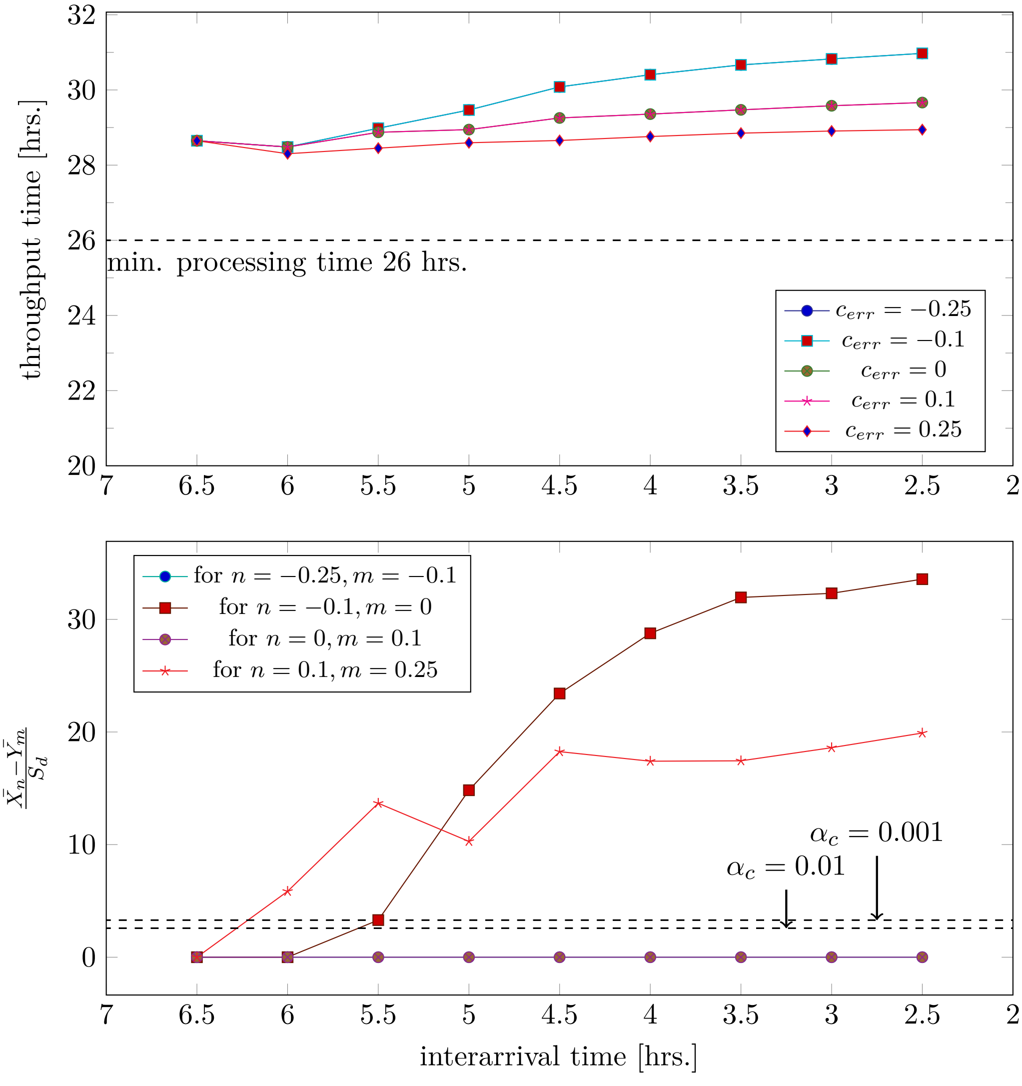


Figure 5-10: Throughput times and single sided level of significance of the normalized difference of the WIP control for mean deviance by error with $WIP_{lim} = 7$

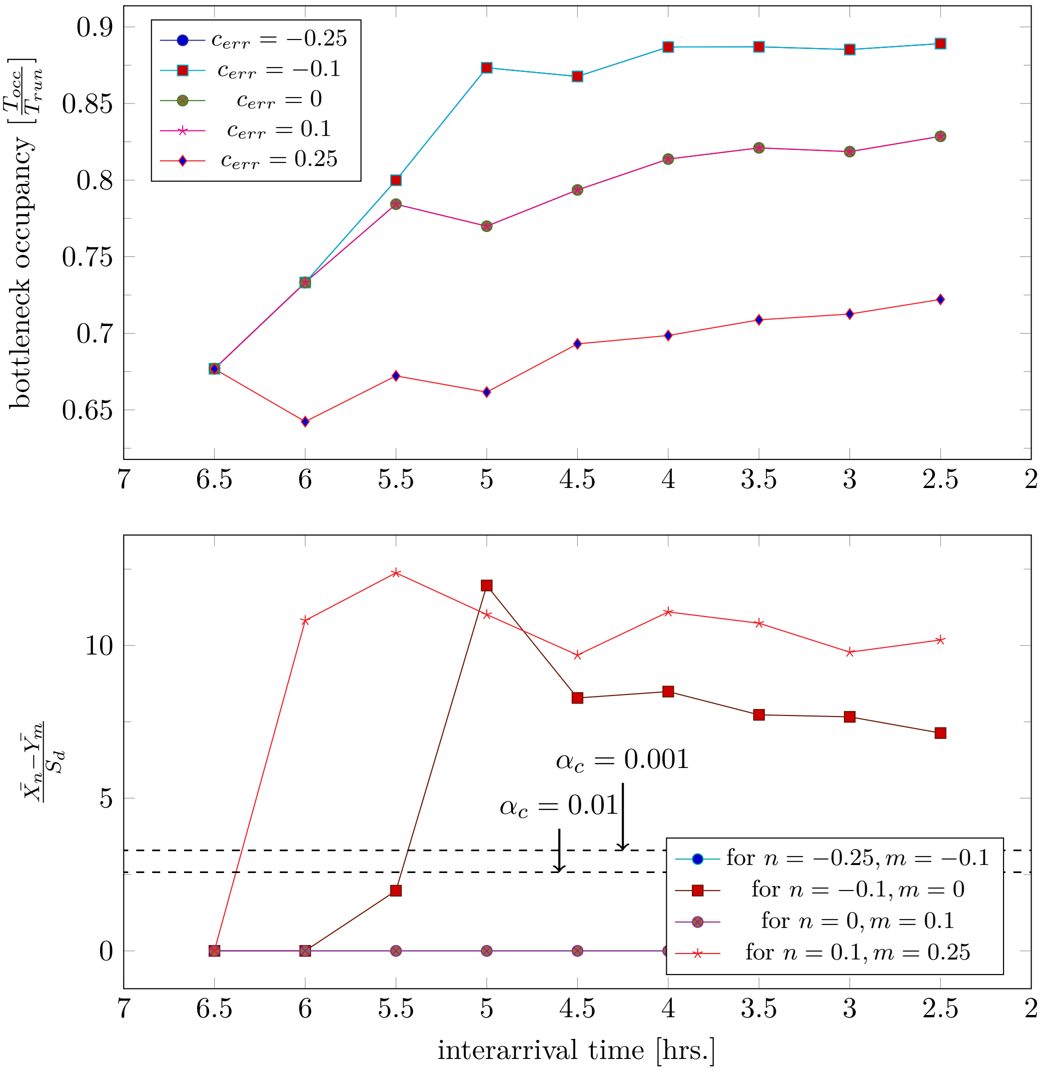


Figure 5-11: Bottleneck occupancy and single sided level of significance of the normalized difference of the WIP control for mean deviance by error with $WIP_{lim} = 7$

EWIP control configuration Figure 5-12 shows the throughput times for the experiment series with different coefficients of error for the repair time estimate of each individual order for the EWIP control configuration. The different series appear in a tight cluster slowly descending whilst gradually diverging as the interarrival time decreases. Evaluating the significance of the difference of adjacent series reveals that the difference between the series is hardly significant. At a level of $\alpha_c = 0.1$ the difference between the 0 error scenario and both positive and negative coefficient of 0.1 becomes significant only after 3 hours of interarrival time and lower.

Figure 5-13 shows the bottleneck occupancies for the experiment series. The very same behaviour as seen in the throughput times can be seen here. Yet the series cluster increases slightly for decreasing interarrival time. With shorter assumed processing time resulting in higher bottleneck occupancies and longer assumed processing time resulting in lower bottleneck occupancies. The difference however is somewhat more significant at the level of $\alpha_c = 0.1$ below an interarrival time of 3.5 hours.

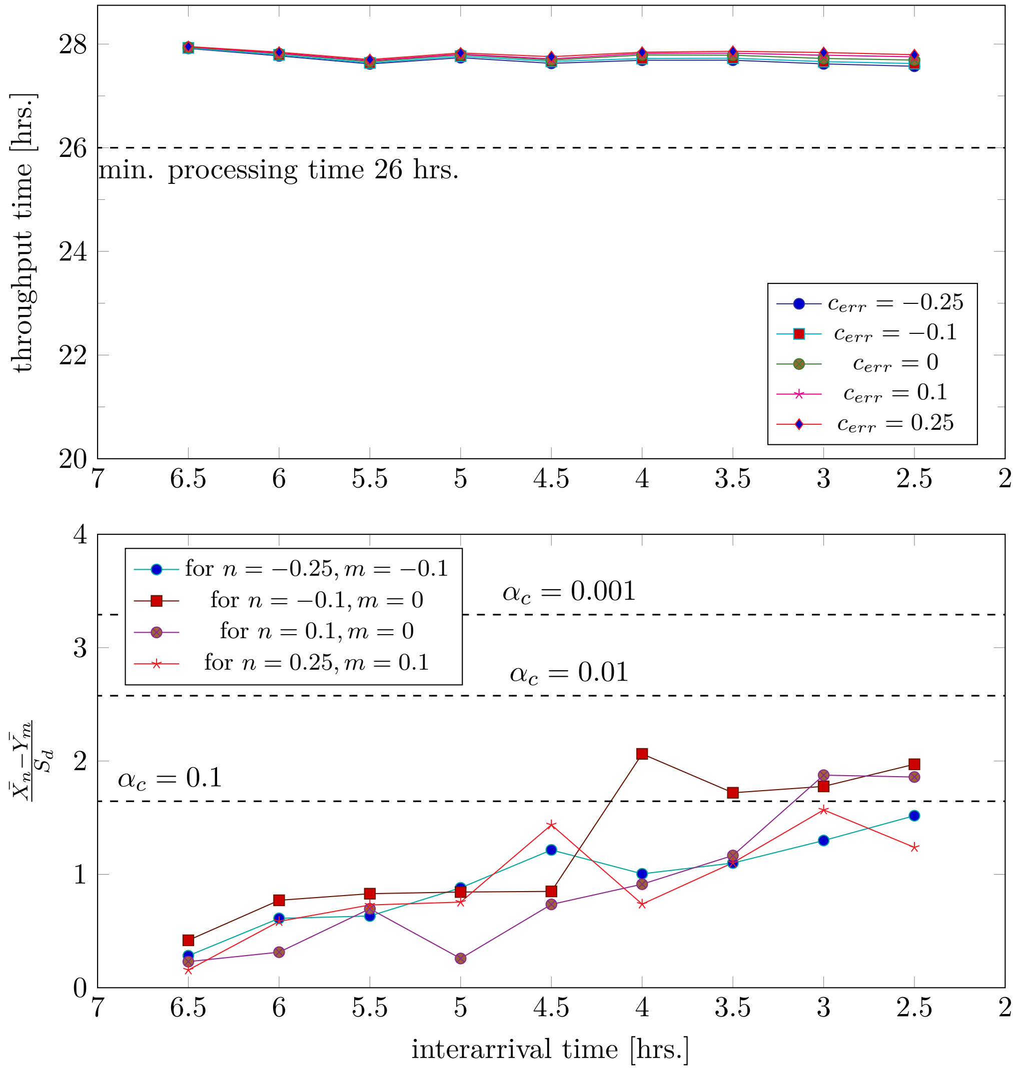


Figure 5-12: Throughput times and single sided level of significance of the normalized difference of the EWIP control for mean deviance by error

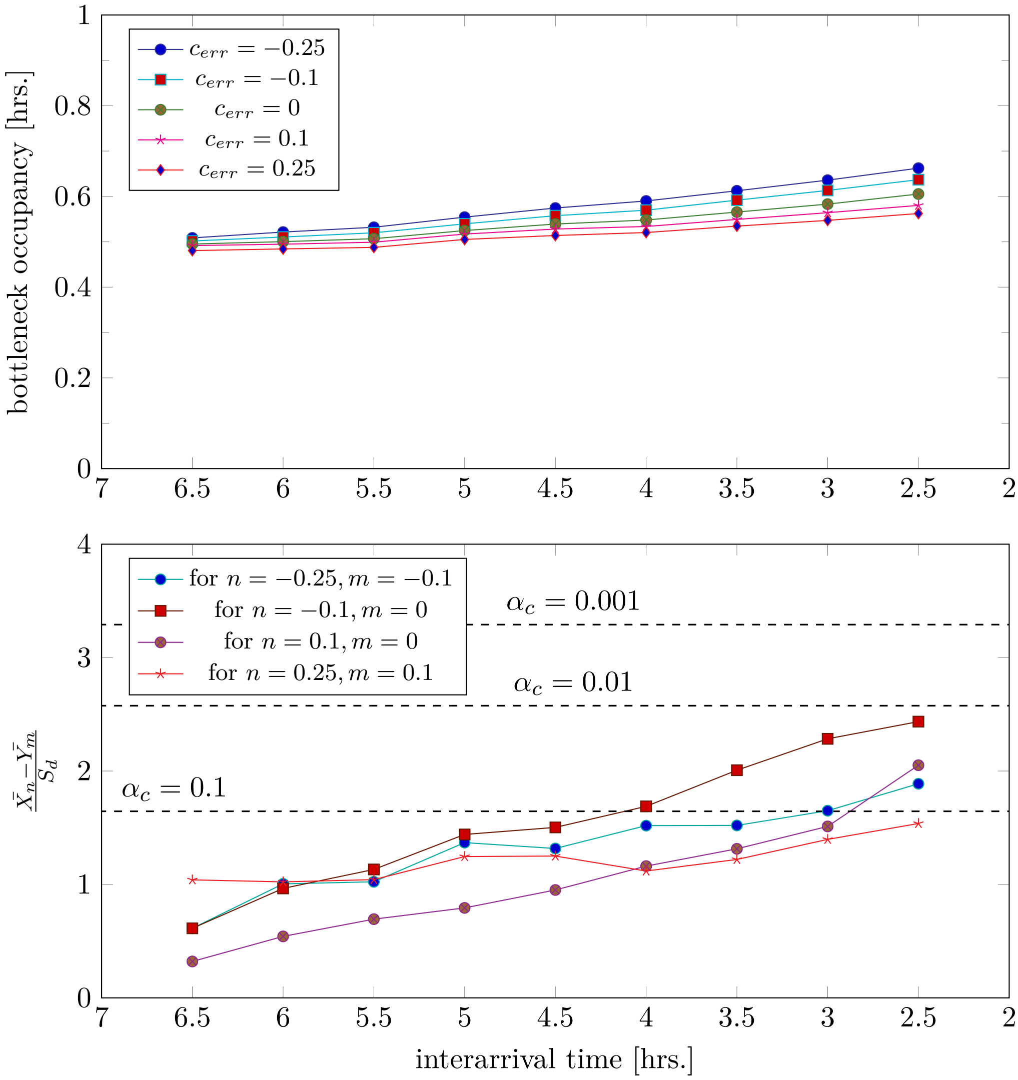


Figure 5-13: Bottleneck occupancy and single sided level of significance of the normalized difference of the EWIP control for mean deviance by error

5-3 Evaluation of results

The results presented in this chapter have implications with regard to various research components and goals. These are discussed in this section by their respective impact area.

5-3-1 Implications for the Discrete Event Simulation (DES) simulation

The use of DES modelling for the evaluation of logistic environments is a much used technique to evaluate performances of a wide range of production related subjects. The current developed DES model shows good conformity to the intended design in all verification experiments.

Additionally, the use of high number of repetitions shows a significant effect on the final values of the system under study, in the case the respective value converge to a final value. Would the configuration cause the parameter to diverge over simulation time, the use of more iterations would not increase the exactness of the result significantly.

However, modelling an environment also requires careful validation of the used model. Validating the model for a general logistic environment allows for studies regarding general logistic systems. The specific characteristics that separates an environment form the general accepted circumstance must therefor be studied in relation to their effects of the model. Hence, the model may not be considered valid for conclusions on the Maintenance, Repair & Overhaul (MRO) process environment at KLM Engineering & Maintenance (E&M) in particular, until the relation between the generic knowledge and the specific environment is known or the model could be validated for the specific environment.

5-3-2 Implications for the control configurations

Applying the control configurations to modelled process shows good response in the performance parameters. The interarrival time at the system is of major influence on the performance parameters and the control of both the WIP and EWIP variants regulate this value effectively. Not controlling the interarrival time will lead to order accumulation in the system and exponential growth of throughput time of the process. This exponential growth will occur after the interarrival time falls below a transition range. Before this interval both throughput time and average WIP level are lower in the uncontrolled system. This was to be expected as both control systems regulate order acceptance and release based on system state causing minor delays in flow, raising both throughput time and lowering the maximum throughput capacity of the system.

Remarkable is the fall of throughput rate for the uncontrolled system, would the interarrival time advance beyond the transition interval the rate would slowly decrease to eventually fall below the rates of both controlled configurations. This was not described in theory studying simulations of general production systems. These are of linear configuration, where this process design has a loop configuration, which is known to incur more complex behaviour. One possible explanation could be the First-in-first-out (FIFO) policy for every station queue, applied when no control is specified. In the specific system, the station queue where the two product flows merge will be filled at bottleneck production rate from the loop flow and at interarrival time from the process in-flow. This queue is moves at the flow merger station process rate. Would the interarrival time increase beyond the process rate of the merger station, an overfilling situation occurs before this station and the loop flow components would be delayed once more, causing an additional reduction of output. As the rate is calculated by the total components leaving the system over time, this progressive delay causes the rate to drop as interarrival time decreases further. This stresses earlier findings that looping of logistic flows is highly undesirable form a process control perspective.

Work in Process versus Equivalent Work in Process

Both controller show their stabilizing potential in the performance verifications. WIP control outperforms EWIP slightly on throughput time average, but can realize less throughput in total orders. Additionally can be seen that WIP is less affected by increasing order size variance than WIP is. From a robustness perspective it would therefore be advisable to implement the WIP regulating configuration, given the criteria.

Figure 5-4 shows how the behaviour of the WIP control system could be altered by adjusting the control settings. The proposed EWIP does not have this kind of feature as the limit is dependent on the individual sizes and machine and manhour scheduling and should therefor be self regulatory. However would a change in system behaviour be desired, no such feature is available.

From a robustness and stability perspective both configurations show opposing behaviour for both throughput time and bottleneck occupancy. The WIP configuration performs superior to EWIP when confronted with increasing external variance. Both systems show a slight decrease in overall performance when the arrival rate intensifies, but WIP manages to hold a regressive increase over increasing intensity where EWIP shows an progressive increase over increased intensity where higher variance results in less even worse performance for EWIP. For WIP control the difference for higher variance is less significant.

For stability the performance is exact opposite, with WIP clearly showing worse performance as the internal error increases. With bottleneck occupancy being the most affected, resulting in a lower general throughput of orders. The effects become apparent at a low arrival intensity. EWIP shows superior for the resistance against internal error for both throughput time and bottleneck occupancy, with hardly any significant difference over the increasing errors.

5-3-3 Implications for the LC process

The model and input configuration could not be validated for the performance environment. This means that in terms of performance parameters, little can be concluded on the ability of the control system to reach the desired performance objectives. However, the design criteria regarding stability and robustness are inherent properties of the system, rather than abilities to reach certain goals. As the model was validated for these properties, the results regarding robustness and stability are regarded valid.

The results of robustness and stability evaluation show how variance of order size does influence the throughput time in the system, but has a less effect than the average WIP level demonstrated in Figure 5-1 and Figure 5-4. This means that a design cannot be selected before a priority ranking has occurred between stability and robustness.

5-3-4 Implications for the design framework

The application of the design framework on the LC case at E&M resulted in the process and control system designs that were studied by the experiment. With the confirmation of the applicability of the control system for general logistic systems, it has been shown that the framework does indeed produce functional control configurations for the design criteria of the test case. It showed that in the special case for stability and robustness, an additional criterion must be added to differentiate between a design promoting stability and a design promoting robustness.

As the model could not be validated for the specific performance environment it remains inconclusive whether the framework is applicable when a specific performance must be obtained. Processes with matching behavioural criteria, however, should produce functional control system designs.

All the implications should be considered in the design regarding the logistic performance of the process and production control design. Performance of the process itself is a different subject of study. The relation between process driving information on logistic performance, has been shown in the evaluation, but the potential for the quality restoration function of the process has not been assessed. Given the nature of what quality performance in a quality restoration process comprises, it should be evaluated as a different research subject.

Chapter 6

Conclusion and recommendations

This study was finalized with the conclusion that answers the main research question presented here. Limitations of the framework and designs developed are developed. Their relation to science and practice are discussed. This chapter is closed with recommendations on how to continue the development of knowledge regarding the subject of production control design.

6-1 Conclusion

This study was conducted to answer the following main research question:

> *How is an information integrated Shop Floor Planning and Control system designed for component Maintenance, Repair & Overhaul in a green field process design situation?*

The answer was developed by the evaluation of the following aspects:

- Identification of the criteria for information integrated production.
- Development of a process and production control model that integrates the information dependencies for the Shop Floor Planning and Control (SFPC) system
- Robustification of the control signals of the control system design.
- Evaluation of the control system design and final answer to the main research question.

6-1-1 Criteria for information integrated production control

To construct a component Maintenance, Repair & Overhaul (MRO) process and production control system that integrates the information requirement of production control in a greenfield design situation, the following criteria need to be defined:

- component supply chain context of the process
- prime logistic performance objective
- component quality state parameters and their information quality requirement
- design characteristics for production control

Additionally, due to the lack of characterization abilities of logistic properties of the process, the design should be constructed for robustness against external variance and stability for internal occurring variance.

The case study is applied to the Liquid Cooling (LC) component process that was under development at the time of this study. The process was intended to be performed completely separated from the component supply chain, meaning component and information enter the process via the same portal at the same time instant. The business case required the component to attain a specific Turn-Around-Time (TAT) and hence due date reliability was the prime logistic target. The initial component quality was represented by the inverse time required for restoration of *serviceable* state of the component. A high-quality corresponds to a low repair time. Finally, the design characteristics for production control were concluded as shown in Table 6-1.

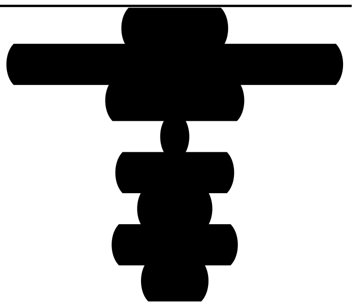
Criterion	Character
Manufacturing principle	
Type of production	
Part flow	
Variants	
Flow complexity	
Variance of load	
Capacity flexibility	
Load flexibility	

Table 6-1: Design characteristics for the production control configuration of the LC process

6-1-2 development of the process and production control model

With the criteria for the control system defined, a detailed design was developed by following the steps of the experimental design framework:

1. Development of Key Performance Indicator (KPI)'s for the logistic process
2. Development of the logistic process model derived from the generic MRO model
3. Development of the process information structure and linking of internal dependencies
4. Linking the external dependencies from the information structure to the supply chain
5. Characterization of information quality

6. SFPC system configuration
7. Development of production control information structure and dependencies
8. Robustification of the production control model

The final control system design consists of clear overviews of the goods and information flows that occur in the process under operation. The control information regarding component quality type must be identifiable as dependent or independent. In addition, the set values for the control configuration must be explicitly identified.

At KLM Engineering & Maintenance (E&M) the prime logistic KPI used to evaluate performance is On-time performance (OTP), which is the fraction of orders delivered within contracted time over all orders accepted. The prime logistic target is expressed in average throughput time. An additional logistic target was concluded to be the maximization of throughput of total orders of the system, which can also be measured over time directly. The development of the logistic process, information structure and information quality resulted in a production system configuration based on Work in Process (WIP) and bottleneck control. Figure 3-8 provides a schematic overview of the complete process control including the control system elements and sequencing policies. The overview is depicted in VSM-i configuration to clearly separate between information and goods flow.

Robustification was achieved by modifying the determination of system load from using WIP to using Equivalent Work in Process (EWIP). WIP is expressed in order quantity and EWIP is expressed in the capacity requirement of an order. It is found that this expression of system load is more constant when orders are expressed in their equivalent capacity requirements, rather than just the quantity.

6-1-3 Evaluation and answer to the main research question

Both control configurations were evaluated for their performance and conformity to the design criteria in a verified Discrete Event Simulation (DES) model. Both WIP and EWIP proved able to control the WIP in system for the test case, and by doing so, kept throughput time at stable levels yet showing significant difference for the prime logistic objective and their response to the internal and external variance. Given that the WIP was stabilized, a maximum throughput rate was kept and would the arrival of orders intensify beyond this rate, all additional orders had to be outsourced. The DES model could not be validated for the MRO performance environment, only the theory for prescribing the general logistic curves for production systems. Hence, the DES model could not be used to evaluate the exact performance of the system in the E&M performance environment. However, this should not dismiss the framework's ability to produce functional designs for production systems. As the framework does not design for a specific performance quantity, but general controller dynamics specified by the specific design criteria. The control system designs both showed their conformity to the criteria by the verification. Herefore both are considered applicable control models for the case study and processes answering to the same characteristics of the LC process.

This provides the answer to the research question: *First, an SFPC system can be designed by a framework that characterizes the logistic requirements. Secondly, it identifies the information* *requirement for the logistic process. Thirdly, it develops a clear process model that separates process drive information from the logistic goods flow to visualize information dependencies. Hereafter the production control can be configured by the configuration framework by Lödding for the dependencies and the production criteria of the environment and additionally, considering system robustness and stability and finally, the control settings can be robustified by using the Taguchi approach to parameter definition to further increase robustness and stability of production.*

6-2 Discussion

Several remarks regarding this study could be made regarding the framework evaluation and the control system evaluation:

Limitations of framework

The framework collects several methods for smaller design challenges of the entire control problem and pioneers the Taguchi method for the development of the dimension of control parameters. The parameter design approach in the Taguchi method is profound in its results for design of products and their production process parameters. However, the use of the method to control the process is sparsely used. In this study its intended use was to improve robustness of the process in a general sense. Evaluation of "robustness" revealed two subcategories. The performance of the robustified design showed worse performance for one category and improved performance for the other. It remains to conclude that the exact effect of the "robustification" of control parameters is yet not fully understood. It therefore should be evaluated thoroughly whether the parameter design approach is indeed applicable to the chosen control parameter design and what the separating criteria are for stability improvement and robustness improvement by Taguchi's method for parameter design.

Limitations of controller designs

This study assumes the variance of the work scope to be uncontrollable at a shop floor level. Throughout the study this is a general assumption for MRO processes. However, recent work has shown by filtering work scope within a certain time band, that the process becomes more controllable [42] Additionally, with the development of *probabilistic techniques* and *machine health measurement*, component state quality could be concluded much earlier in the process, increasing the actuality of control information, hence improving overall controllability of the MRO process. The framework has been designed to accommodate this, however with the used case study, this was not possible due to the lack of IT-structure throughout the supply chain. It does not exclude the potential of the framework to achieve this goal (better process controllability) but does not support this either.

The test case performed at E&M for a process under development. This study resulted in a qualitative answer to the control system question. This leaves several important questions unanswered regarding the quantitative performance and prerequisites for proper process performance. Additionally, the EWIP configuration does not include a control system setting for adjustment of the reference signal. Where in WIP configuration, the number of orders in system can be altered to influence production performance, the current EWIP configuration cannot be "tuned" for satisfactory performance.

6-2-1 Scientific contribution

This study aimed at the of SFPC system design for MRO with integrated information dimension, by consolidation of several well-established knowledge bases and proposed concepts to form a practical well founded method. The theory phase showed that the SFPC system cannot be seen separate from the total production control system and when adding the information quality dimensions in MRO, evaluation is required of the supply-chain context where the respective process is situated. The concept of integrating these several layers of production is one of the key concepts proposed by **Industry 4.0**, by the name of *interconnectivity* [7]. Much literature focuses on the architecture of IT systems to enable the connectivity but does not consider the interrelationship between the current process and production control systems. These are assumed static, whereas with this study it has been showed that information flows drive the MRO process, changing the interconnectivity from the *improving* realm, to the *enabling* realm.

Additionally, this study pioneered Taguchi method for parameter design for robustness and stability. These properties are often named under one term: "robustness", but have proven not to be the same when developing or studying detailed production control.

6-2-2 Contribution to practice

The study has been conducted with practical applicability of both the test case and the framework in mind. The framework provides practical instructions and an example of the method for the use of production control design, whilst leaving freedom to the practitioner to choose the preferred detailing techniques in the design execution. The final design is not ready for implementation and will require further detail as will be covered in the recommendation section.

6-3 Recommendations

6-3-1 Recommendations for continuation of the study

The validation of the framework could not be done for the specific environment. This was caused by the absence of detailed performance data, since the process was still under development by the time of study. It remains to conclude that the test case was a poor choice for the evaluation. Alternative processes could be found but required a thorough similarity study to come to a conclusive result. It is therefore recommended that future projects that attempt to develop design methods for specific environments do select their test cases based upon the availability of validation data rather than a design requirement. It therefore is of high most importance to evaluate the repeatability of this study and to apply the framework to different cases in industry.

6-3-2 Recommendations for practice

With the completion of this work, a series of control design methods have been developed for the MRO environment. These cover following the layers: supply chain control design[12], process control design[42] and finally **this** study with the subject of process and production control design. The combined knowledge should provide a comprehensive framework for practitioners to generate component supply chains with the flexibility to adapt to future emerging trends such as described by **Industry 4.0**. It is therefore advised to demonstrate the potential efficiency gain by the end-to-end design integrating the supply chain, process and production layer by the design and implementation of this framework in a real process. This should preferably be concurrent with the contemporary supply chain alongside it. This would leave real opportunities for control design innovation.

Appendix A

Research Paper

A green field design method for production control in Maintenance, Repair and Overhaul, integrating information and process control

L.F. Svedhem, Dr. W.W.A. Beelaerts van Blokland, and Dr. ir. D.L. Schott

Abstract

A design framework for the design of a Shop Floor Planning and Control (SFPC) system for a Maintenance, Repair & Overhaul (MRO) component supply chain was developed, assuming "green field" restrictions. By combining proven design methods developed for control challenges present for MRO processes and introducing an information requirement mapping that reaches beyond the control scope of contemporary design methods for SFPC systems, additional features were added to serve MRO environment specifically. A case study was used to verify the applicability of the framework for control system design, that resulted in one control system designs and two control parameter designs. It showed the developed control systems to exhibit the desired behaviour with regard to robustness and stability. These results stress the importance of proper understanding of the role of information in relation to control over the different control layers in a process.

Index Terms

MRO, process control, production control, design framework, remanufacturing, information structures.

I. Introduction

THE last decade, the developed world has seen a rapid increase in interest in the life-cycle management of production assets from an environmental and operational perspective [1]. Reuse of equipment after restoring or repairing can be realized with far less resources, where estimates range from 9% - 14% and 11% - 15% of energy and materials respectively required compared to new production [2]. This has developed to the practice of MRO for capital intensive assets in use by organizations. This practice has existed since the end of the second world war in various industries [3], [4], [5].

Earlier research regarding operation control of remanufacturing and MRO identified the returning issues: Repair orders from clients arrive in an intermitted pattern and the exact workscope of an order is subject to heavy variance as little is known on the history of the subject.

Whereas the characteristics and issues of control within MRO and remanufacturing are stated by several scholars, little research looks beyond the known control realm of production control. A multitude of studies evaluated the control problem with various focus areas such as shop floor policies [6], [7], [8], [9], [10], [11], predictive modelling of demand and production [12], [13]. All these studies base design solutions on process data for the system under study.

In normal production a new trend emerged towards high flexibility in systems to enable mass customization in large scaled production. From this trend a new revolution in industry was declared [14]: *Industrie 4.0*, where mass customization of orders is enabled by virtulization, decentralization of production control and the forming of adaptable information networks [15]. These developments have found ways into remanufacturing and MRO research in the form of concepts repair system [16] and increased control ability through complexity [17]. However, the industry itself sees little application [18] due to the lack of complexity understanding of the control systems and the lack of standardization in design to overcome this [19].

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Regarding process design, methods have been developed for remanufacturing, but these disregard the relation process and production control and information structures. [20]. Whereas information structuring and interconnectivity of process layers is found of major importance for mass customization potential [15]. Hence this study will attempt to design a framework that develops an implementable control design of a MRO process and will be guided by the following research question: *How is an information integrated Shop Floor Planning and Control system designed for a component Maintenance, Repair & Overhaul process that does not rely on previously recorded process data?.*

II. Methods

For the construction of the framework a proper understanding of the relation between information, process control and production control and their design criteria has been developed by studying the scientific literature on the MRO environment, design practice of control and information modelling. With found criteria and methods a framework was constructed that encompassed the desired field of design application.

As the goal of the project was to design a SFPC system that was deployable in a MRO process under development at the MRO organization, it was chosen to use the case as an example to evaluate the framework and see to what degree the case's design requirements could be satisfied. To evaluate the validity of the drafted design produced with the framework a Discrete Event Simulation (DES) was used. This is a well established method for control system design validation for logistic processes [21]. A full design study was conducted for the control design of the specified case assuming no restrictions in the control boundary creating a "green field" design situation. DES model specifically developed to simulate the company environment was built for the verification of the generated control design.

III. Literature review

The component MRO processes show substantial differences with normal manufacturing in process type, input requirements, work content and application of knowledge [11]. Several studies cover covering the subject of remanufacturing evaluate MRO operations [17], [9], [18]. The MRO process show a returning set of activities [22]. The process should the least have one form of input quality state determination before actual processing can commence and an evaluation of the processing result [23].

Earlier studies on SFPC for remanufacturing in MRO reveal specific characteristics for the control problem. (1) The high value and criticality of the component require short throughput times [3]. (2) The work scope is largely unknown when the component arrives at the process. This includes the capacity requirement to complete the order [9], [24]. (3) The demand for incoming parts is of stochastic nature [25]. The nature of the behaviour has been classified, but shows to be dependent on factors such as component uniqueness, wear mechanisms and supply chain layouts and its protocols [25], [26], [23].

Information systems are required to enable full MRO cycle control [16]. On a process level two distinct classes are distinguished: information independent on component state and information dependent on component state. The first acts as the reference and the second as the measurement for a specific component. For a specific entity of the part, both classes must be present for the process to function [27]. In production control system-state and component information enable the comparing function of the control system [28]. The system state is not part of the process driving information. However, the some specific component information such as work scope, relates to both the process and the production control and should attain a certain quality for the production control to work. Three dimensions have been stated for this quality measurement [29]: Granularity, the level of resolution; Actuality, the relation of the information and time; Accuracy, the uncertainty of the information. Production control design should be developed in relation with the complete process information structure. [30]

Production control is aimed at achieving logistic performance in the organization where implemented and has three internal dimensions of which one must be chosen to be the prime objective

[30]: Due date reliability, maximization of output and prioritization of specific order groups. The four control elements for the production control design are [30]: (1) Order generation; translates orders from clients to interpretative work orders for the shop. (2) Order release; the release of an order into the actual shop. (3) Sequencing; systemizing the sequence of working on orders at a work centre. (4) Capacity control; the short term increasing or decreasing of production capacity to safeguard the logistic performance goal. Lödding proposes a configuration method for the four elements in the sequence of mentioning earlier, that considers the design criteria: (1) manufacturing principle, (2) type of production, (3) part flow, (4) number of variants, (5) material flow complexity, (6) fluctuations of capacity. For these criteria, several comparative studies have been made of the influence of different design solution for a given MRO environment. [7], [8], [9], [17]

IV. The experimental design framework

With the conclusion of the literature review an experimental framework was sythesized based on the production control design method by Lödding and extends the design sequence from the process level to the shop floor level with integration of the information model. This resulted in a sequence consisting of eight steps with a possible iteration route:

1) Formulation of the logistic objectives: These are the main logistic objective and possible secondary logistic objective of the process and their measures as Key Performance Indicator (KPI)'s. The objective is dependent on the design criteria of the specific MRO process.

2) Formulation of the logistic process model: A logistic process model is derived from the generic MRO process model to suit the specific requirement of the case. A graphical representation is made.

3) Drafting of process information structure: This information structure reveals the *process driving information* and their sources in two steps; first, the internal process structure is identified and second, the links to the over arching supply chain are made. The structure can be added to the logistic process for overview.

4) Information quality characterization: Information is characterized in the quality dimensions. This done for the initial design information leading to the logistic process design and the information flows in the process information structure.

5) Configuration of the production control: The control configuration is done by the sequence described by Ł"odding and configures with the information gathered in the previous steps the elements in the following sequential order: (1) Order generation, (2) Order release, (3) Sequencing, (4) Capacity control.

6) Production control information structure: The control configuration will require its own information structure for the functionalities of the various elements. This structure is drafted into the existing process control design and its information flows are characterized for their quality. This is the preliminary design.

7) Robustification: The preliminary process and production control design describes control, reference and state signals for control. The dimensions and exact measurement of the parameter is determined by the Taguchi approach for parameter design to attempt to identify the best way to define the control signals.

8) Design evaluation: The final design is evaluated for testing by means deemed applicable for the specific field.

V. A test case

A. Implementation

The framework was evaluated with a test case in the component MRO department of Koninklijke Luchtvaart Maatschappij (KLM), KLM Engineering & Maintenance (E&M) . This organization has an extensive history within in aeroplane MRO . At the time of study the process was under development. The process would perform services on cooling units that are part of an Environmental Control System. With the framework the following design characteristics where found:

The prime logistic objective of the process was due date reliability, which was measured with the fraction of late orders. A secondary objective was required due to straining capacity deployed.

Criterion	Character
Manufacturing principle	cellular
Type of production	mass production oriented
Part flow	One-piece
Variants	2
Flow complexity	Medium
Variance of load	High
Capacity flexibility	Very low
Load flexibility	Low

TABLE I: Design characteristics for the production control configuration of the Liquid Cooling (LC) process

Based on the information quality characterization the additional design requirements added were: robustness to varying work scope and stability for incorrect norm time assumed for repair.

For the drafting of the logistic process design a Value Stream Mapping (VSM) was used and the information structures where drafted in accordance with IDEF0 standards [31], [32]. For the final draft the VSM was combined with a swim lane visualization earlier seen [33]. The result of the final design is visualized in figure 1.

The design study resulted in a control configuration with a order generation method based on the CONstant Work In Process (CONWIP) method [34] and an orders are released with a Drum-Buffer-Rope (DBR) regime [35]. No capacity control could be added due to the lack of capacity flexibility, but outsourcing at order generation was included to ensure all orders could be accepted. With the robustification, the dimension of Work in Process (WIP) was altered from quantity of orders into a sum of respective capacities required of the orders. This parameter was called Equivalent Work in Process (EWIP). Rather than setting a limit on number of orders, the amount of capacities required, could be matched with the capacities available. This method has been proposed earlier by Bertrand *et al.*[24].

B. Design verification

To demonstrate the validity of the design cycle, both configurations have been evaluated by Monte Carlo simulations with the DES model. The DES model was specifically built for this purpose and incorporates the capacity design of the process as planned in the business case. The DES model shows valid behaviour for the general relation of WIP and throughput time and throughput rate described by the logistic curves [34], [30]. However no validation could be obtained for the specific performance environment at E&M

An experiment series for absolute production performance and an experiment for robustness were performed. Based upon the expert assumptions on the processing times and their stochastic behaviour the control configurations are simulated for a range of Interarrival Time (IAT) starting at 6.5 hours descending to 2.5 hours, as the theoretical average bottleneck time has been calculated for 4.4 hours. An IAT bellow this time would supply the system with more orders that it could theoretically process. For reference the uncontrolled configuration has been included in the performance evaluation. For the performance evaluation the resulting throughput times and throughput rates are depicted in graph 2 and 3.

In the performance experiment the throughput time, both controlled configuration maintain control with a slight increase in time as IAT decreases. For a WIP limit of 7 orders, the WIP controlled system maintains significantly shorter throughput times over the entire range of IAT for $\alpha = 0.001$. The uncontrolled system was found to have exponential growth for throughput time after the IAT decreases below 4.5 hours. For throughput rate, both controlled configurations keep a flat rate through the range of IAT. The uncontrolled system increases vastly, to decrease after 4.5 hours of IAT and eventually drops bellow 2.5 hours.

In the robustness experiment throughput time showed to be most affected by orders size variance. The results of the of experiments with different coefficients of variance are given for WIP and EWIP control in graph 4 and graph 5 respectively. All though both experience significant higher throughput times for increasing work scope variance at a level of $\alpha = 0.001$, the the throughput

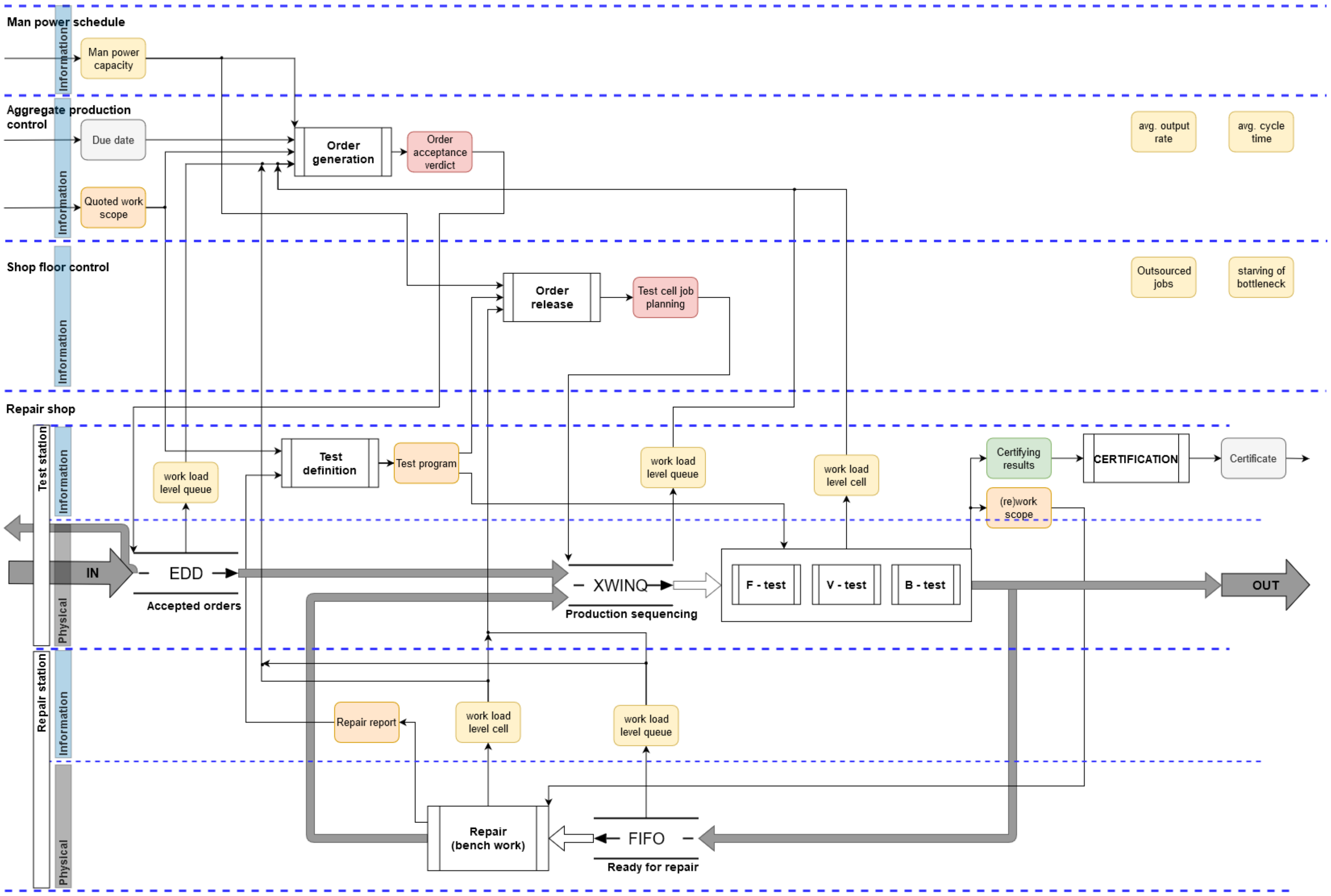

Fig. 1: Integrated production control system for the LC process in depicted in a VSM-i scheme

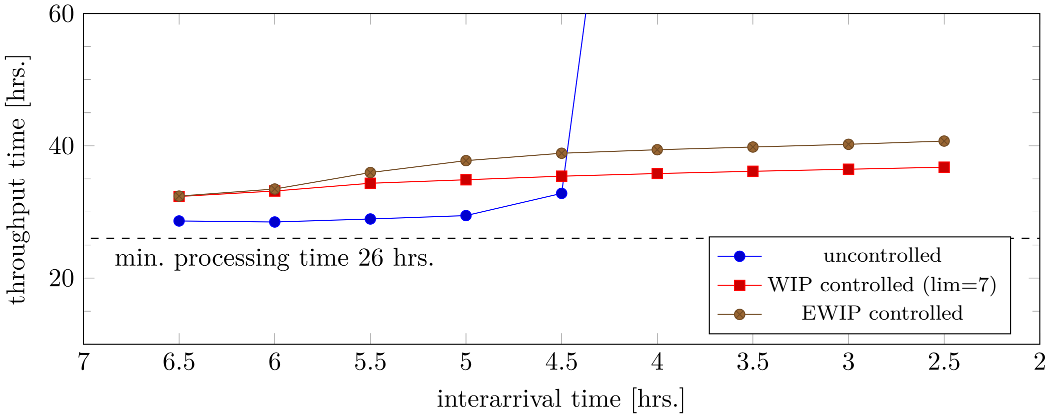

Fig. 2: Average throughput times of the control configurations over order interarrival time

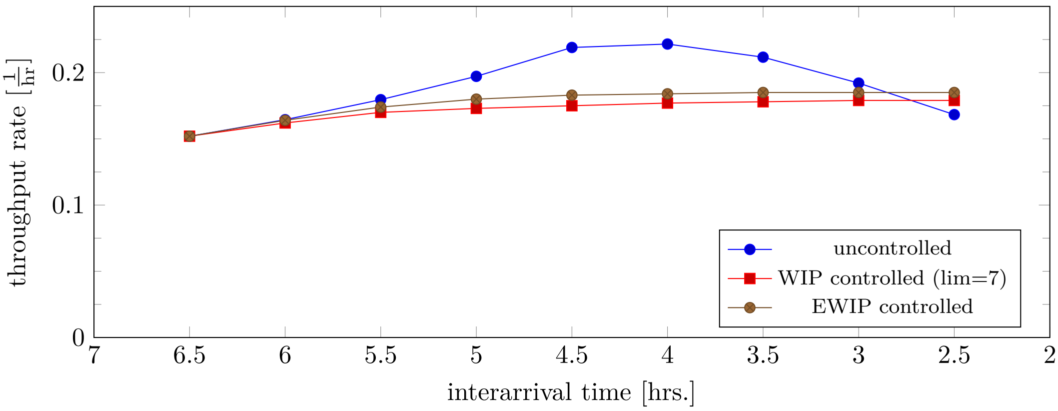

Fig. 3: Throughput rates of the control configurations over inter arrival time

time is kept at a maximum value over the range of IAT. The effect is more substantial for the EWIP controlled situation than the WIP situation. Where the EWIP shows a significant tightening at 5 IAT.

The control configuration showed capable of protecting the system from overfilling and showed robust to variance of its main uncontrollable influence factor: order size. In the performance experiment was seen the WIP controlled system realized shorter throughput times at lower throughput rates, where the EWIP controlled system attained longer throughput at higher utilization, as seen in its throughput. This difference is also seen in the robustness experiment, where the WIP controlled system shows to be more robust than the EWIP system. This confirms the phenomenon described in theory that systems with higher utilization rates are more sensitive to variability [34], [34], [36].

VI. Discussion

The DES model did not validate for the performance environment, hence little can be concluded on the fitness of the configurations regarding the performance requirement of E&M . A validated model would have to produce the same performance as the real world case for the model input parameter setting. However the framework did produce a valid controller design for the behavioural requirements. This means that behaviour could be studied relative to the validated behaviour. Additionally, the robustification resulted in a less robust design for the prime uncontrollable external influence factor. This was contrary the expectation and has therefor not shown the Taguchi method not to be of reinforcing influence for this particular situation.

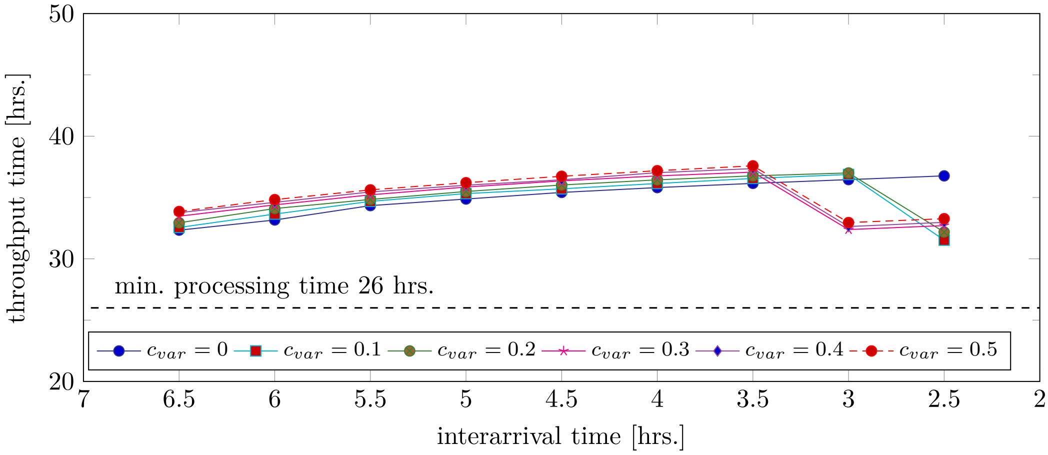

Fig. 4: Throughput times of WIP control for work scope variance for $WIP_{lim} = 7$

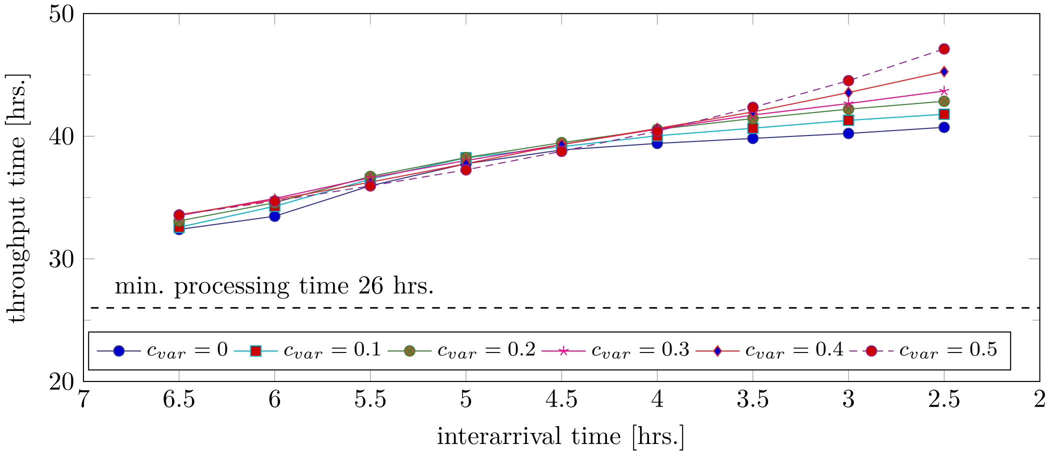

Fig. 5: Throughput times of EWIP control for work scope variance

VII. Conclusion

This project was aimed at developing a method for SFPC system design that encompasses information design and does not rely on previously recorded process data.

By developing the generic component MRO process the foundation of the control model can be laid for the process control information that showed to be part an integrated part of the production control design. The use of information modelling has shown to be essential to form a functional design. Previous research often concludes variance as a obstruction to overcome in the process, but hardly assesses the problem beyond the production control realm. By starting the design from a process perspective, the role of information in quality restoring systems becomes apparent and can be included in the design criteria. It is recommended that the framework is applied in more test cases where plenty of data is available for validation and live experiments are conducted. Additionally, the use of Taguchi's method on robust design should further be evaluated for its use in control system parameter design.

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MRO	Maintenance, Repair & Overhaul
KLM	Koninklijke Luchtvaart Maatschappij

E&M	KLM Engineering & Maintenance
DES	Discrete Event Simulation
WIP	Work in Process
EWIP	Equivalent Work in Process
SFPC	Shop Floor Planning and Control
KPI	Key Performance Indicator
LC	Liquid Cooling
ECS	Environmental Control System
VSM	Value Stream Mapping
DBR	Drum-Buffer-Rope
CONWIP	CONstant Work In Process
IAT	Interarrival Time

Appendix B

Detailed description of framework execution

This appendix describes the detailed design study that was executed for the test case by stepping through the design framework developed in the study.

B-1 *Step 1: The logistic objective*

De logistic objectives collected from the business case developed for the Liquid Cooling (LC) capability as provided by KLM Engineering & Maintenance (E&M). The scope is set to surround the end-to-end process of the component Maintenance, Repair & Overhaul (MRO) process. Hence, a clear definition for the control scope for this design study must be developed, herefore the objectives will be translated to internal objectives for the repair shop housing the component MRO repair process.

The *component availability* department as the sole customer of the process and is tasked with the management of the entire end-to-end process. The objectives mentioned are expressed in the yearly throughput of machines and a maximum for throughput time for this process. The yearly throughput is subject to change over the years as sales, warranties expiring and fleet expansion are foreseen. Figure 3-1 depicts the expected annual shop visits.

The goal is to execute any MRO service within Boeing's Product Support and Assurance Agreement (PSAA) stated service time for the respective component group, minus one day. For an electrical component this would be **14 days**. This is the full Turn-Around-Time (TAT) for the client and does not account for weekend days, when no work is done in the shop. A period of 14 days will include two weekends which count **4 days**. E&M reserves an additional [redacted] for internal and external logistic processes, leaving a total of [redacted] available for the shop process.

- Throughput time: 6 days

The current shop has a performance Key Performance Indicator (KPI) called *On-time performance*, it comprises the fraction of orders with a throughput time equal or below the required cycle time. As no other internal KPI's regarding the logistic objectives are required from the system.

None of the other logistic performance goals have been defined for the process goal in the business case. In addition to performance, the amount of means have been determined in the case description, setting an upper limit of the capacity available to achieve the logistic objectives. Moreover, the way of working is specified as one-piece oriented bench work. That the presented logistic objectives have not been fully defined does not mean that no restrictions on the objectives can be assumed, as the other process parameters defined do have implications for the *undefined* logistic objectives. This will be addressed further in step 2 and 5

objective	value	unit
throughput time	[redacted]	[redacted]
due date deviation	-	-
due date reliability	-	-
inventory	-	-
utilization	-	-
cost of delays	-	-

Table B-1: List of internal logistic objective developed from the business case

B-2 *Step 2: The logistic model*

Initial test

The Component Maintenance Manual (CMM) describes three different tests to be executed on a unit: an electrical bonding test, a functional test and a vacuum proofing test.

Functional test For a function test, the unit is connected to a testing machine that runs a full automatic function test of the refrigeration circuit, the power circuit, pump functions of the unit. The test report presents the performance of the machine under study along with the required values in a print-out. An operator is required to install the component in the machine and to remove it after the test has been completed.

- touch time needed un-/installing[redacted]
- test time: [redacted]

Vacuum proofing test To evaluate gas tightness of the system, a proofing test is performed in a vacuum chamber. For the test the unit is placed in the chamber and a vacuum is pumped. The circuits under study are filled with a proofing gas, that is detectable with a manual "sniffer" device. The readings of the measurements are noted manually. Additional to the taking of measurements an an operator is required to install the component in the chamber and to remove it after the test has been completed

- touch time needed un-/installing: [redacted]
- test time: [redacted]

Electrical bonding To ensure electrical connections are properly installed, measurements are taken from different electrical connectors with a hand held device. The readings of the measurements are noted manually. This test is fully manual, meaning an operator is required for execution.

- touch time execution: [redacted]

The CMM does not describe a particular order of the tests, nor does it require all tests to be performed by default. The systems and sub-systems that are subject of service determine what tests need to be included in the initial testing. The shop is however free to perform additional tests if deemed necessary. It must be noted that for the decision to drop a certain test, it must be clear what service must be tested for. This requires some form of initial description of the reason of shop visit by the component. If none is prescribed, it is up to the shop to determine how the diagnosing of error shall be done.

Work scope determination

The pre-routing phase is closed off with the determination of the work scope. Here all test results and additional information is being used to form the service program. There is no exact requirement on what information should be present to make a work scope. Ultimately the visit should lead to qualifying test results, but what tasks and what tests should be performed is up to the judgement of the employee composing the work scope.

Additionally, the work scope is a set of tasks or range of paragraphs from the CMM that should be executed. This could include actual service work, but also checks and assessments of minor components. It is therefore not possible to include a definite list of spare parts required to the scope.

- no time specified

Shop routing

The actual service tasks are done by bench work. The respective component is on a fixed or semi-fixed positions where tooling is moved around to execute the tasks. The business case plans for five employees available to work on the various work benches.

- component dis-/assembly: [redacted]

Final testing

To evaluate the new quality status of the component, final tests are executed. The CMM prescribes what tests need to be performed after works on which systems. It may be assumed that test program will entail at least the test executed in the initial test. There is only one machine available for each test type. This causes a physical back flow of components leaving the repair cell as depicted in Figure B-1. The scheme encloses physical position specific function in their respective laid out cells; the test cell and the repair cell.

Should the component fail to reach the required test output a new work scope must be determined and the component re-enters the repair cell with a new scope assigned or more detailed error isolation. Theoretically this loop continues until the component reaches a certifying test result.

Certification

When the component passes the certifying program it can be declared *serviceable*. The certificate should contain the certifying test results and a description of the activities executed during the service visit.

- paperwork: [redacted]

Visualization

The information from the previous paragraphs has been summarized in Figure B-1

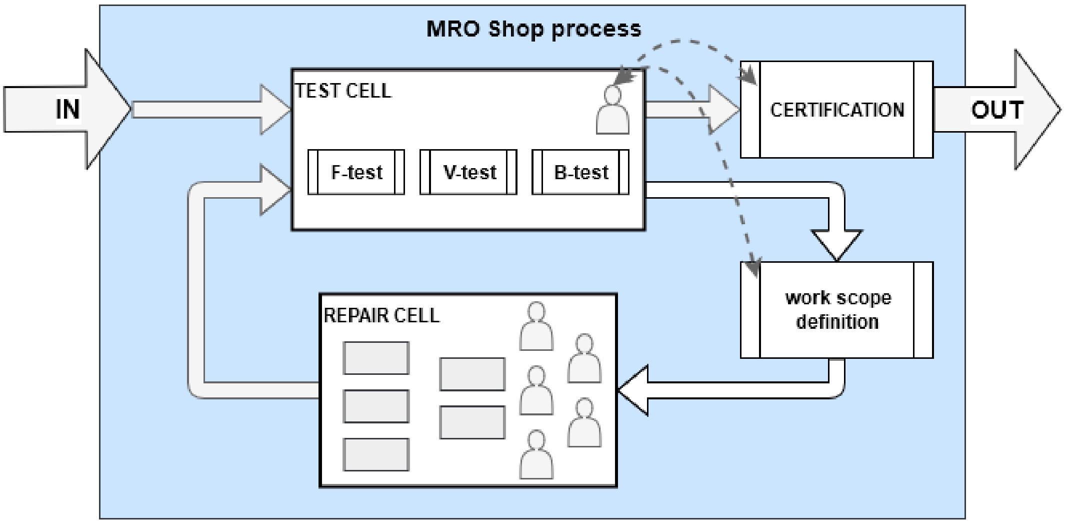

Figure B-1: The logistical process scheme including assigned capacities

B-2-1 Deterministic capacity analysis

The figures mentioned in the business case used for a deterministic capacity analysis. This means, the resulting capacity is the capacity to be expected as a result of means provided, answering to the prerequisites of a deterministic analysis. Table B-3 shows the deterministic analysis split for machine capacity and man power capacity for the different work centres. With the means distributed over the different centres, first the availability of capacity at the

year	total removals
2020	[redacted]
2021	[redacted]
2022	[redacted]
2023	[redacted]
2024	[redacted]
2025	[redacted]

Table B-2: Expected of annual removals of LC components

Work centre	Means available		Line availability		Repair requirement		Throughput capacity	
	machines	operators	Machine-hours	Manhours	machine time	touch time	Machine-hour	Manhour
Units	no.	no.	[1/hr]	[1/hr]	[MaH]	[MH]	[1/hr]	[1/hr]
Functional	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Vac Chm	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Repair	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Functional	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Vac Chm	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Bonding	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Cert	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table B-3: The deterministic capacity analysis showing basic system limitations per processing station

line is calculated, second the requirement for production for one unit is stated, to finally result in a potential with with the respective production capacity. As some work centres do not have an explicit machine capacity assigned, a arbitrary very large number is assigned, to ensure this centre will not be restricted by machine capacity in the analysis.

The main column *throughput capacity* shows the production potential of the respective means in units per hour. It should be noted that the throughput capacity of each work centre is the minimum of the machine-hour - manhour pair stated for the centre. Short evaluation of the analysis shows the following:

- Manhours in the repair stage have the lowest capacity by [redacted] an hour.
- The functional test machine is the most pressed capacity regarding machines.
- The operator assigned to testing and certification is carries out a large number of task sets.

It remains to conclude that this process, by deterministic capacity analysis, is largely restricted by labour. The manhour capacity available for the test cell shows to be the least restrictie, however, the deterministic analysis assumes no effect of the production system; this includes schedule inefficiencies and task focus inefficiencies. Given that so many task sets are to be executed by one operator, it is likely that test operator time will not be spent efficiently.

Supply chain context

Previous analysis of the supply chain of the total component MRO services offered by E&M provides a detailed overview of the current state of the chain, as depicted in Figure 1-2. It shows the external logistical process that is part of the product that E&M offers to its pool and non-pool clients. The business case mentions *component availability* as the overall component MRO supply chain managing entity. For these operational logistics E&M has reserved 2 days for the entire process, as mentioned earlier in the logistic objective. Additionally, it can be seen that E&M accounts for MRO services to be subcontracted externally. In the case of the LC components, the current Original Equipment Manufacturer (OEM) performs the actual service activity of the component MRO and will continue to offer this capacity as the LC process at E&M is taken into operation. However, this option is not preferred as besides loss of profit margin, the current On-time performance (OTP) of the OEM as a MRO service provider is unsatisfactory. The possibility for extra capacity will be covered further in step 5.

B-3 *Step 3-4: Process Information structure*

This step analyses the process information structures found for the case study at E&M. The analysis of the information models has been performed concurrent with the information quality characterization, hence these are presented here as one step of the analysis.

B-3-1 Design information structure

The capability design process is the result of a capability design process, that should lead to the full preparation of the capability at the shop. For the process design this resulted in three groups of information to be included in the basic design of the process:

- Business case
- Basic logistic properties
- CMM

Table 3-1 provides an overview of how the logistic objectives and logistic process model relate to the design information structure. A elaboration of the three information groups and their information quality follows.

Business case

The business case has been developed by a committee of internal stakeholders with the purpose of evaluating the idea of an expansion of the MRO service portfolio. A decision is taken on strategical grounds within the market environment and the potential profit that can be realized. This requires a market prospect and a knowledge of of the basic logistic requirements to answer to the foreseen market demand.

The market demand has been calculated based on the expected number of removals of units of the own KLM fleet. As the current LC MRO services are performed by the respective OEMs of the units, there is a substantial benefit for moving the services in-house.[78] At the moment of writing it is already foreseen that the expected removals for the own Koninklijke Luchtvaart Maatschappij (KLM) fleet will already be higher than provided by the analysis done in 2012. This is based on the warranty repairs that have been performed on operational LC systems in the commissioned fleet. An exact number has not been calculated, as this study has been limited to the design of a Shop Floor Planning and Control (SFPC) system in accordance with process design, exactness of the design input information will not be pursued and hence, the improvement of the market prospect is out of scope of this research. The quality of the information on market demand however, will be considered in the quality assessment of design information.

In addition to the expected yearly demand, E&M maintains an own standard on TAT which sets restrictions on the time limits of throughput times of the individual processes in the supply chain. These have been detailed in section B-1. The business case does not prescribe these limits explicitly, but given the environment where the process is designed to take place, these restrictions follow for the respective environment.

Basic logistic properties

The basic logistic properties have been developed concurrent with the business case. Final decisions on to implementation of the proposal is partially based on the results of the basic logistic properties. The goal of the basic logistic properties is to supply the business case with an feasibility assessment in the form of a capacity requirement for the expected market demand. Additionally, the properties serve as a starting point for the detailing of the process design, this includes the process control system and the SFPC system. Therefor the information provided to the business case solidifies when the case has been approved. The target setting then occurs from the business case document.

Much of the basic logistic properties have to be estimated, as no statistical data is available to base predictions on. Some information can be supplied with a higher certainty. Tests that are prescribed by the CMM require machinery and programs that have been predetermined. Test machine manufacturers can supply this information with higher accuracy in the event it has been specified for the machine (and hence is a machine property).

Component Maintenance Manual

The CMM is provided by the OEM of the respective component. Section 2-1-1 describes the role of CMM in the maintenance process. Given that the CMM is an institutionalized entity, it can be regarded as highly accurate and while subject to change, to be accessible in updated version. However, the besides the task oriented descriptions, the CMM does not provide much detail on experience with the described tasks. It is not common practice for an OEM to provide other MRO organizations with the CMM as OEM has its own market share in MRO services for its respective component. It is however, obliged to deliver the manual to every single operator of the aeroplanes that carries its respective components. Would direct exchange occur between OEM and other competing MRO organizations is mostly a form of strategic partner ship.

B-3-2 Process information model

With the physical process functions defined in the second step of the framework. The process information model can be added to the total process design. These have been split into two layers. One providing the internal passing of information and control signals, and one for passing information from and into the overarching supply chain.

The information process model formatted in IDEF0. IDEF0 methodology is a function based modelling language that is used for the integration of information structures into logistic flow structures and is applicable to automated and non-automated processes. It shows a function's input, output, controlling signal and resources [79]. To fit the IDEF0 format, the logistic process overview from Figure B-1 is reduced to a pure function display of elements and their respective relation to flow and information. Additionally, a separation has been made between physical object flows and information flows. This has been done to visualize the effect of information and its quality on the physical flow. This will be covered in the next design step, regarding information quality.

Internal drive information

To obtain the internal drive information, all process functions have been evaluated for their requirements to perform their given function in terms of physical flow and information flow. This resulted in a flow scheme depicted in Figure B-8. Here follows a short elaboration of each element in the information side of the process scheme.

Pre-test program prescribes the tests that must be executed by the test cell for failure isolation or general performance checks. It is the result of the comparison of quoted work scope and visual state with the CMM.

Pre-test results of the pre-test program are produced by executing the pretest program and will define the current state of the component.

Work scope prescribes the work that needs to be executed on the repair bench. It is the result of the comparison of pre-test results and visual state with the CMM standard.

Repair report is produced after the bench work has been completed. It should contain what work has been performed on what systems to deliver the work scope and possible additional works performed.

Final test program prescribes what tests must be executed by the test cell to receive certification as *serviceable*. It is the result of the comparison of the work scope and executed work with the CMM.

Final test results of the final test is produced by executing the final test program and will determine a pass/no-pass for certification.

Rework scope is made would the component fail the final test. It is the result of the pass/no-pass decision made during the certification. Rework also means the component is loops though the repair process once more.

Uncovered by the analysis is yet the materials supplied to the repair function of the process, that can be seen in Figure B-8. In manufacturing materials must be supplied for a unobstructed logistic flow. The requirement of materials is the result of an exact order triggered in the manufacturing process. In the particular process under study, this happens at conclusion of workscope which is right before the point of need: the benchwork. This means that this process in particularly is very vurnable to stock-outs or slow supply processes, thus material management plays a crucial role for logistic performance. However, the question of material and spare part management is a complete knowledge and research field on its own and has been excluded from the scope of this process control design framework.

Transgressing information structure

Analysing the process information model shows two pieces of information to be part of driving information structure; the quoted work scope, the CMM standard and the certificate. The first two should be supplied to the process before the process can operate, the last is a *proof of execution* and will be required in the sequential steps in the supply chain.

Component Maintenance Manual standard Section 2-1-1 describes how the OEM of a aviation component composes a maintenance directive with aviation authorities and other stakeholders. MRO organizations apply willing to become *capable* for providing MRO services for a specific component must design their process before being authorized by a respective authority. Herefor the CMM must be obtained from the OEM before the authorization occurs. This means that the CMM should be accessible before the first component can be taken in for service, and thus is part of the design information requirement and not the process operation requirement.

Quoted work scope Along with the component should instruction be delivered what should be quoted what is expected from the MRO organization. The quoted work scope starts at the maintenance programme of the operator of the aeroplane. In this program is dictated why a component should be removed during line maintenance activity, this could be a mandatory removal or an unscheduled removal. Multiple logistical routes can be seen in Figure 1-2 for a component after removal from the airframe.

Certificate the certificate will entail the test results on which grounds the component has been declared serviceable after comparison with the CMM. The pre-test result and repair report are also included. The certificate will be used to drive other processes in the component supply chain. As this is out of the design scope. This will not be covered further.

B-3-3 Information quality characterization

Design

Table B-4

				Information Quality		
entity	source type/ origin	component state dependency	signal type	Granularity	Actuality	Accuracy
TRANS						
CMM standard	OEM	independent	active	very high	high	very high
Quoted workscope	Line maintenance party	dependent	passive	very low	low	very low
certificate	test operator	dependent	input	very high	very high	high
PROCESS						
pre test program	test operator	dependent	control	high	very high	medium
pre test results	test machines	dependent	input	very high	very high	high
workscope	test operator	dependent	control	medium	very high	medium
repair report	repair man	dependent	input	medium	very high	medium
final test program	repair operator + test operator	dependent	control	high	very high	high
final test results	test machines	dependent	input	very high	very high	high
approving results	test machines	dependent	control	very high	very high	high
rework scope	test operator + repair operator	dependent	control	medium	very high	medium

Table B-4: Full process drive and information qualities

Control

The current state of IT solutions and information handling in aviation regularly results in a reason for removal being lost at E&M. This is confirmed by shop employees tasked with component reception [10]. Therefore the quoted workscope cannot be assumed to be complete, up to date or precise in its instruction and hence is given a low rating in all three dimensions.

B-4 *Step 5: Configuration of the SFPC system*

With the mapping of the process from the previous steps, the production control configuration design loop can be initiated. This section starts with the summing of the key design characteristics for the production control in Table B-6

Step 5.1: Order generation method

The order generation method will be selected by defining and evaluating the three criteria stated in section 2-4-2:

- Predictability of Demand

			Information Quality		
	entity	source/origin	Granularity	Actuality	Accuracy
LOGISTIC OBJECTIVE					
	throughput time	BC	very high	high	high
	due date deviation	-	-	-	-
	due date reliability	-	-	-	-
	inventory	-	-	-	-
	utilization	-	-	-	-
	costs of delays	-	-	-	-
	yearly output	BC	high	medium	medium
LOGISTIC PROCESS MODEL					
Process					
	task descirption	CMM	very high	very high	high
	task order	CMM	very high	very high	high
	manhours	BC	medium	very high	very high
	machine arrangement	BC	medium	very high	very high
F-test					
	touch time	expert estimate	very high	medium	low
	machine time	machine manual	very high	medium	high
V-test					
	touch time	expert estimate	very high	medium	low
	machine time	machine manual	very high	medium	high
B-test					
	touch time	expert estimate	very high	medium	low
Bench work					
	touch time	expert estimate	medium	medium	low
certification					
	touch time	expert estimate	very high	medium	low

Table B-5: Basic design information and their qualities

- Planning Necessity
- Suitable generation scope

Predictability of demand The predictability of the demand is shows to be one of the main difficulties in the process design. The projected annual demand provides an average figure, but does not specify any property of the stochastic nature of the figure. Given the assumed workload for aeroplanes Environmental Control System (ECS)s over the annual seasons, a form of seasonal remand variance may be expected. However how this behaviour is described, is dependent on the actual failure mechanisms in the component. As these have not been properly modelled, it is concluded that, at moment of the design process, the predictability of demand is low.

Planning necessity The production process is contains mainly manual assembly, disassembly work or installation work. No setup time is needed for the few automated tests present in the process. The operator is expected to tell the two variants apart and except of a few hand tools, the no special tooling per variant is required. This means that the planning necessity for

Criterion	Character
Manufacturing principle	cellular
Type of production	mass production oriented
Part flow	One-piece
Variants	2
Flow complexity	Medium
Variance of load	Medium
Capacity flexibility	Very low
Load flexibility	Low

Table B-6: Design characteristics for the production control configuration of the LC process

the process is very low. It should be noted however, that the immediate presence of materials required for repair is crucial, but for SFPC system design, this is considered out of scope.

Suitable generation of scope The process information structure in section B-3 shows every exact task set to be dependent on the resulting information of the previous process steps. This means that before the prevailing step has been executed, the exact scope of the subsequent task set can not be known. This makes the use of a *multi-stage* order generation impossible. Hence, the suitable scope for this process is a single stage scope generation.

The solution space for the control design is limited by the environment that it is to function in. This is specifically seen in the control elements with transgressing information, such as the order generation. In the component supply chain at E&M, the department *component availability* sends a component to its respective shop with or without work scope without knowing the current situation on backlog, capacity or any production related potential. This pure push mechanism results in a direct event where order acceptance or refusal must be handled by the shop.

The deterministic capacity analysis showed the production process to have barely the capacity to make the expected average demand. These type of systems have a tendency to buffer orders in various places along the process, which increases the amount of Work in Process (WIP) in the system, resulting in increasing throughput times for the production of the WIP. For this reason a pure push system is vulnerable to any varibility in occurring in the production process.[45] The process under study has been concluded to be high on process variability and hence a pure push system is not chosen.

By regulating the total amount of orders inside the production system, the production time can be kept within the required control boundaries. This effect has been described widely and is the basis of several advanced production control systems, such as kanban and CONstant Work In Process (CONWIP). Comparing these pulling production systems stated shows that for a "line" type of production with high utilization requirement that CONWIP performs superior in terms of minimizing throughput time. Additionally, a higher output could be realized with a lower WIP level compared to kanban in a deterministic environment.[61] Hence is chosen to generate orders with a CONWIP order generation method. This means that the total amount of orders present in the system is limited by a predefined number and all orders not fitting the process will have to be refused by the shop. The organizational structure at E&M does not allow for refusal of orders, this open end will be covered later in section B-4.

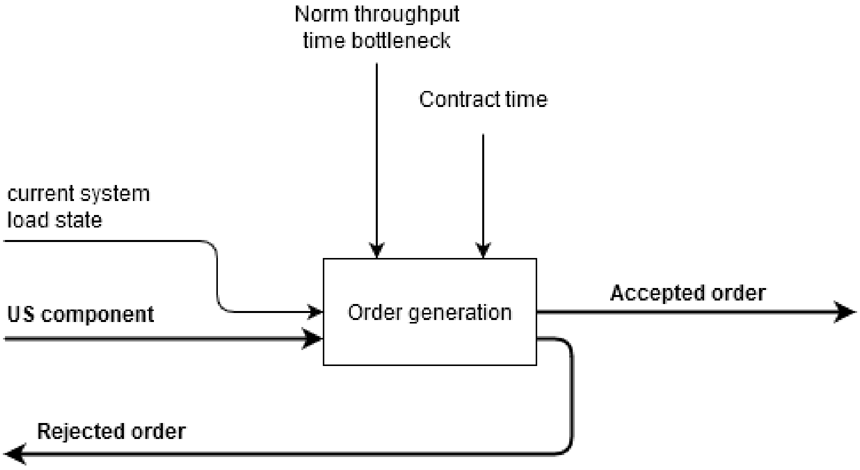

Figure B-2: IDEF0 representation of the order generation function

Step 5.2: Order release method

The release method dispatches an order into the production system, hereby influencing the workload on the different work centres. Each work centre can accommodate a limited amount of orders over a certain period. Would the workload exceed this limit, orders would temporarily be stuck in the process, resulting in congestions. This process has a varying workscope, which means the exact production load of an order is not known upon release. Herefore, the effect on the total load onto the system by the specific order release is also unknown. Causing risk of overload. *Pull* systems are a category of release mechanisms specifically designed to release an order only when the process is known to be ready for it, hereby averting the risk of overload and reducing the variable nature of the incoming production orders [45]. The mechanism results in a WIP regulation in the system. WIP regulating order releases are known to have the following properties [27]:

- Robustness to errors in planned work sizes
- Robustness to deviations in planned input
- Predictability of throughput times
- Protects the process bottleneck form overload
- Less tied up capital

It is therefor decided a pull mechanism will control the order release method.

In this process a clear bottleneck has been identified and is the number of operators at work in the repair centre. Therefor, the number of units that can be worked on simultaneously is limited. Due to the total output required to satisfy the projected demand. This bottleneck process must run with high utilization to realize the output. The Drum-Buffer-Rope (DBR) system is specially aimed at high output generation by minimizing the bottleneck process starvation.[62]

In *bottleneck control* the order release is related to the capacity of the bottleneck in the system. By not allowing the release pace to exceed the production rate of the bottleneck the process will be protected against excessive buildup of WIP and ensure high utility of the bottleneck process.[62] However, due to the workscope not being defined upon order release, the load effect on the bottleneck of the particular release can not be determined. Hence, a paced or time triggered release policy can not be applied [27]. Instead a direct measurement on the occupancy of the bottleneck station must be applied. In the event of a future under utilization, the production control releases an order to increase the future work load of the station. To further protect the bottleneck form starving a limited buffer is kept prior to the bottleneck step. However given the slack available for each component in the process, the number of buffer time must be kept to a minimum. Since the prime goal of the process is the minimization of delivery lateness, a buffer to protect the bottleneck station from starving will not be used.

By choosing not to release orders directly into the system as they are generated a buffer before the process entry can not be prevented. By releasing orders in the event of a form this buffer into the process, the bottleneck performance can be controlled. The release is triggered by the the future vacancy of an operator at the repair station. DBR has one weakness with regard to flow complexity, it cannot regulate WIP when backflow is allowed and rework may occur, hence an additional condition for release has been added: The WIP limiter

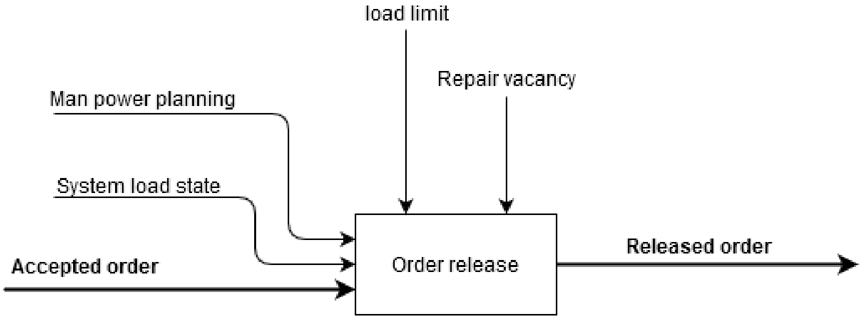

Figure B-3: IDEF0 representation of the order release function

Step 5.3: Sequencing rules

Sequencing rules determine the specific working order of jobs at the individual work stations and should herewith further improve the overall performance of the process. Selection of the sequencing rules should answer to the criteria described in chapter 2-4-2 for sequencing. First the criteria for selection that concern the entire process are evaluated, followed by the criteria for the work station specifically and final selection of the sequencing policy for the respective station. The process covering criteria are the prime logistic target and the general quality of the order schedule.

The prime logistic objective of the LC process at E&M has been determined in section B-1 and is the realization of short through put times, which is in the category of schedule reliability.

Additionally it must be realized that due to the capacities deployed, the process must attain a high utilization of scarce resources in order to attain the foreseen output.

The order schedule for the process is rather simple. Due to the unknown status of incoming components, a detailed schedule can only defined after initial testing has been performed. This limits the ability for the initial production schedule to a sequence where only the due date of the component is known and processing time must be developed by the process itself. The remainder of this step will assess the two work stations for their relation to the main criterion and the other two criteria for the respective station.

Order acceptance

The test station collects both processed and unprocessed units for testing. The tests result in the information on the quality state of the specific unit. This influences general process as the work load in process a MRO process is defined by the total quality deviance of all WIP. Additionally, this station supplies the bottleneck station with work. Its processing time of one LC unit is substantially lower than the processing time of the bottleneck station. Work is delivered to the station with specific information for testing, either by the work scope quoted (for new arrivals) or a repair report (for repaired items) and orders queue up for the centre to get processed.

As the order release method applies *bottleneck control* an order is only released when a *pull* signal is sent from the repair station. Ideally the signal for release is sent out prior to a vacant position at the bottleneck station, so the process is allowed time to perform the prevailing steps. This would prevent the bottleneck from starving. With a queue formed prior to the testing station, the signal would, in an ideal situation be sent out the time period it would take the released unit to pass the test queue and testing. The longer the queue is, the earlier the release signal should be sent. The deeper this prognosis would be in the future, the more uncertainty for correct release would be. Additionally, the an operator in the repair shop, would constantly have to be aware of the current situation of the occupancy of queue and test station, which is expected to invite human error. By prioritizing the released job to towards the bottleneck, the ideal time between vacancy signal and actual release can be minimized to the processing time of the unit at the test station. This policy corresponds with the Extended Work in Next Queue (XWINQ) sequencing rule, suggested by Conway, Maxwell and Miller.[80]

Using the XWINQ policy at a station that precedes the bottleneck station could effectively move the starvation buffer one work centre up the chain. In this specific case this has the advantage that this buffer can be kept as unreleased orders, where they do not affect WIP yet. This keeps the WIP level low and enables an effective *rope* system that prevents the bottleneck from starving.

The repair station executes the required work scopes for the LC units and forms the core of the quality restoring property of the component MRO process. Units repaired are sent back to the test station where there new quality is measured and a fail/pass decision on success is made. Orders arrive at the station from the test station as soon as these have been processed in testing. Would more units arrive at the station than it can accommodate a queue is formed.

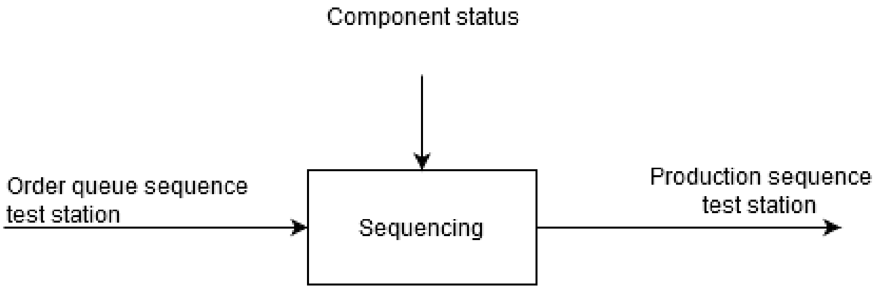

Figure B-4: IDEF0 representation of the sequencing function for the test centre

The repair station is the bottleneck station of the entire process and thus has the most significant impact on the logistic objectives of the process [62]. No starving prevention buffer has been included in the production design to increase the time slack for individual orders which promotes schedule reliability, which has been chosen as prime objective for the process. For the same reason a due date based sequencing rule is implemented to serve the prime logistic objective of the process. The test station releases work directed at the repair station in due date based order, as the station itself is a deterministic process, with a relatively short processing time compared to the repair. Additionally, as the bottleneck "pulls" a job release only when a repair job can be accommodated in the centre, the odds of queue forming longer than 2 with substantial waiting time are low. It has therefore been chosen to implement a First-in-first-out (FIFO) rule here, for simplicity.

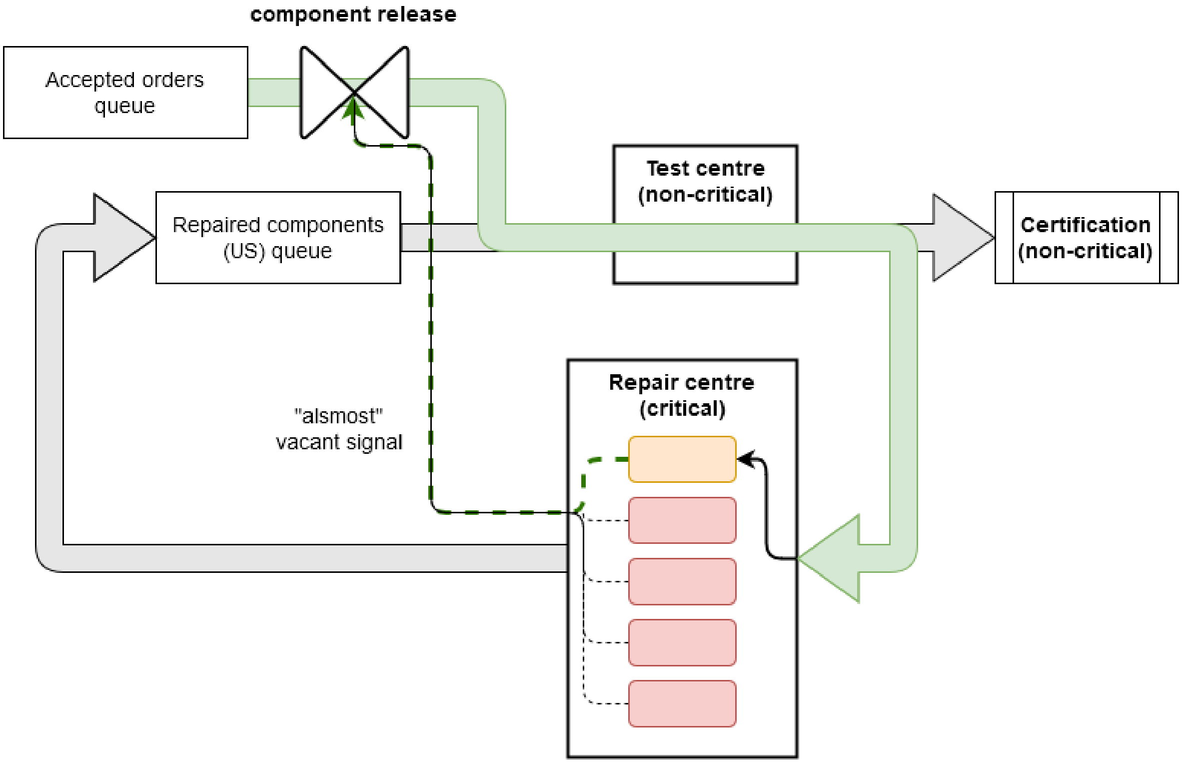

Figure B-5: The buffer-rope mechanism for bottleneck pull in schematic overview

Step 5.4: Capacity control method

The final step in the production control system configuration is the method for controlling capacity in the production system. The general range of capacity control is not limited to the assignment of means for production, it also includes potential control that can be exerted on the load of the production system or specific work stations in the process. This step assesses the characteristics of the capacity control required for the LC process and explores the possibilities for control methods.

The characteristics of capacity control have been stated analysed in chapter 2-4-2 and comprises three characteristics; the criteria, scope of adjustment and trigger logic.

The criterion for capacity adjustment in the LC process should relate to the logistic objectives of the process. With the prime logistic target for due date reliability, the prime criterion should focus on the effects of the backlog present in the system. More precisely, as the prime KPI for the process only considers late orders, the risk of lateness should be mitigated by adjusting the capacity in the system. The probability of lateness is affected by several influences: [81]

- Sum of current WIP and accepted orders in queue
- Sum of planned capacity available within the avaiable production time of orders

This is a simple sum of capacity of the system and the load exerted onto the system for the available production time. These two values are however of stochastic nature and the production load has shown to be of unknown nature at moment of design. This limits greatly limits the measurement exactness of present load in the system. With the limiting capacity on man power, the total capacity deployed can be modelled with existing productivity models for operators in a workshop. At E&M the productivity ration of the true total hours available for one shift is rated at 80%.

Scope of adjustment the determines where and what is changed in capacity. And is highly dependent on the process properties and the task definitions. At the LC process, the prime scarce resource is the labour available in number of operators available to work in the entire process simultaneously. In the deterministic capacity analysis in chapter B-2 it shows that by an assigning an additional operator to the repair centre bottleneck changes towards the test centre, with the functional test machine operation as specific bottleneck. This means that if the capacity is increased, both the work centres need more manhours assigned. Additionally, the type of task in the process limit the options for capacity adjustment. The manual work performed in both the test centre and the repair centre is of assembly and disassembly nature. The automatic test execution is pre-programmed for a fixed amount of time. Which means that there is no possibility to increase work speed. The only way to produce more productivity is to add more man hours to the system for the production period.

Trigger logic for the capacity change should relate to the scale wherewith the criterion for capacity change is measured. In the case of the LC process the probability of lateness is a valid option for capacity change. The trigger to change capacity should therefor be event orientated, and more precisely the point where the load onto the system will exceed the capacity for the respective period. To calculate the approaching load, an estimation of the individual jobs in the order buffer and the WIP must be made, as the actual load of a single order can only be estimated accurately after the initial test has been completed and work scope is defined. Hence the initial assumption on repair time required for an order is used to estimate the load for that order and some safety factor. The total load onto the system is the sum of the loads of all orders.

The capacity control configuration is largely dependent on the prerequisites and environment of the process. These determine what the amount of additional capacity available and how flexible this can be mobilized.

The scope for capacity control indicates the manhour requirement to be increased over the entire process for a capacity change to take effect. This could be done by dispatching more operators to the process. With the LC process being a new process with new certification requirements, the current work force available at E&M for the process is limited by 6 operators. Other employees can not be dispatched to the lack of full cross-training of operators in the different workshops. This leaves the only option for additional manhours to work additional hours outside regular working hours with the entire process. Given the pressure on the normal work schedule, this can only be applied in very short periods of time. These kind of over time methods have shown to increase general stress in operations and an overall decrease in employee well being. Additionally, *overtime-stress* makes employees susceptible to error making in increasing complicated tasks and more casual in secondary tasks such as keeping of records [45]. It has therefor been decided that due to the by effects of the pressed schedule, the design will not include an official over time capacity reserve.

The supply chain environment described in section B-2 describes the opportunity to outsource orders. Outsourcing orders that have an unacceptable risk of being late could be valuable option for production.[27] However the total throughput time available does not allow for an extensive logistical process to be added to the total shop throughput. By adding additional sub-processes to the routing, the risk of lateness only increases. It is therefor crucial to allow as much time possible for outsourcing to take place. This would be at the beginning of the entire supply chain process. As this is, at the moment of writing, not possible due to IT infrastructural limitations. The outsourcing decision is made upon arrival of a component at the shop. This makes the outsourcing part of the capacity planning rather than capacity control.

This evaluation concludes that the due to the straining environment that has been created for the LC process. It is not possible to add capacity control to the production process.

Presentation of control configuration

With the four configuring substeps of step 5 of the design framework completed, the total logistic scheme of the process can be presented. Figure B-6 depicts the controlled production process including all the control elements that have been configured.

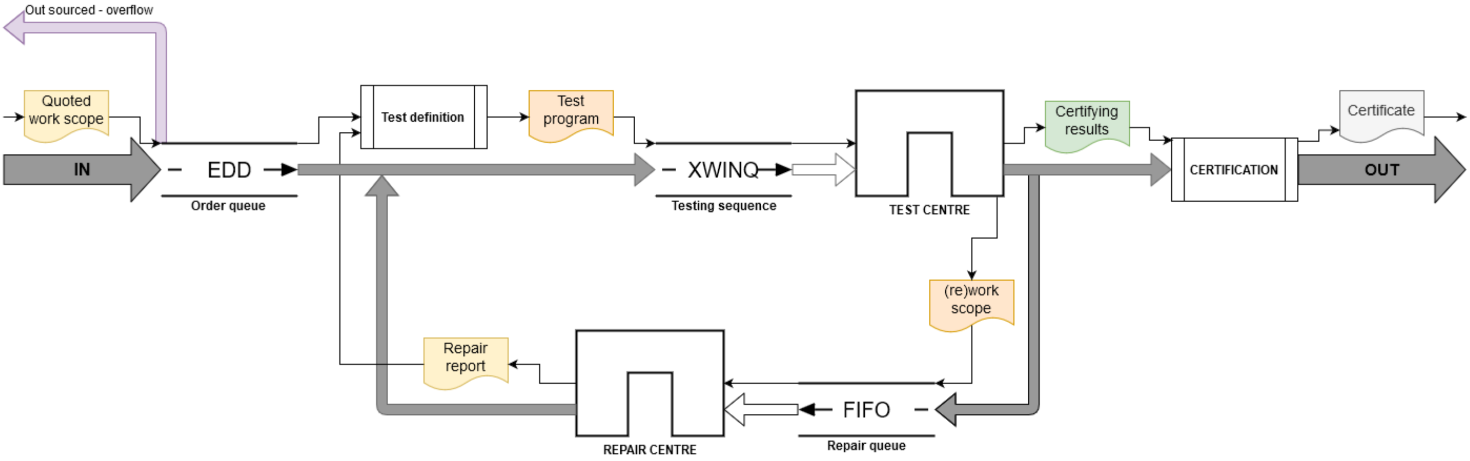

Figure B-6: The controlled production process overview in Value Stream Mapping (VSM) configuration with control elements added

B-5 *Step 6:Production control information structure*

Figure B-6 depicts an overview of all control elements defined in step 5 and their integration in the MRO process. Additionally, step 5 provides the schematic representation of the control functions, including their information requirements of the separate elements. These control elements can be included in the LC MRO process scheme of Figure B-8. This forms the integrated process and control information overview, depicted in Figure B-10.

For each control function the information requirement regarding quality has been determined. Each table contains a description of the minimum of information quality of each of the quality dimensions for each signal. Additionally the signal types are mentioned. The signal type can also be seen in the IDEF0 schematics and distinguishes information to base decisions on and information on the reference. Analysing Table B-7 for the quality dimension actuality, shows several signals to be determined prior to operation start. These are set values that for the control system and are the actuating parameters wherewith the control system can be regulated and are listed below:

- norm throughput time of bottleneck station
- load limit

Norm throughput time The norm throughput time of the bottleneck is used in all calculations regarding the current load on the stem. It is the translating value between an order and a spendable capacity. The fraction of throughput time available for the system and the time required for the order determines if the order would be on time if the decision would be made to accept the order. Time available t_{av} for the order is determined by summing all prevailing jobs WIP_i in the system and subtracting this value from the available contract time t_{DD}:

$$t_a = t_{DD} - WIP_i \times R_b \tag{B-1}$$

The value R_b is bottleneck rate of the process. In this particular case the bottleneck rate is a function of number of operators in the repair centre and the norm throughput time the estimated processing time at the station.

$$R_b = \frac{N_{op}}{T_{norm,b}} \tag{B-2}$$

The order generation function accepts orders on the occasion that these can be accommodated in the process without an order being late. As all previous mentioned parameters are determined by the production environment (staffing, WIP and contract time) the only parameter setting for influencing order acceptance is the norm throughput time.

Load limit The load limit is a fixed amount of production load the system is allowed to be subjected to. Every order release the load on the system is increased. Expressing this value in the number of orders or units this number would correspond with the WIP of the system. With the logistic curves in Figure 2-5 it is shown that increasing the production load will increase output through the expense of increased throughput time. After a critical value, throughput time keeps increasing whilst the rate remains stable. In practice this critical value is more of a transitional zone and can be varied to achieve desired performance. This value is determined before operation commences under full load the position of the process along its logistic curve. Setting the load limit, restricts the process from moving up the logistic curve. Hence controlling the production system throughput rate and throughput time. Under operation this value can be altered to suit the current needs of the shop.

B-6 *Step 7: Robustification of control information*

The previous step produced the information structure required for the production control system to function and the specific quality of the information signals. Additionally, two control variables are produced that can be used to regulate the production system in its environment, being the norm throughput time and the load limit or WIP and are for the current system expressed in LC units released into the system. Tuning the control system for desired performance is done by increasing or decreasing the values simultaneously or individually.

However, the analysis of theory in Chapter 2 and analysis of practice in the steps 1 to 4, shows that a number of units is not guaranteed to correspond with the amount of capacity available in the system, as work load of every order is subject to variance, which includes the estimation error for the initial norm throughput time at the repair centre. It is therefor decided to evaluate the potential other expressions for the control parameters.

Definition of work load

There are different ways dimensions to define work. The current proposition measures work in the amount of orders that are present in the system. One "job" is one unit and represents a load required of the deployed capacity. The amount of load is predetermined with a norm quantity. This quantity should represent the entire set of units put through the system.

			Information Quality		
Control element	Signal	signal type	granularity	actuality	accuracy
Order generation					
	client order	input	confirmation of presence in shop	current	binary
	System load state	input	number of orders in system	current	by whole orders
	Norm throughput time	input	throughput time of bottleneck	pre ops determined set value	tenth of hour
	Max expected order load	input	expeted load in decimated hours	at moment of arrival	total hours of bottleneck processing
	due date	input	date of required departure of shop	current	departure day
	load limit	reference	a number of units allowed in system	pre ops determined set value	whole LC units
	contract time	reference	number of days available for the shop visit	current	days
Order release					
	accepted order	input	confirmation of presence order buffer	at trigger signal	binary
	System load state	input	number of orders in system	at trigger signal	by whole orders
	manpower planning	input	number of operators and their hours available for the upcoming contract time	current	total hours of bottleneck processing
	trigger signal	reference	bottleneck vacancy	default test time before bottleneck vacancy	to the degree it prewarns for vacancy

Table B-7: Information quality requirement for Order generation and Order release function after step 5

			Information Quality		
Control element	Signal	signal type	granularity	actuality	accuracy
Order sequencing					
	accepted orders	input	one queue position for every order	current	by whole orders
	due date	reference	date of required departure of shop	from order generation	departure day
Test centre sequencing					
	component status	input	untested or repaired	current	binary
	sequence of orders	reference	status of the prevailing components	current	binary

Table B-8: Information quality requirement for Sequencing functions after step 5

An other option is to split all orders into the required resources that are needed for the completion of the respective orders and the time required to spend the resources on the orders [21]. The load on the system is the sum of all the requirements per order for their respective resource. This leaves a detailed insight on the load on each resource and is a direct representation of the actual WIP. In production systems clearly restricted by one resource, the order can also be expressed in that particular resource only, to reduce the control parameter complexity.

Redefining system load measurement

In Section B-3-3 the analysis has shown to expect high variance of load per order. By restricting the number of units in the system by the CONWIP control method, the number of orders in the system is limited, but the total load on the system is subject to variance, as the individual orders in system represent varying loads. This undermines the production load stabilization of the WIP restriction. To tackle this issue the WIP could be expressed not in units in system, but in its equivalent of capacity requirement [21]; this concept will be referred to as Equivalent Work in Process (EWIP).

The new approach to load measurement has implications for the control configuration parameters. The control parameter *load limit* that was previously expressed in whole units to deployed bottleneck capacity. For the LC process the deployed capacity would be the number of manhours available in the repair station. The control parameter *norm throughput time* changes dimension. Instead of having a standard for value to estimate the amount of work in the system, the sum of individually estimated workloads of the respective orders is used. For this control configuration, every order an estimate of bottleneck capacity must be made. This changes the control function variable substantially as now no reference signal can be defined for the individual orders. Therefor a factor is used to readjust the total sum of estimates.

With this new dimension the order generation function changes to Figure B-7. The other control functions are the sequencing control functions. Their control parameters are based on component status in the repair loop and due date of the component. These are both values independent of the work scope detail and do not change over the redefinition of load measurement, hence these remain unchanged. Figure B-10 shows the order generation function implemented into the total IDEF0 process overview.

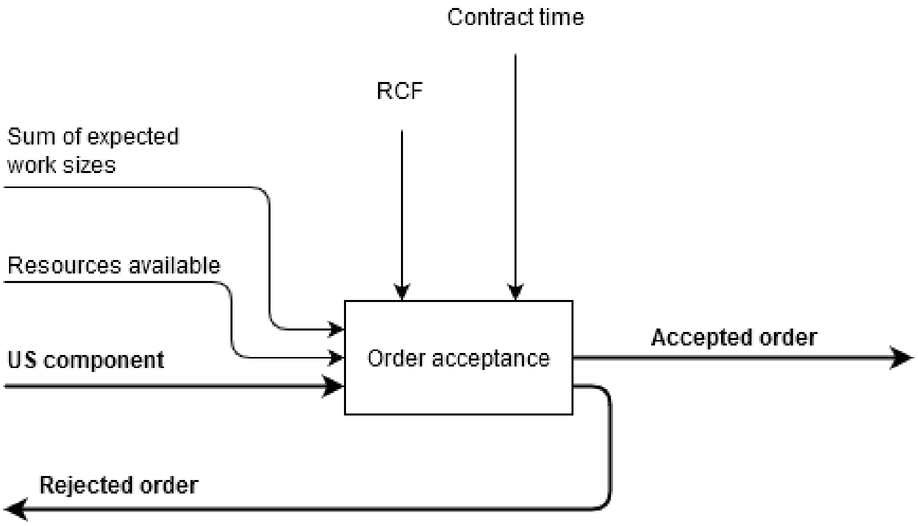

Figure B-7: IDEF0 representation of the robustified order generation function

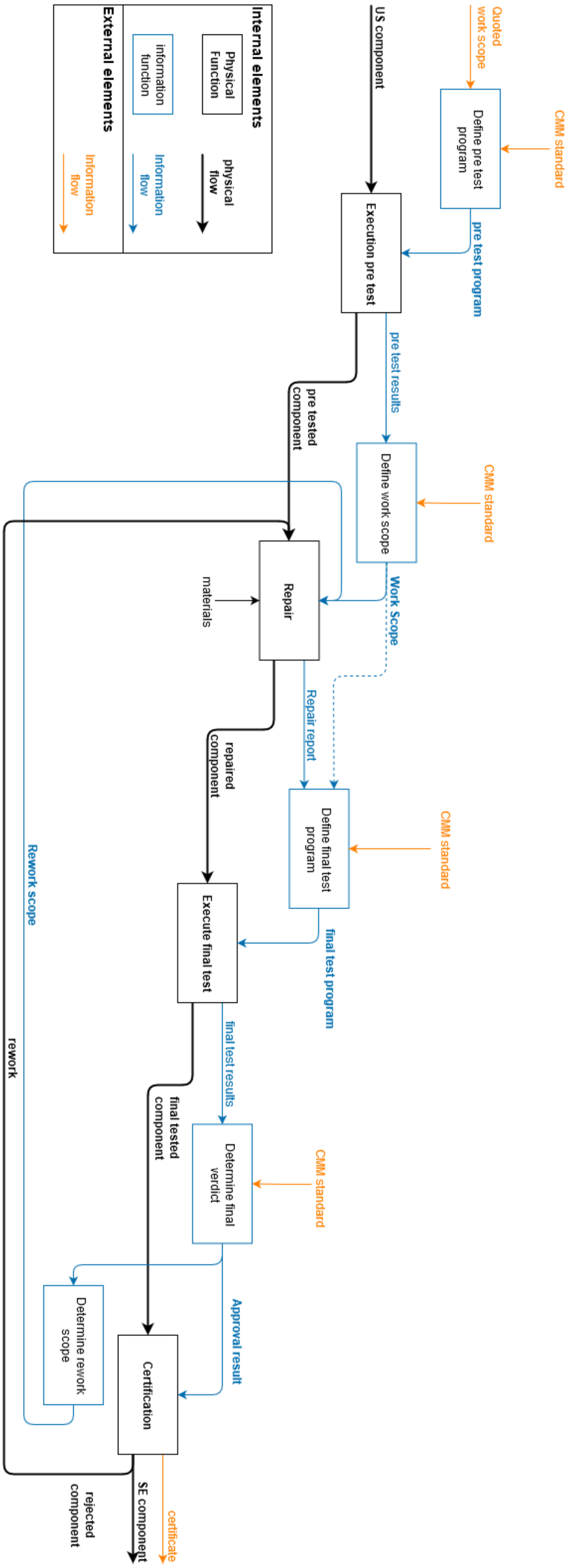

Figure B-8: The MRO process in IDEF0 format showing process logistics and information

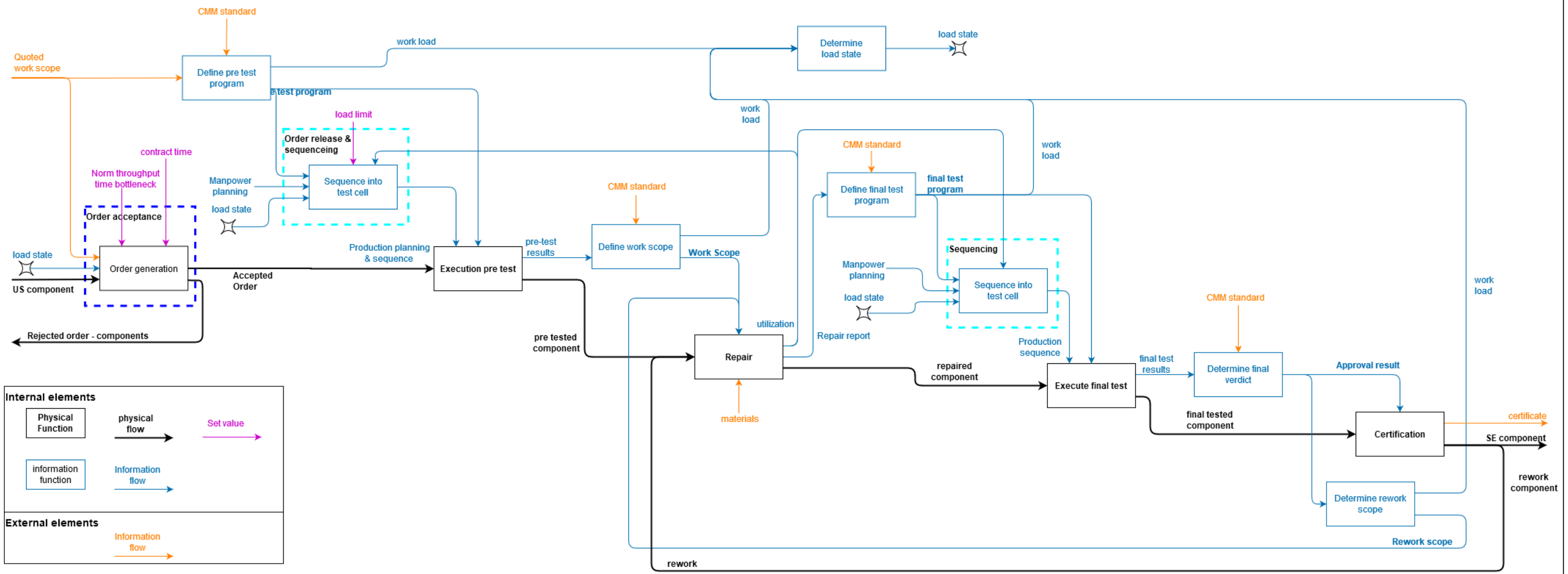

Figure B-9: The integrated process control function in IDEF0 configuration

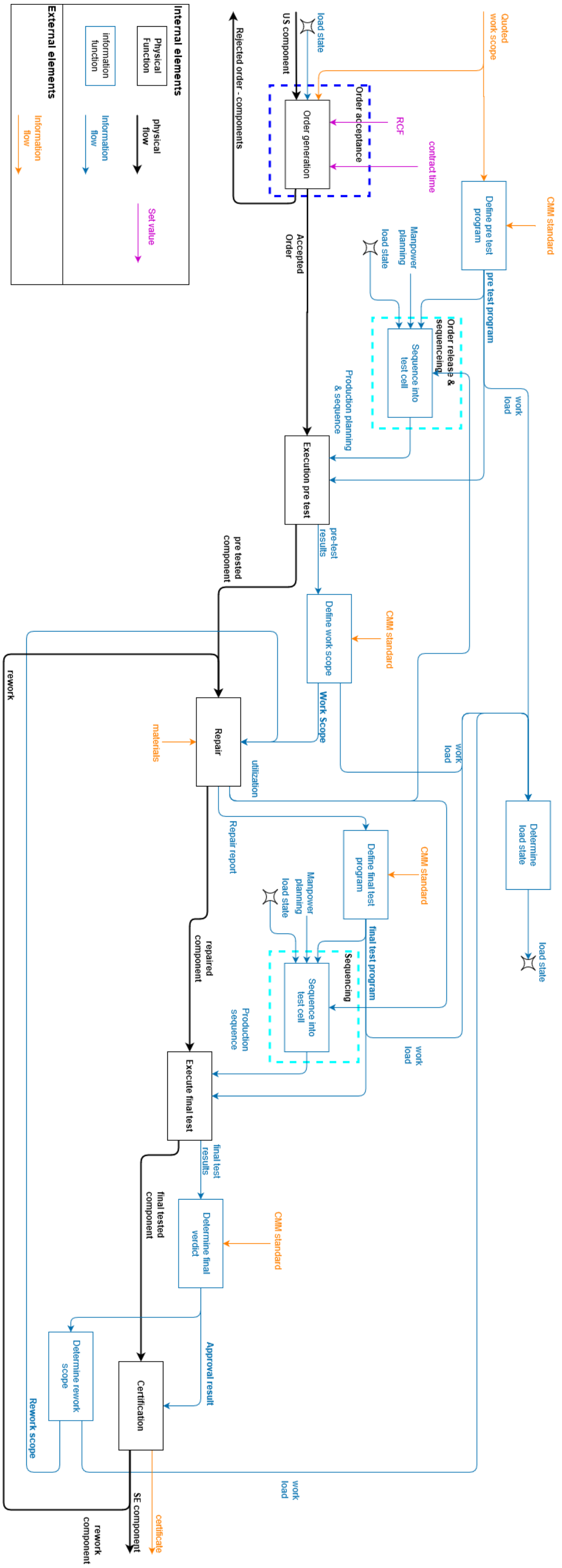

Figure B-10: The integrated process control function in IDEF0 configuration

Appendix C

Input-Output parameters for Discrete Event Simulation

The Discrete Event Simulation (DES) simulation model has been constructed to evaluate Liquid Cooling (LC) process at KLM Engineering & Maintenance (E&M). To broaden its applicability and possible scalability the model is fully parametrized with the following features:

- Toggle switch for Work in Process (WIP) and Equivalent Work in Process (EWIP) control configuration
- Custom characterization of stochastic properties of job processing requirements
- Custom characterization of stochastic properties of estimation errors
- Custom characterization of stochastic property of rework
- Qualification of production means including availability factors for the production environment
- Qualification of the control system set parameters

Data from the simulation can be extracted manually by event logging of:

- Status and residense of all orders arriving at the process
- Queue stats of all equipment
- Queue stats of all operators

Or the software can run iterations and automatically extracts information form each iteration and provides detailed overview of all system properties, including the standard deviation of average values.

No.	Category	Element	Attribute	Type
1	SIMULATION CONTROL		experiement number	int
2			random seed	int
3			simulation time	flaot
4			iterations	int
5			time off-set for analysis	float
6			event tracing	bolean
7	CONTROL CONFIG OPTIONS		run-in drive option	bolean
8			ctrl WIP option	bolean
9			ctrl EWIP option	bolean
10			job ejection option	bolean
11			estimation errors option	bolean
12	PROCESS CONTROL	control parameters	wip limit	int
13			manhours for testing	fraction
14			manhours for repair	fraction
15		planning assumptions	test machine availability	fraction
16			repair position availability	fraction
17			manhour availability	fraction
18			time per day	float
19			due days	int
20		v-test	norm time	float
21		f-test	norm time	float
22		b-test	norm time	float
23		repair	norm time	float
24		yield after passes	norm	int
25	SYSTEM DESIGN	repair cell	repair positions	int
26			repair men	int
27		test cell	machine v-test	int
28			machine f-test	int
29			machine b-test	int
30			test operators	int
31	ORDER DESIGN	routing required	repair	int
32			v-test	int
33			f-test	int
34			b-test	int
35		v-test	distribution type	name
36			shape	multilpe
37			touch time	float
38		f-test	distribution type	name
39			shape	multilpe
40			touch time	float
41		b-test	distribution type	name
42			shape	multilpe
43			touch time	float
44		repair	distribution type	name
45			shape	multilpe
46			touch time	float
47		yield after passes	distribution type	name
48			shape	multilpe
49		error	distribution type	name
50			shape	multilpe
51		interarrival time	distribution type	name
52			shape	multilpe

Table C-1: Input parameters, entities and data types

Simulation input-output parameters

The simulation software receives input that is specified prior to simulation. Different categories exist and several parameters are used to describe the elements and their attributes. A full overview of the parameters and categorization is provided in Table C-1.

Output of the simulation is passed the simulation control environment surrounding the DES model. The simulation control module summarizes the output of all iterations for a configuration and stores it in a data array given by Table C-2.

No.	Category	Parameter	Types	
1	SIM STATS	run no	value	
2		config no	value	
3		it no	value	
4		sim time	mean	
5		analysis time	mean	
6	JOB STATS - gen	Analysis time start	mean	
7		Analysis time span	mean	
8		Jobs completed	mean	
9		Jobs rejected	mean	
10		Jobs ejected	mean	
11		Throughput r	mean	
12	JOB STATS - All	buffer time	mean	var
14		cycle time	mean	var
16		in-process waiting	mean	var
18	JOB STATS - perfomance	buffer time	mean	var
20		cycle time	mean	var
22		in-process waiting	mean	var
24	JOB STATS - non-performance	buffer time	mean	var
26		cycle time	mean	var
28		in-process waiting	mean	var
30	WIP level	pieces	mean	var
32	EWIP level	test1_T	mean	var
34		test2_T	mean	var
36		test3_T	mean	var
38		repair_T	mean	var
40	d EWIP level	test1_T	mean	var
42		test2_T	mean	var
44		test3_T	mean	var
46		repair_T	mean	var
48	true WIP level	pieces	mean	var
50		test1_T	mean	var
52		test2_T	mean	var
54		test3_T	mean	var
56		repair_T	mean	var
58	true d-EWIP level	test1_T	mean	var
60		test2_T	mean	var
62		test3_T	mean	var
64		repair_T	mean	var
66	REPAIR CELL	occupancy	mean	var
68		queue length	mean	var
70	TEST OPERATOR	occupancy	mean	var
72		queue length	mean	var
74	TEST MACHINE 1	occupancy	mean	var
76		queue length	mean	var
78	TEST MACHINE 2	occupancy	mean	var
80		queue length	mean	var
82	TEST MACHINE 3	occupancy	mean	var
84		queue length	mean	var
86	QUEUES	accpeted orders	mean	var
87		accpeted orders		
88		main queue size	mean	
89		main queue size	mean	
90	SYSTEM EFFECTIVENESS	capacity	mean	
91		inventory	mean	
92		time	mean	
93		OTP	mean	

Table C-2: Output parameters, entities and data types

Appendix D

Default simulation input

The standard input data set has been used for all validation and evaluation experiments unless the experiment description states otherwise. For some parameters the values could not considered standard. These have to be defined for their respective experiments.

No.	Category	Element	Attribute	Type	units	*a*	*b*
1	SIMULATION CONTROL		experiement number	-			
2			random seed	44			
3			simulation time	2200	hrs.		
4			iterations	400			
5			time off-set for analysis	200	hrs.		
6			event tracing	-			
7	CONTROL CONFIG OPTIONS		run-in drive option	FALSE			
8			ctrl WIP option	-			
9			ctrl EWIP option	-			
10			job ejection option	FALSE			
11			estimation errors option	FALSE			
12	PROCESS CONTROL	control parameters	wip limit	7	pcs.		
13			manhours for testing	1			
14			manhours for repair	1			
15		planning assumptions	test machine availability	0.98			
16			repair position availability	1			
17			manhour availability	0.8			
18			time per day	8			
19			due days	6			
20		v-test	norm time	1			
21		f-test	norm time	2			
22		b-test	norm time	0.5			
23		repair	norm time	22	hrs.		
24		yield after passes	norm	1			
25	SYSTEM DESIGN	repair cell	repair positions	5	pcs.		
26			repair men	5	pcs.		
27		test cell	machine v-test	1	pcs.		
28			machine f-test	1	pcs.		
29			machine b-test	1	pcs.		
30			test operators	1	pcs.		
31	ORDER DESIGN	routing required	repair	1			
32			v-test	2			
33			f-test	2			
34			b-test	2			
35		v-test	processing mean	0.5	hrs.		
36			distribution type	binom		0.8	
37			touch time	0.25	hrs.		
38		f-test	processing mean	1.5	hrs.		
39			distribution type	binom		0.8	
40			touch time	0.25	hrs.		
41		b-test	processing mean	0.5	hrs.		
42			distribution type	binom		0.8	
43			touch time	0	hrs.		
44		repair	processing mean	22	hrs.		
45			distribution type	uni		22	22
46			touch time	0	hrs.		
47		yield after passes	process mean	1			
48			distribution type	uni int		1	1
49		error	process mean	0	hrs.		
50			distribution type	uni		0	0
51		interarrival time	process mean	6	hrs.		
52			distribution type	uni		6	6

Table D-1: Input parameters entities and data types

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Glossary

List of Acronyms

AF	Air France
AFI	Air France Industries
CMM	Component Maintenance Manual
CONWIP	CONstant Work In Process
CRU	Cargo Refrigeration Unit
CS	Component Services
DDD	due date deviaction
DDR	due date reliability
DES	Discrete Event Simulation
DBR	Drum-Buffer-Rope
ECS	Environmental Control System
EDD	Earliest Due-Date
E&M	KLM Engineering & Maintenance
ES	Engine Services
EWIP	Equivalent Work in Process
FIFO	First-in-first-out
FMEA	Failure Mode Effect Analysis
IAT	Interarrival Time
KPI	Key Performance Indicator
KLM	Koninklijke Luchtvaart Maatschappij
LC	Liquid Cooling
LRU	Line Replacement Units
MSG	Maintenance Systems Group

MPD	Maintenance Planning Documents
MRB	Maintenance Review Board
MRO	Maintenance, Repair & Overhaul
OEM	Original Equipment Manufacturer
OLS	Ordinary Least Squares
OTP	On-time performance
PSAA	Product Support and Assurance Agreement
RCM	Reliability Centred Maintenance
SCU	Supplemental Cooling Unit
SE	Serviceable
SFPC	Shop Floor Planning and Control
SRU	Shop Replacement Units
TAT	Turn-Around-Time
US	Unserviceable
VSM	Value Stream Mapping
WIP	Work in Process
XWINQ	Extended Work in Next Queue