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Exploratory Assembly Process Evaluation through Manufacturing Simulation

A Discrete Event Simulation Case Study in Mass Customized Manual Assembly

Master's thesis in Production Engineering

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Cover: A view from the simulation model in Siemens Plant Simulation, illustrating a worker moving a cart with kitted components.

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Abstract

The rise of mass customization imposes significant challenges for manufacturing companies regarding management and development of manufacturing systems, where advanced digital technologies such as simulation can serve as central enablers. The assembly process of the truck manufacturer Volvo Trucks in Tuve handles a broad range of customized product variants. This imposes complexity in process redesign and rebalancing, increases reliance on buffers and challenges efficient resource utilization. In this study, Discrete Event Simulation is applied as a data-driven and visual support tool for iterative, Lean oriented redesign and evaluation of a manual assembly process, supporting close collaboration with process and data domain experts of the company. An approach for handling of detailed Predetermined Time System process data and production levelling rules is applied, generating a detailed, stochastic simulation of product based variation, enabling the model user to conduct subsequent experiments covering changes in both demand and levelling restrictions. The developed model is used as a basis for analyzing the effects of implementation of parallelized, stationary assembly and kitting, where the resulting workload and manning requirements, as well as required buffer levels safety margins in a Kanban implementation, are evaluated with regards to product based variation and production pace. The study indicates the usefulness of Discrete Event Simulation in mass customization environments, and underlines challenges of data management and model complexity. The study identifies a number of benefits in the implementation of kitting and parallelization, as well as several drawbacks and potential risks.

Keywords: Discrete Event Simulation, Lean Manufacturing, Production Levelling, Mixed-Model Manual Assembly, Methods-Time Measurement, Predetermined Time Systems, Process Development

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Erik Ingemarsson, Edvin Thorstensson, Gothenburg, June 2024

List of Abbreviations

AGV Automated Guided Vehicle. 36, 38, 52

CAD Computer Aided Design. xv, xvii, 37–40, 62

DES Discrete-Event Simulation. 2, 3, 5, 9, 11–14, 16, 18, 21, 23, 24, 26, 61, 62, 66, 68, 69, 71

GTO Group Trucks Operations. 1, 24, 71

MTM Methods-Time Measurement. 17, 18, 27, 29, 31, 32, 54, 63, 68
MTTR Mean Time To Repair. 34, 52

OTD On-Time Delivery. xvi, 42, 43, 46, 52–55, 59, 62

PTS Predetermined Time System. 3, 17–19, 31, 61, 63, 67, 68, 71

WIP Work-in-Process. 1, 2, 9, 26, 66, 71

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1

Introduction

1.1 Background

Manufacturing companies face several challenges in adapting to the increasing demand for customization [3–5]. The implementation of mass customization presents a paradox for these companies: they must manage highly customized products within a high-volume, high-efficiency, mass production environment [6]. Manufacturers embracing mass customization face two central challenges: managing the ability to design systems and processes capable of handling broad variant ranges, and managing the ability to assemble the broad range of materials corresponding to the variant flora [6, 7]. To tackle these challenges, research underlines the importance of Industry 4.0 digital technologies as key enablers of mass customization management [8], involving aspects such as simulation and digital twins [9, 10].

Volvo Group Trucks Operations (GTO) is a Swedish manufacturer of engines, transmissions, and trucks [11]. In their truck manufacturing plant in Tuve, Gothenburg, Volvo GTO manufactures heavy duty trucks in a process centered around a Mixed-Model-Assembly line, handling the assembly of highly customized products in accordance to customer orders. The assembly process is largely manual, both at the production line and in pre-assembly. This is also the case in the Valve Assembly, a pre-assembly process handling the assembly of several types of valves and similar components, supplied to the main line in moving kits.

The amount of components, component types, and detailed configurations vary significantly for each chassi at the main line, inducing high levels of product based variation in the cycle times of all assembly stations. This variation imposes several challenges for the process itself and the work of process development and waste elimination. For example, workload balancing between the stations is significantly hampered by the need to consider both variations in assembly time for product variants, and variations in the demand of variants affecting the production sequence and distribution. At present, the variation is handled by the operators themselves taking initiatives of additional buffers of assembled pieces at their respective stations. This leads to unnecessary levels of Work-in-Process (WIP), increases the risks of mix-ups in the kitting process, and demands additional process time to handle buffered material. The wide range of variants to assemble also make the process at the stations difficult for less experienced operators to learn, making stations reliant on more experienced operators, and reducing the possibilities of work rotation. A redesign of the assembly process is anticipated to reduce these problems significantly.

A number of ideas for improvement have already been generated by process experts, but these have not yet been specified in detail nor tested or verified. One central idea to avoid the issues of balancing is to introduce parallelization of the tasks of the stations. Furthermore, there are initiatives at place with the aim of increasing the levels of kitting for high value material in order to reduce material storage close to the production line, a change which would likely also affect the assembly times of the stations. However, such redesigns are both expensive and resource demanding to conduct, and due to the high levels of variation and complexity of the process, the outcome of such a change is highly difficult to predict using traditional methods.

Discrete-Event Simulation (DES) offers the possibility to analyze the behavior of complex processes and production flows [1,12–14], including the effects that changes in layout [15], buffer allocation [16], process time variation [17], or numerous other system parameters have on the performance of a system. Simulation is currently used in the Tuve plant at a low scale, but there is a desire to further promote the use of simulation as a support tool both in analysis and as a development. The simulation tools currently in use are commonly criticized for being unpedagogical and for lacking visual representation, factors that make the simulation models and results difficult to comprehend for other stakeholders than those involved in the model construction and/or well versed in the subject of simulation. By implementation of a more detailed and visually supportive simulation tool, it is hoped that simulation could be of increased support in the work of manufacturing process development and analysis, with increased possibilities of understanding and handling product variant based variation.

1.2 Aim

The project aims to examine the usefulness of DES as a support tool for developing and evaluating process design changes, and supporting the assessment of resource demand and minimization of buffers in mixed-model manufacturing systems featuring high levels of product variant based variation. The project evolves around a case study, where the introduction of two conceptual changes in the valve assembly process are to be implemented in detail, simulated and evaluated using DES. The first change concerns the division of work for each order, where the current task distribution is to be exchanged with a parallelized workflow, where each assembly station is to handle all assemblies for one order. The second change relates to the material delivery, where the current material picking by the operators of each station is to be replaced by kitting of high value/low volume material. The DES model should illustrate the behavior of the manufacturing process after implementation of the specified process design changes and enable subsequent experimentation for the user. Based upon the simulation model, evaluations of system performance, resource and operator utilization are to be made by regards to different levels of production pace on the main production line. Furthermore, required buffer locations and sizes are to be studied, with the aim of minimizing WIP.

1.3 Research Questions

To support the realization of the project aim presented in Section 1.2, the project conduction was guided by a set of research questions presented below.

RQ1. How can DES support studies of assembly processes featuring high levels of product based variation?

RQ2. What are the effects of parallelization & kitting on a manual assembly process?

1.4 Delimitations

This Master's Thesis project is set to correspond to 30 higher education credits, and is thus to be conducted within a limited time frame of 20 weeks, spanning from January 15 to June 16, 2024. The defined duration imposes several constraints on the project scope. The main delimitations established for the study are specified below.

The project focuses exclusively on detailed studies of processes within or directly related to the valve assembly stations. It does not cover detailed studies of component supply and restocking for the assembly process or subsequent operations at the main line. The implementation of kitting does not include a detailed analysis of suitable components for kitting or the design of kit containers.

Furthermore, the project does not include forecasting or considerations of future demand and product ranges. The assembly methods and process times specified in the Predetermined Time System (PTS) data of the current process design are assumed to be accurate, and this project does not involve detailed validation of these times.

1.5 Report Structure

In this section, an overview presentation of the contents and structure of this report is provided. Chapter 1 provides a description of the project background and the problems that motivate the study, as well as the project aim, research questions and delimitations established to guide the study. Chapter 2 presents the theoretical background of the project used to support the project aim, research questions, and applied methodology. The chapter also provides an overview of the latest research related to the focus of the project. Chapter 3 explains the methodology applied in the project in order to achieve the project aim and answer the research questions. The subsequent project results are then presented in Chapter 4. In Chapter 5, the achieved project results and methods used are both discussed and used as a basis of answering the research questions, and recommendations are given for further studies. Finally, Chapter 6 presents the conclusions drawn on basis of the project results.

2

Theoretical Background

In this chapter, the underlying theories and literature supporting the project focus and applied methodology are presented. The contents constitute the result of a literature study conducted in parallel, and in support of, the simulation study. Section 2.1 provides an overview of the subject of manufacturing systems with a focus on serial and parallel production flows. The section also includes an overview of the subject of Lean manufacturing and waste in production processes. Lastly, common methods of mapping and development of production systems are discussed. Section 2.2 provides an introduction to the subject of Discrete Event Simulation, its common areas of application and the theoretical guidelines for the structure and important steps involved in a simulation study. A brief introduction to the subject of DES software is also included. In Section 2.3, in introduction to the subject of Time Data Management is provided, covering the common methods used for process time determination commonly used in manufacturing industry. Finally, Section 2.4 provides an overview of present research relating to the project scope.

2.1 Manufacturing Systems

In its most general form, a manufacturing system could be viewed as a transformation of input to output through a process [18,19]. The inputs and outputs constitute the interfaces between the system and the outside world, whereas the process serves as a representation of all internal elements and activities conducted within the system, between the input and output. The process constitutes a transformation of an operand from one stage to another through changes in structure, location or in the time dimension, commonly with an overall purpose of creating added value [20]. A manufacturing process is differentiated by the involvement of one or several of the fundamental manufacturing techniques: cutting, changing of material properties, joining, coating, casting and molding, or forming [21]. Manufacturing constitutes one of the central steps in the process of product-realization, commonly described to consist the overview steps of design, process planning, manufacturing, and inspection [3].

2.1.1 Assembly Systems

In the context of manufacturing, assembly could be defined as the activity of fitting together different parts into a product, conducted as a continuous, economic pursuit [22]. The performance of an assembly system is controlled by two primary factors: parts supply, and assembly work design. Parts supply, in its essence, concerns the way that a part arrives in the hands of an assembler. The parts supply depends on aspects regarding both the specific parts to be delivered, the size, quantity and usage frequency of parts, and the organization and physical constraints of the delivery location, i.e. the assembly station(s). The assembly work design concerns factors such as structure and sequencing of sub-assemblies, the design of assembly procedures, distribution of assembly tasks along assembly stations, and the equipment and fixturing of the assembly stations.

2.1.2 Assembly Flow & Work Design

The moving assembly line has been a highly popular approach of assembly process design ever since its successful adoption by Ford in the early 1900's [20]. Despite an increased demand for flexibility in production systems and the rise of several substantial influences in production philosophy, the concept of the assembly line has remained successful [20, 22].

Alternative assembly flow designs were researched under the scope of humanized assembly work around the early 2000's. Organizational methods different from the assembly line were studied for example in Volvo plants in Kalmar and Uddevalla, where parallelized production flows and significantly increased cycle times were implemented [20, 23, 24]. An underlying idea in the early phases of this research was that the costs of increased worker learning time would be compensated by a reduction in turnover rate and abseentism due to increased work satisfaction. The theoretical framework for this research is referred to as *Reflective Production*, and was characterized by human adaptation of the technical system, oriented around parallel, organic flows enabling the building of complete products in self-governed teams [20].

In the context of parallelized, stationary assembly, [23] presents results indicating economically beneficial cycle times of above two hours. While work satisfaction is likely to be increased in such environments, [22] argue that this factor could be pointed out as the single factor affected positively, while several other substantial factors are affected negatively. The author points out risks such as reliance on highly skilled and trained operators, risk of decreased quality, lack of standardization and inefficiencies in material supply.

The differences between parallel, stationary assembly and serial assembly line flow provide different conditions for the operator in terms of cycle time [22]. Very short cycle times, covering only 5-10 seconds, can be highly stressful for operators and lead to injuries due to high level of repetition. Long job cycles, which may commonly be the case in parallel flows, lead to the work not being repetitive enough for the worker to fall into routine. Workers may risk forgetting where they are in the sequence, resulting in missed steps in the assembly. Long cycles demand specific care to mitigate the risks of errors and support the operator.

A common approach to reduce these problems is modularization, where products are broken down into several identical or similar modules, which enables the complete assembly to be divided into sub-assemblies with shorter job cycles [22]. Long cycles can also be divided into operation sequences, resulting in a series of shorter cycles. With smaller products, the operation sequence can be further clarified for the operator by allowing the operations to be performed in a series of stations which the operator can move the product between, which helps the operator keep track of their position in the sequence.

In addition to the above mentioned risks regarding quality, [22] also underline factors of potential waste in resource demand and logistics. In a stationary, parallelized assembly, the delivery locations for components are distributed across all stations, whereas specific components commonly only need to be delivered to a few use points in an assembly line flow. Similarly, a parallelized flow results in a full set of equipment for the assembly required for each station or workbench, which results in increased costs and space requirements for each station for tooling and fixturing.

2.1.3 Material Delivery Design

In addition to the factors of assembly work and flow design, material delivery is the main factor that affects performance of an assembly system [22]. In-plant material feeding principles can be sorted in the three main categories of line stocking, sequencing, and kitting, all commonly occurring in automotive manufacturing industry [25]. Each type features different advantages depending on factors such as ranges of components and component variants, layout and space factors, and the design and pace of the manufacturing system [25, 26].

In line stocking, components and parts are delivered to the point of assembly in unit-loads with multiple instances of the same component packed in containers [25]. The containers are presented at the point of assembly, where the operator handles the picking of the correct parts and amounts. Replenishment can be handled through consumption based replenishment or based upon replenishment signals such as Kanban. A general division is made between the line stocking principles of continuous supply and batch supply, where the latter concerns a controlled, commonly smaller, amount of material is delivered, corresponding to the amounts needed for a specified amount of end-products.

Kitting and sequencing instead concern the delivery of specific components for a future delivery sequence [25]. The unit of delivery in kitting consists of a kit, defined as a container holding the specific assortment of parts required in an assembly sequence. The purpose of this approach is to provide only the required material for a certain assembly at the time of the assembly. This can reduce space requirements for material storage and the required movement for material fetching for operators. Furthermore, the cognitive load, and thus the risk of assembly errors, can be reduced by presenting only the right components to assemble.

Kitting provides several benefits, such as space efficiency for part presentation, improved quality and reduced learning time [26]. Meanwhile, some potential benefits also need to be balanced against a number of drawbacks. While kitting can help reduce the time for picking material at the assembly and the space requirements for material storage at the assembly station, it also demands additional resources for kit preparation. This includes both the resources needed to prepare the kits and the workspace for kit preparation, which may increase operational costs. [25]. It may also result in additional need of material transportation, if kitting is not performed in close connection with the assembly [26].

2.1.4 Lean Manufacturing

Lean Manufacturing is a Japanese philosophy based upon ideas and concepts from the Toyota Production System, with the focus on elimination of waste [27]. In the specific context of assembly operations, [22] specifies the following main factors of waste

Overproduction Operators continue assembly despite enough having already been produced and buffered, indicating overcapacity.

Waiting Operators waiting for material, machines finishing automatic processes, for co-workers to finish their operation, etc. indicating a failure to successfully plan the use of an operator's time.

Transportation Time and resources used on moving parts unnecessarily, indicating failure to arrange a process to facilitate flow.

Process Unnecessary activities, inefficient working methods or similar factors.

Excess Inventory Unnecessary material storage with parts, unfinished assemblies, etcetera, resulting in wasted capital and/or extra work tasks for handling, indicating overproduction, a push of material from Material Handlers (MH), etcetera.

Motion Unnecessary steps for fetching far away material, handling of the same part several times, etcetera.

Production of Defectives Errors in assembly causing wasted material or requiring additional time for disassembly.

In addition to this, [28] adds the following factor to the list

Unused Employee Creativity Loss of time, ideas, skills and improvements through lack of engagement and listening to employees.

and [27] also specifies the included focus of environmental sustainability in Lean theory through the factor

Environmental Waste Wastes in terms of emissions or environmental impact.

Lean theory divide waste in three main categories commonly referred to as Muda, Muri and Mura. Muda constitutes waste-generated tasks listed above [27]. Muri concerns the aspect of overburden caused by lack of structure and standardized work. Finally, Mura involves the factor of variation or unevenness in production volume and/or workload.

Lean manufacturing features a range of different concepts and tools that support systematic analysis and elimination of waste [27]. A central principle is the categorization and reduction of non value-adding work, with the focus on activities that produce value to the customer, and implementation of Just-In-Time principles. The pull principle constitutes one of the central elements in Lean, which aims primarily to reduce the means of overproduction, which is commonly considered the most central factor of waste, and the common cause for a majority of the other factors [28]. Pull production enforces production strictly controlled by customer demand, which serves to streamline WIP and inventory, and enables Just-In-Time production and material delivery [27].

The theory of Lean manufacturing provides a set of concretized, core support tools such as Poka Yoke and Kanban, which can serve to support the enforcement of Lean principles in concrete industrial applications [27]. Poka Yoke is an approach of error prevention, aiming to prevent or reduce the possibilities to do wrong by implementing hindering mechanisms, such as Design-for-assembly solutions to prevent errors in assembly, gates or marking lights to highlight correct parts to pick, or sensors to detect and warn when errors occur [27–29].

Kanban is an inventory control function that imposes a visual pull signal in a material replenishment loop through a calculated number of Kanban cards, which regulate the amount of material units allowed in the system and specify the allowed levels of safety stock [27,30]. However, in order to enable efficient implementation of Kanban, a number of prerequisites need to be fulfilled, such as relatively stable demand and relatively few disturbances to production flow [31]. The factor of stable demand is however questioned by the study of [32], who suggest an approach of iterative recalculation of Kanban safety stock. The study indicates that safety stocks can be further reduced even contexts of broad product variant ranges.

2.1.5 Variation in Assembly Processes

All industrial processes are subject to factors of variation [18]. The factors of variation can be of many different types and stem from a range of different sources, such as the operator, material, process, product or the environment. A central differentiation can be made between *Common cause variation* and *special cause variation*. The former refers to variation occurring randomly and without clear cause, while the latter type refers to variation that has an assignable cause. Identification and addressing of the root causes of special cause variation is a central aspect of process improvement.

The possibilities of studying effects of variation in complex, interconnected systems could be pointed out as a common motivation for the use of DES [1]. Both common cause and special cause variation are factors possible to study in DES. Predictable aspects of variation can be handled through specification of the occurrence of this event in time, whereas unpredictable variation is instead commonly handled by calculation of statistical distributions, from which random numbers are used to draw samples and trigger the event.

As pointed out in Section 2.1.4, variation is considered a central factor of waste in Lean manufacturing, commonly referred to as Mura. An basic principle to reduce variation in production suggested by Lean theory is production levelling, commonly referred to as Heijunka [27]. Heijunka concerns the levelling of both production volume and mix by distributing variations evenly across a specified period of time [28].

2.1.6 Manufacturing Process Development

Manufacturing systems can be designed and configured in a vast amount of ways depending on the processes that are to be included, the type of product, the demand, and many other factors. In modern manufacturing system development, a holistic perspective including aspects of both technical, physical, and organizational aspects, as well as consideration of the human in the process, is commonly emphasized [20].

Theory of Operations Management involves a number of generally applicable theories based upon three main categories connected in an improvement cycle: Design, Measurement, and Improvement [18]. Regarding design, the principles underline that the throughput of a process is to be considered stochastic. Regarding the choice of process design, a fit between the task itself and the external requirements of the process is always necessary. Regarding measurement, the theory underlines the fact that no single measure can capture the performance of a process and that nothing can be manage if it can not be measured. Thirdly, regarding the subject of process improvement, the theory states that the improvement of processes is given by reductions in throughput time or in reduction of undesired variation.

Work studies are a central aspect in the detailed designing of a production system [20]. This includes studies of both the activities included in the work, the detailed methods applied, and the time requirements for these activities. A general methodology for process mapping, as an initialization to the work of process improvement is suggested by [18], who suggests the following steps

1. Go to the place where the work is done (Commonly referred to as "Gemba").
2. Capture the key processes, flows and products.
3. Capture the essential aspects of the system using a selected mapping methodology

Process Mapping concerns the conceptual representation of a process, covering the essential activities, flows and other relevant mechanisms that constitute it [18]. There is a range of different approaches available for process mapping, depending on which aspects that are found relevant to map. Examples of of such mapping approaches are process flow diagrams, information flow diagrams, value stream mapping and spaghetti diagrams.

2.2 Discrete Event Simulation

In highly generic terms, the concept of simulation could be described as the *imitation of a system or process* [1,13]. A primary, fundamental differentiation in the concept of simulation lies between *static* and *dynamic* simulations. Static simulations capture systems in a fixed state, while dynamic simulations imitate systems or processes in their progression through time [12]. DES, in its turn, constitutes a specific type of dynamic simulation characterized by state changes conducted in discrete points in time corresponding to events in the system, resulting in the formation of event sequences called *sample paths* [13, 14].

Another common differentiation in simulation is given by *deterministic* and *stochastic* simulation models [12]. Deterministic models are defined as models without probabilistic elements, which means that given a set of system relationships and input quantities, the sequence of events and simulation outcome are solidly determined. As opposed to this, stochastic models contain one or more probabilistic, or random, element, which induces variability in the simulation and its results. In most operations systems, elements of either predictable or unpredictable variation are commonly occurring [1]. In fact, the stochastic nature of throughput time in a process is considered a foundational principle in operations management [18]. Discrete Event Simulation is commonly referred to specifically in the context of stochastic modelling [13].

DES is a highly flexible tool that enables the studies of behavior and performance of complex, dynamic systems containing aspects of both variability and interconnections, which can be found useful in a wide range of study fields [1, 13]. Examples of applications can be found within a variety of sectors, for example in healthcare [33, 34], construction and infrastructure [35], logistics and transportation [36, 37]. The most common use is found in the manufacturing industry, where DES has become one of the most commonly used methods for studying the dynamics of manufacturing systems [38]. The potential application areas of DES in manufacturing are vast, spanning from studies of bottleneck detection [39], resource utilization [40] and buffer sizing [16], to subjects such as manpower planning [41], economic and environmental sustainability [42] and supply chain resilience [43].

2.2.1 Structure of Discrete Event Simulation Studies

Several variants of recommended structure for Simulation studies can be found in literature [1, 12, 13]. While the detailed steps of these approaches differ, there is a general consensus regarding the overall structural elements that need to be involved in such a project. A structural outline illustrating the main stages and deliverables in a simulation study is suggested by [1]. This outline consists of four main stages connected in a loop, as illustrated in Fig. 2.1. The model begins with a *Real world problem*, from which the first stage, a *Conceptual Model*, is generated. The conceptual model serves as a description of the model that is to be constructed. The second stage, *Computer Model*, refers to the translation or coding of the conceptual model into a computerized implementation. The third stage, *Solutions/Understand-*

ing refers to the derived results and conclusions that are generated through experimentation with the computer model. Finally, these results are to be fed back to the *Real World Problem* stage through implementation of the generated solutions or understanding.

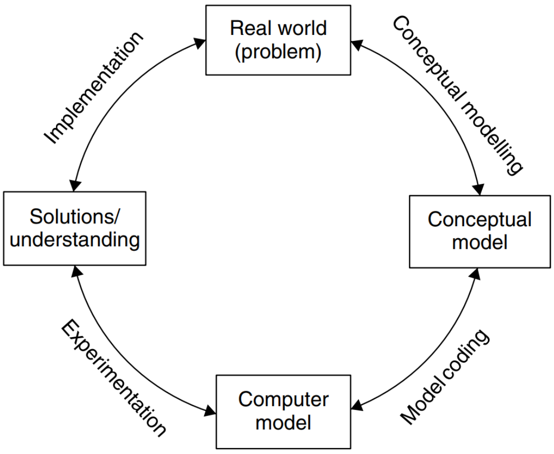


Figure 2.1: Four key stages of a simulation study [1].

A similar outline is brought into further detail by [13], who suggests a workflow divided into 12 steps. The steps can be divided into four main phases, similar to the key stages suggested by [1]. The first phase involves the steps of problem formulation and setting of objectives and overall project plan. The second phase involves the processes of data collection, model conceptualization and construction, also including the verification and validation of the constructed model and incorporated data. This is followed by the third stage, which involves the experimental design, running of the model and analysis of the achieved results. Lastly, the fourth stage involves the documentation, reporting and implementation of the achieved results.

While the overview workflow suggested by [13] could be interpreted as a sequential flow, the author points out the importance of considering the conduction of a simulation study a largely iterative process, as it may often be necessary to move back to previous steps and make adjustments in accordance to new discoveries. Furthermore, it could often be beneficial to start off with a simplified prototype model at early project stages, and then add complexity levels in an iterative fashion. [1] underline the iterative aspect of DES modelling as a central methodology to ensure trust in the model through continuous involvement of the project owner or stakeholder. The iterative approach is further argued for by [44], who state that a range of models of different complexity may be a beneficial approach to ensure that the final model is of adequate detail level for its intended purpose, since the appropriate level may not be possible to know the early stages of a simulation study.

A description of the overview steps of a DES study in accordance with the descriptions of [1, 12, 13], is presented in the following sections.

2.2.1.1 Problem & Objective Formulation

A simulation study is commonly initiated by purpose, given by the identification of a problem that needs to be studied and solved [1]. The initial problem is commonly identified by a problem owner or stakeholder [13]. A problem formulation describing what to be studied and solved should be generated by the problem owner and the modeller, in order to outline the focus of the study. This step could require several iterations, since the details of the problem may not be known until later in the study, and since the problem owner may not have enough knowledge regarding DES to know the possibilities and limitations of this technology [12].

Based upon the problem formulation, a list of objectives should be generated that specify the questions that the study aims to answer [13]. In this stage, the suitability of simulation as a means of solving the specified problem and objectives should be evaluated.

2.2.1.2 Conceptual modelling

Conceptual modelling involves the mapping of the system that is to be modelled and the inputs and outputs of the model, based upon the specified study objectives and problem formulation [1]. The purpose of this step is to determine the essential features and components of the system, which can serve to guide the subsequent modelling. A central aspect in this determination is the selection of detail level and model complexity [13]. The level of detail needs to be enough to serve as a baseline for sufficiently accurate results, while unnecessary levels of complexity and detail should preferably be avoided to reduce time for model development as well as simulation runtime.

A recommended approach to achieve a suitable level of detail is to begin with a simple model, and increase the level of detail iteratively [13]. [12] suggest the following general aspects to be considered in the selection of detail level:

1. Project Objectives
2. Performance Measures
3. Data availability
4. Credibility Concerns
5. Computer Constraints
6. Opinions of Subject-Matter Experts
7. Time and Money Constraints

The development of a conceptual model should preferably be conducted in collaboration with the problem owner [13]. Initial data collection regarding the context of the problem, the nature of the modelled system and the data that is needed to enable the modelling and analysis is commonly needed as a baseline for this step [1].

2.2.1.3 Data collection & Management

The quality of input data in DES modelling is a key factor for useful results in DES [12]. However, the collection and handling of such data can commonly also be a highly time consuming task, requiring 30% or even more of project conduction time [45]. A structured approach to reduce the time requirements for input data management is suggested by [45].

There are several different types of data needed in a simulation, ranging from the high level contextual data needed to map the interrelations between system components, to detailed time data and/or statistical distributions [1].

A central factor in manufacturing simulation is the determination and handling of process times. Process time determination methods is a broad subject in both manufacturing industry and research. A deeper study of the subject of Time Data Management can be found in Section 2.3.

2.2.1.4 Simulation Model Construction

The model construction involves the translation of the conceptual model into a computerized version, programmed in a format that enables simulation [13]. The simulation model can be constructed in several ways. One method is to construct the model using a general purpose programming language, such as Java or C++ [13]. Some general purpose programming languages offer specialized frameworks for DES, for example SimPy in Python [46]. There are also dedicated simulation programming languages available, such as GPSS/H [13]. The use of programming languages can offer several different perks, such as high levels of program control, lower purchasing cost and potentially faster simulation runtime [12].

Another approach is to use dedicated simulation software. There is a broad range of dedicated simulation software available, designed for use in manufacturing, material handling, and many other sectors and application areas [12, 13, 47, 48]. The use of dedicated simulation software may instead result in a reduced programming time and lower project cost [12]. A more detailed overview of Discrete Event Simulation Software is provided in Section 2.2.2.

2.2.1.5 Verification & Validation

In order for a simulation model and its results to be useful, a certain level of model accuracy is necessary, and trust for the model needs to be established [44]. Verification and validation concern the process of determining whether a constructed model and its results are suitable for use for a specific purpose [49], with the purpose of establishing a basis of confidence for a model and its results [1]. This process is commonly pointed out as both one of the most important, and difficult, tasks in simulation model development [1, 12, 13]. While illustrated in the model structure by [13] as a separate step, several authors underline that this step is heavily intertwined in all other steps of a simulation study [1, 12, 13, 44].

Verification can be defined as the process of *ensuring that the computer program of* *the computerized model and its implementation are correct* [49]. In its essence, this covers the steps of ensuring that the specified conceptual model has been translated correctly into a computerized simulation model that behaves as intended, commonly including processes such as debugging and testing [12]. Validation, in its turn, can be defined as the *substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model* [49]. The consideration of validity constitutes a trade-off between cost, time, and computational constraints by regards to accuracy and detail level requirements given by the specific purpose that a model is to serve [44].

In the studies of complex systems, complete validation is commonly pointed out as an impossible task [12, 44]. In practice, the task of validation could often be explained as a continuous lookout for factors that prove invalidity of the model. In the common environment of a simulation study, a physical representation and/or detailed performance data may not be available for reference in validation, which commonly results in the necessity of subjective evaluation of the accuracy and sufficiency of model parameters and data [12]. A simplified structure for studies of verification and validation is suggested by [49] involving the four main categories of conceptual model validity, model verification, operational validity, and data validity, all of which should be considered to ensure sufficient model validity.

2.2.1.6 Experimental Design & Analysis

In the phase of experimental design, the simulation model is used to perform experiments with the purpose of providing insight in the behavior of the system studied, evaluating the effect of changes in the system construction or input data [1, 13].

A central property of simulation models with stochastic elements is that the output of such models is also by definition random [12]. Thus, the output of such a model is only to be treated as an estimation of the model characteristics, or one possible outcome out of many. It is therefore common practice to conduct experiments with several observations, or repetitions, of each model state, providing a set of samples for the selected output value. To illustrate the accuracy of a selected output, it is common to consider the minimum and maximum values, or the margin of error given by the calculated Confidence Interval, based upon a selected level of confidence. The Confidence Interval, CI, for a set of samples can be calculated as

$$CI = \hat{x} \pm z \cdot \frac{\sigma}{\sqrt{n}} \tag{2.1}$$

where $\hat{x}$ is the mean value of the samples, z is the critical value based on selected confidence level, σ is the standard deviation and n is the number of samples [50]. For large sample sizes n, z is determined based upon the standard normal distribution. For small sample sizes, z is instead calculated based upon the students t-distribution in order to account for the increased uncertainty.

As seen in Eq. (2.1), the sample mean is completed with a lower and upper bound representing the Margin of Error (ME), given by

$$ME = z \cdot \frac{\sigma}{\sqrt{n}} \tag{2.2}$$

The level of confidence z is selected by the researcher by regards to the required or desired level of certainty. A selection in the range between 0.90 and 0.99 is typical [50].

2.2.2 Discrete Event Simulation Software

Discrete Event Simulation models can be constructed using many different types of software tools, ranging from customized spreadsheets to dedicated software applications [12]. [1] list three general categories of simulation tools for the modeller: spreadsheets, programming languages, and dedicated simulation environments. An additional denominator is suggested by [13], who divide the category of programming languages into two main sub-categories: general-purpose programming languages, and simulation programming languages.

General-purpose programming languages are programming languages not specifically designed for simulation [13]. This includes for example Python, Java, C, and C++. While not designed for the specific use of simulation, general-purpose programming languages can feature special-purpose packages or libraries which provide specific capabilities for simulation. An example of this is the package SimPy for Python, which offers a framework for DES based on standard Python [46]. Special-purpose programming languages are programming languages specifically designed for simulation, such as GPSS, SIMAN and SLAM, which can be used for simulation of highly complex systems [13].

Dedicated simulation environments involves a wide range of software products adapted for various application areas, types of simulation, and within various price range [13]. Examples of dedicated simulation software are Anylogic, Arena, Automod and FlexSim. Dedicated simulation environments commonly offer animation features and a graphical user interface, and features of automatic output collection and experimentation for evaluation of system performance.

Animation and visual features are one of the reasons for the increasing use of simulation modelling [12]. Visual features of dedicated simulation environments can also contribute to simplify communication regarding model behavior or system details with stakeholders, management or project teams. For the modeller, the visual support can be useful as a support for debugging, verification and for detection of invalid model functions.

Tecnomatix Plant Simulation is an object oriented DES software from Siemens featuring 2D & 3D simulation environments [47]. Plant Simulation features a library of standardized objects to enable rapid modelling of standard manufacturing simulation features. A high level of customizability is enabled through the specialized programming language Simtalk, enabling the user to construct customized methods [51]. Plant Simulation also offers advanced features of graphic adaptation of simulation objects, including the possibility of importing and editing CAD graphics for simulation objects, as well as several built-in analysis tools for experimentation and optimization.

2.3 Time Data Management

Process time data is a highly essential aspect in the management of manufacturing systems, serving as a baseline for both strategic and operative planning and decision making [52]. The subject of Time Data Management involves the processes of determination, pre-processing, application and administration of such time data. Regarding the methods of process time determination, a general distiction can be made between the categories of actual process times and target times. An illustration of this separation and the involved methods under each category is presented in Fig. 2.2.

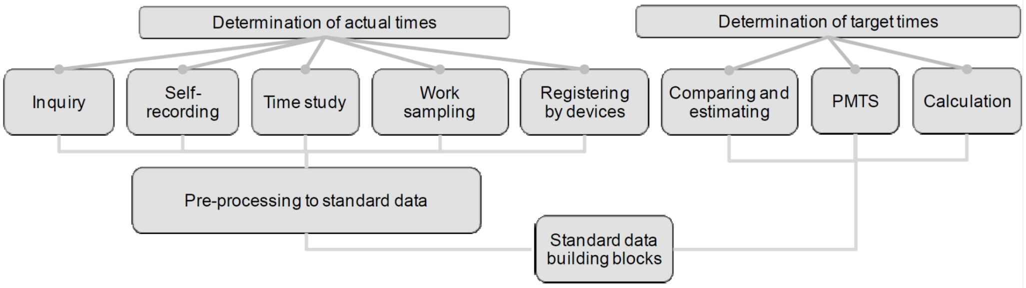


Figure 2.2: An overview of methods for time determination [2].

In many cases, the processes considered in time data involve aspects of manual work performed by human labor, conducting tasks such as manual assembly operations, material handling, manual machining, or similar. While automated processes may often feature production logs and similar sources for process time determination, operations conducted by human labor is often not as accurately, if at all, logged. In order to evaluate the time requirements for such work tasks, time studies have historically been a highly popular approach [53]. Time studies concern the procedure of measuring the amount of time required for an experienced operator to perform a certain work task in accordance with a specified method and at normal work speed.

An alternative approach to determine process times is given by PTS, also commonly referred to as Predetermined Motion Time Systems (PMTS). The methodology of PTS evolves around the determination of process times through breakdown and detailed mapping of the exact motions required to conduct a process or activity [53]. Several methods of PTS have been developed and can be found in use in industry today, such as Methods-Time Measurement (MTM) [54] and Maynard Operations Sequence Technique, MOST [53]. While conduction of PTS analysis is commonly time consuming and requires experienced analysts, several methods have been developed with the aim of simplifying the analysis and reduce the demanded time, commonly using a standardized range of standard time elements used as building blocks in the calculation of process times. A common approach of manufacturing companies is also to develop and use a set of custom time elements representing the common activities and process times within their manufacturing processes based upon PTS and/or time studies [53]. This is also the case at Volvo GTO, where a range of standardized time elements based upon MTM are used for the calculation of process times, commonly used for balancing and process improvement.

PTS allows for precise and detailed determination of target times for processes [53]. This makes PTS a suitable source for process time data in DES applications. Application of PTS based processing times can support a high level of detail in a simulation study, but may demand larger amounts of project conduction time due to substantial data handling and detailed modelling [45]. The division of process times into different elements and groups provides the opportunity to rearrange, filter and edit the calculated times, which also supports the analysis of process times in re-designed and/or re-balanced processes without the need of significant, additional data collection. PTS is also a relatively objective method for determination of process times [53], which can contribute to reduce factors of inaccuracy in process time determination such as the Hawthorne effect [45].

2.4 Related Studies

Applications of DES in the context of manufacturing and assembly are commonly occurring in research. The literature review of [38] covers the research of DES support in both operations and layout design between the years 2002 to 2013. The study of [55] covers the combined problems of buffer allocation and mixed-model assembly line balancing with processes involving parallel stations. The subject of line-less assembly systems is examined by [56], who apply simulation based optimization in order to generate and evaluate optimal system configurations. The study emphasizes the usefulness of parallelized assembly stations as a means to increase resilience and reliability by regards to introduction of new product variants, lack of material availability and personnel shortages. In particular, the study points out the benefits of line-less assemblies in product-variant rich environments, and in environments featuring frequent introduction of new products and/or product variants. The subject of bottleneck identification in a manufacturing setting is covered by the study of [39] who applies a Python based approach to data-driven DES using detailed historical data for experimental distributions.

In the context of process redesign of manual assembly processes, and/or in cases where a high level of detail and accuracy is required, PTS based process data, using for example MTM analysis, can be a beneficial approach [45]. A few studies can be found covering the explicit subject of PTS data usage in DES. The study by [57] utilize MTM time analysis and DES to solve the Assembly Line Balancing Problem. The study indicates that MTM and simulation can be a beneficial combination to enable increased efficiency, minimize idle time and support the solving of line balancing problems, a subject where a high level of accuracy is required to enable differentiation between the tasks to be balanced. A study of the reliability of simulations of assembly operations based upon variability in Time Standard data is presented by [17]. The study underlines the usefulness of PTS data in the development of processes without physical representation, and provides guidelines for the simulation of variability in manual assembly processes when implementing PTS process times. The results indicate that variability in process times can have considerable impact on the accuracy of simulation results. Application of a triangular distribution, with adjusted maximum and minimum limits depending on the context and process specific factors, is shown to provide accurate results in simulation. Several recommendations are provided regarding the upper and lower limits of the distributions.

3

Methodology

This chapter presents the methodological approach employed in the project, largely based upon the iterative DES project structure argued for by DES literature [1, 12, 13]. An overview of the main steps included of the methodological approach is provided in Fig. 3.1.

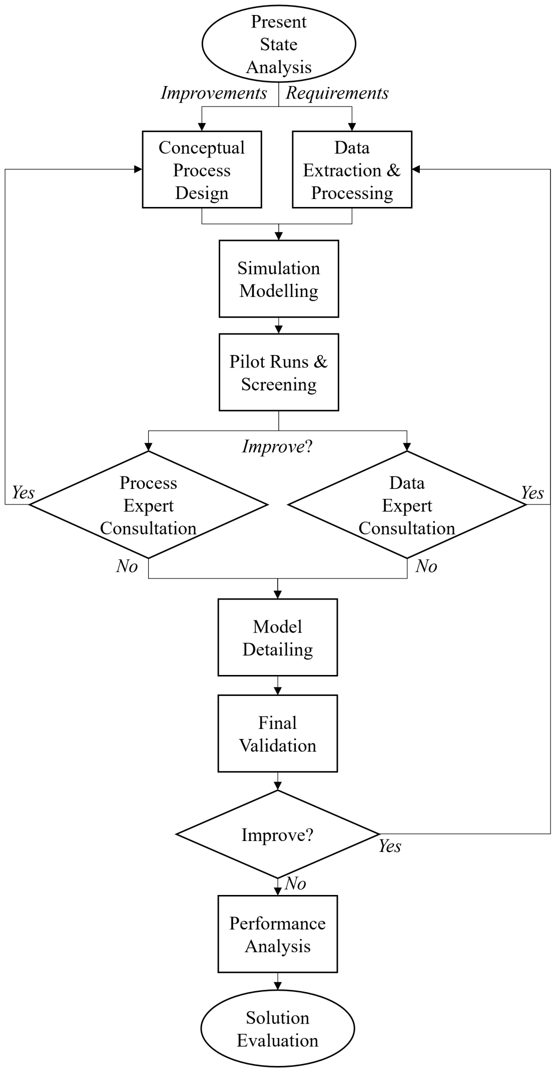


Figure 3.1: A flowchart outlining the main steps and connections in the iterative project methodology.

The purpose of the iterative methodology was to support a progressive increase in the level of detail in the model based upon progress in data extraction, while simultaneously supporting the iterative concretization and refinement of process design. This iterative progress was based upon model screening in pilot runs and evaluative discussions in collaboration with data and process domain experts, which also served as a central aspect of model validation. This provided the framework for a continuous feedback loop, where the need for increased detail and further improvements were thoroughly discussed. This served to support the development of mutual understanding regarding both the simulation model and aspects of the process design, such as the sequential flow and division of work, ensuring that each iteration brought forth a more refined design.

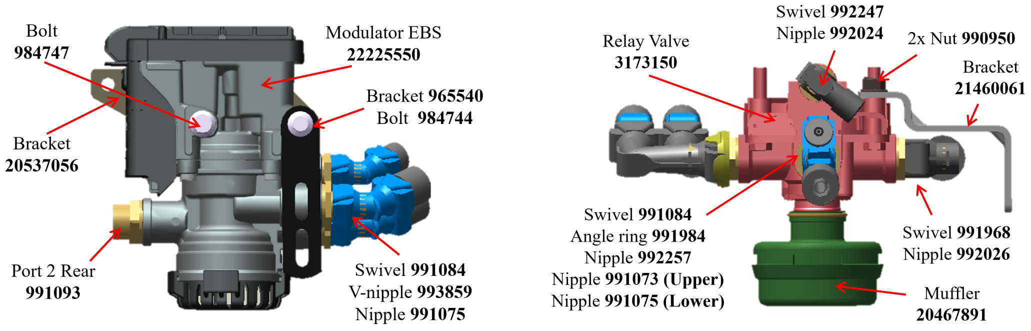
The first step of the project involved the conduction of an introductory Present State Analysis, with the purpose of mapping the present state process and the main aspects of improvement. This process is described in detail in Section 3.1. Based upon the findings of this analysis, conceptual suggestions for process redesign were generated, which were then revised continuously throughout the project, as described in Section 3.2. In parallel with this process, a phase of data mapping, extraction and processing was conducted, as described in Section 3.3. The conceptual model was then translated into a computerized model, which was updated continuously based upon iterative progress in the previous steps. This process is detailed further in Section 3.4, followed by a detailed description of the steps of verification and validation of the model and system presented in Section 3.5. Finally, following the final process design selection and validation of the model representation, a series of experiments were conducted to support the process evaluation, as described in detail in Section 3.6.

3.1 Present State Analysis

Analysis of the existing, "as-is", process is a crucial initial step in operations improvement endeavors, as highlighted in the literature [18]. To begin this study, a Present State Analysis was conducted to map the activities and interrelations within the studied process and facilitate the initial identification of problematic areas and potential improvements.

Firstly, an initial stakeholder mapping was performed, followed by semi-structured, qualitative interviews with all identified stakeholders to gather information on the functionality of the current system, prevalent issues, the flow of information, and the availability of process data and statistics. These interviews also explored initial improvement ideas, identifying key areas of concern for each stakeholder and discussing parameters of interest for experimentation and analysis in a redesigned model. The semi-structured interviews were adapted to the expertise of each stakeholder, following the recommendations of [58].

Based upon the results of these interviewees, a product mapping was conducted, where the range and structure of products and product configurations handled in the assembly process were mapped, based upon data from multiple databases, results from the qualitative interviews, and studies at the assembly process. Given the vast range of product variants and minor differences in specific assemblies, such as the angles of nipples on valves, it was determined necessary to categorize the product range into a limited number of main valve types for clarity and manageability. Fig. 3.2 showcase two examples of valve configurations, illustrating the type of components handled in the assembly.



(a) EBS valve **(b)** Relay valve

Figure 3.2: Example configurations of two valve types assembled at the valve assembly, and their included components.

In addition to this, an introductory process mapping was conducted, based upon the structured approach for process improvement in operations management suggested by [18]. In the context of DES studies, such process mapping provides critical input for the conceptual modeling phase, detailing the essential elements to be included in the DES model [12,13]. Several Gemba walks were conducted at the Valve Assembly process, where the responsible engineer and operators of the assembly were allowed to demonstrate and explain the process structure and involved activities. Additional details were collected from qualitative interviews with station team leaders, operators, and other process experts.

3.2 Conceptual Design

While the conceptual changes of kitting and parallelization where established as baselines for the project, the details of implementation in terms of process design were not specified from the project start but expected as a project output. In the conceptual design phase, a number of different alternative process and layout structures were studied and evaluated for feasibility. The conceptual design phase was conducted in an iterative fashion, closely aligned with the reoccurring stakeholder meetings, where layout and process design aspects could be discussed and altered. In the initial steps of the project, conceptual designs could be evaluated and reviewed directly in the conceptual modelling phase. In subsequent stages, conceptual designs were translated into a computerized model representation and pilot runs were conducted in order to enable evaluation of the process design.

The initial conceptual design was based upon the output of the initial present state analysis, where several aspects of waste and other undesirable aspects of the present assembly process could be identified. The initial stakeholder interviews also supported a number of these factors and brought forth several additional aspects desirable in a redesign of the production system. A number of conceptual ideas for process redesign could also be collected from the process experts in this phase. In addition to process expert consultation, several Gemba walks were conducted, studying other processes within the Tuve plant involving similar processes or implementing similar production flows. The corresponding valve assembly process implemented in other plants of Volvo GTO were also studied.

3.2.1 Selection of Detail Level

The purpose of a simulation model is to serve as a sufficiently accurate approximation of the real system/process [14]. The validity and usefulness of a DES calculation is highly dependant on the selected width and depth of the underlying simulation model. Meanwhile, boundaries are required for the model, and simplifications may be needed in order to reduce both workload and computational complexity. Inclusion of unnecessary complexities in the system will only lead to increased model building and computer expenses without any valuable contribution to the result [13].

In order to determine a desirable level of model complexity, consultation with the model user is a commonly suitable approach [13]. A recommended strategy to approach the problem of complexity is also to start off with a simple model or prototype, and then add complexity levels in an iterative fashion. The iterative aspect of simulation modelling is also underlined by several other authors [1,12]. The project methodology was adapted in several ways to support an iterative adaptation of model complexity, content and visualization in accordance to discoveries made along the project progression. Meetings with a group of main project stakeholders were conducted continuously throughout the project, where the current progress, project status, discovered opportunities and limitations for the simulation modelling were discussed and possible solutions could be discussed or adaptations be made.

The visual aspect of the simulation model has been a central priority throughout the project. The visual aspect of the simulation software used in the project was also determined as a potentially useful tool to illustrate the current model designs and the outcomes of the selected detail level. Therefore, it was determined a priority to generate illustrative simulation models as early as possible in the project. The models were then continuously updated in accordance with the input provided from project stakeholders and other process experts.

The selection of simulation complexity level is highly dependant on the desired experimental factors, i.e. the model input that the user wishes to analyze, and the desired output, or more specifically the response factors of the system which the user wishes to study [1]. The experiment factors can concern both qualitative aspects, such as the model structure or rules, or quantitative factors, such as numbers of orders or processing times. A list of desired input and output parameters was generated in the early stages of the project based upon introductory stakeholder interviews. As additional limitations and possibilities where discovered along the project conduction, the list was updated.

In a parallelized flow, the tasks previously divided across several stations are instead combined into one large task conducted by each station in each cycle. Considering this aspect, it was determined sufficient to only consider the total process times for each order in the model rather than dividing the tasks into sub-tasks in component or component group level. This limitation in detail level provides a complete representation of the process times for each order at each station, while enabling a relatively simple interface for the application of process times in the model. This limitation however did not provide an equivalent limit for the data used in pre-processing, where a higher level of detail was necessary to enable time element filtering.

3.2.2 Handling of Delivery Sequence

One of the early aspects to be solved considered the sequential flow of the orders passing the parallel stations. Due to the significant variations in assembly time, many cases would occur in which the stations would not be finished with their received orders in the same sequence that the orders were first received. This was expected by process experts to be a potentially significant problem with the parallel setup. Several different approaches to solve this problem were studied during the project. The main versions studied in earlier iterations are presented below.

> **Sequenced parallelization - progressing stations** An implementation of sequenced long cycle assembly, inspired by the recommendations of [22] and similar assembly processes at the plant.
>
> **Unsequenced output - parking lot** An implementation of unsequenced assembly, where all workers are allowed to work in their own pace without restricting each other. The task of adjusting the output back to sequence is handled by the receiving unit at the main line, who fetch the correct kit from a buffer of carts with assembled kits in a parking space.
>
> **Subsequent sorting task** An implementation of unsequenced assembly with correction to sequence handled by one, or several, of the valve assembly operators in a subsequent, additional task.

The version of progressing stations was found potentially problematic in several ways. Firstly, while the implementation of similar methodology had been implemented at other stations, these processes typically involved assembly work on one single part. The handling of a multitude of parts required for assembly for a truck would pose problems in terms of fixture design. Furthermore, the waiting of operators for others ahead of them in the sequence could result in reduced resource utilization.

The second and third option involved the release of unsequenced output into one buffer or parking space, which would either be handled by one or multiple operators rearranging the buffer in cases where the orders would differ from the sequence, or by line operators locating and fetching the correct, assembled kit when needed. Additional handling of the assembled kits was deemed undesirable, as it would result in non value adding tasks for one or more operators, and as it was perceived as difficult to standardize and structure. Regarding the unsequenced output without further handling, it was pointed out as a risk that operators could pick the wrong kit.

A final version was developed as a response to the above mentioned problem by consideration of Lean Poka-Yoke principles to enable error prevention [29]. A system of parallel, small buffers before and after each station was created to enable decoupling and ensure placement of the assembled kits in correct order.

3.2.3 Pull System Implementation

A key improvement focus of the project was minimizing WIP and inventory requirements. Initial observations revealed a common tendency for overproduction at the assembly stations. Variations in process times forced operators to rely on buffers to manage orders with very long assembly times. While approximate buffer target levels had been established based on operators' experience, these were considered guidelines rather than strict limits. Additionally, tasks such as ordering materials and handling buffers extended the actual work cycle time, further increasing the need for buffers.

During initial interviews, operators expressed a sense of disconnection from the actual assembly line. This made it difficult for them to perceive their current status in relation to the line during assembly, causing stress. To address the issues of operator disconnectedness and unclear buffer limits, the redesigned process aimed to implement a Kanban system. This system supports controlled buffer levels and imposes a pull signal to regulate the assembly process [28].

3.3 Data Extraction & Processing

The aspect of input data is critically important for the validity and utility of a simulation model and its results [12]. Data collection and preprocessing are often the most time-consuming stages in DES studies [45]. Therefore, a structured approach to data extraction and processing is essential. The requirements for data in simulation modeling depend heavily on both the concept and design of the model. These requirements determine which parameters and mechanisms need to be modeled and the purpose of the model, which in turn dictates the level of detail and accuracy required [12]. Additionally, the availability of data significantly constrains the possibilities for detailed modeling and can limit the achievable detail and accuracy of the model.

The methodological framework of this project was designed to support an iterative exploration of these constraints. The level of detail in the model was progressively increased based on additional requirements and improvements in data extraction, facilitated by continuous consultation with company data experts. To provide a structured overview of the expected data requirements and the availability constraints, an initial data requirement and availability mapping was conducted. The details of this analysis are described in Section 3.3.1. Based on the identified requirements and available data sources, the data was extracted and processed as outlined in Sections 3.3.2 and 3.3.7.

3.3.1 Data Requirements & Availability Mapping

As part of the Present State Analysis, an initial data requirements and availability mapping was conducted. The primary goal was to identify the approximate data needs for the project and locate potential data sources, while also identifying any gaps in data availability. This early mapping aimed to expedite the data extraction and processing phase due to its estimated time requirements. The data requirements list was continuously updated throughout the project as changes occurred in the conceptual model. Key data requirements included order, assembly process time, operator movement time, assembly errors, components for kitting, kitting times, main line pace, pitch, speed, order statistics, and line availability.

Consultation with process and data domain experts provided an overview of the available data. A primary source of data identified here was Avix [59], a software used in company's the balancing of assembly operations. This program implements order statistics for simulation of tested balancing configurations, and provides an overview structure of the MTM based time element groups and assembly tasks sorted between the stations and categorized based upon product groups. Furthermore, the structure for variant based triggering of applicable assembly times is handled using variant codes. However, the possibilities of exporting the data in the required level of detail, involving the individual MTM time elements and detailed variant conditions for time element groups, were found to be significantly limited.

Furthermore, a number of Volvo databases were involved in the study, located through the consultation of data domain experts. A internal database was examined for the possibilities of detailed time element export. The company's Engineering Database enabled exports of variant descriptions for a specified order range and enabled alignment of variant codes to variant families. The production database Prodify was used for the exporting of production data and downtime statistics.

3.3.2 Assembly Process Time Elements

In this section, the methodology for extraction and handling of process time elements is described. This involved a series of steps covering extraction, transformation and connection of several sources of data, as described in the following sections.

3.3.2.1 Extraction and Transformation of Avix Raw Data Files

The primary raw data inputs for Avix include assembly instructions (see Tab. 3.1 for an example), timestudy elements, build location information, material contents, and order history with the corresponding variant strings for a period of six months leading up to the project's start date.

It is important to note that this list is a simplification, as the different documents contained varying information that needed to be combined to obtain a comprehensive view. These inputs are available as text files in a proprietary format, requiring specialized processing. Consultations with IT specialists were conducted to understand the file structure and the methods for linking data using synthetic keys. Instruction documents detailing the text file structure were also received.

Table 3.1: Example snippet from a raw data file: Assembly Instructions Raw Data.

```
010M00124074203BDE2-73C5-44F7-8FAF-476DE57098D 00281515(PC24)
Fästelement boggiebalk RSS-AIR (RAA21T/RAA22/RAA32T/RAA32P/RAA31PT)
053C3588B610001FE0636C83618372EB 02559916053C3588B60F001FE0636C83618372EB
020P0127440 0000001080000000008600Cmin 07437B88C93D908DE0636C8361839307
Qty 1 07437B88C93E908DE0636C8361839307 00644288
030F86FA64-E3DA-4466-A754-68E9C3B108B
040RAPDT-GRF2XFDX 040RADT-GR F2XHAX 040RAPDD-GRF2XFGX 040RADDT-GRF2QIX
040RADD-GR F2XQAX 040TRACTOR DDX10X 5024
020P0127440 0000001010000000000000Cmin 07437B88C946908DE0636C8361839307
Tighten Qty 1 07437B88C947908DE0636C8361839307 00644289
030F86FA64-E3DA-4466-A754-68E9C3B108B
040RAPDT-GRF2XFDX 040RADT-GR F2XHAX 040RAPDD-GRF2XFGX 040RADDT-GRF2QIX
040RADD-GR F2XQAX 040TRACTOR DDX10X
```

The processing of these files varied. Some were straightforward comma-separated values, while others required more complex handling as they had other syntax with different rows starting with different keys grouping the information that is linked. A Python script was developed to parse these files and convert the data into a structured column-based format. During this transformation, non-essential information was strategically omitted to streamline the process. Tab. 3.2 shows a few columns from transformed data.

Table 3.2: A table illustrating a selection of Time Study Elements & associated data.

Key	Element	Time [s]	Description	Comment
FF74-4D8E-8DAE	VU.	7,8	To rack (tooling) - to object - to rack	Gå
FF74-4D8E-8DAE	B4.211	2,58	Get and place 1 tool/equipment	Ta maskin
FF74-4D8E-8DAE	P8.222	7,32	Use pistol- and anglemachine 14 - 79 Nm	Dra 2 muttrar

3.3.2.2 Connection of Detailed Information to Orders & Database Storage

Each order within our system is identified by a variant string detailing the specifications required for assembling the truck, see Tab. A.1. This string plays a critical role in determining the appropriate materials and assembly steps for each truck, based on a set of predefined conditions. These conditions dictate whether a particular order's variant string matches the criteria needed for the associated time studies and materials. The logical flow for linking is: Order matches IF: Time study matches AND (Any of the materials related to the time studies correspond with the order).

The methodology for filtering and processing data from an Excel file to identify relevant variants and categorize them based on predefined rules involves several steps. It begins with importing necessary libraries for data manipulation, SQL-like querying, parallel processing, and regular expressions. Functions are then defined to escape SQL special characters and convert rules into SQL WHERE clauses. The DataFrame is filtered based on the provided rules, with relevant columns added. Data is loaded from Excel files into pandas DataFrames, and parallel processing is employed to handle multiple rules efficiently. All filtered DataFrames are combined into one, which is then saved to a new Excel file, with a confirmation message printed upon completion. For detailed pseudo code (see Appendix Listing B.1).

Time studies are not only linked to orders but are also categorized with several factors containing related information, such as the station location of the time study, grouping into task clusters which may encompass multiple time studies, textual descriptions to aid in data understanding and interpretation, and details on the materials involved in each time study.

Each time study is further broken down into smaller components, such as various MTM codes. Unlike the conditions linking time studies to orders, this associated information is connected using synthetic keys, designed to facilitate data integration and avoid duplicates.

In addition to establishing links between all time studies and orders, the system must also handle the categorization of time studies with the associated information. This categorization is achieved using Power BI to build relationships between different spreadsheets that utilize various synthetic keys.

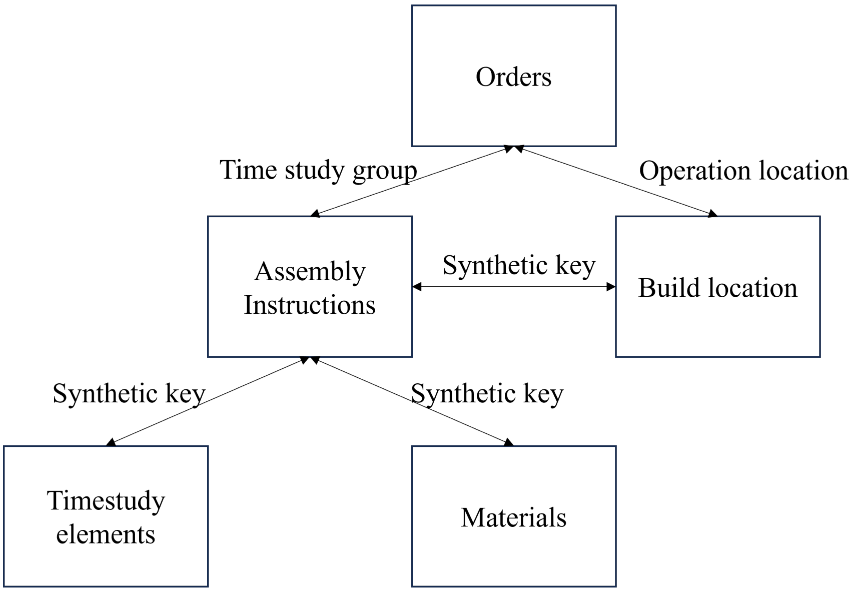


Figure 3.3: Schematics of the data connections between data sheets.

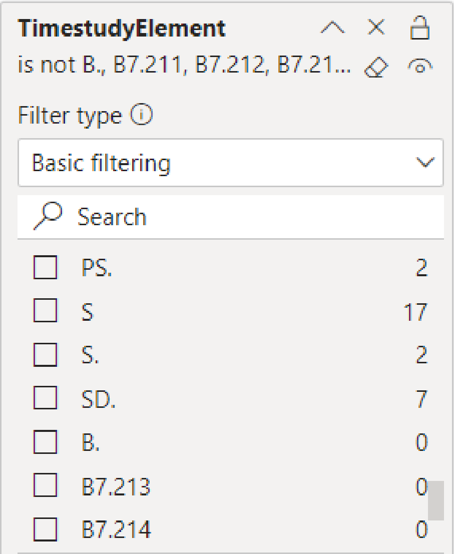
The methodology employed to manage variant conditions involved writing a Python program that compares conditions across all of Volvo's existing time studies with all orders' variant strings over a selected time range, 6 months. Similarly, synthetic keys were utilized in Power BI to create and manage relationships between different datasets, illustrated in Fig. 3.3. This approach enabled the compilation of all data within the Power BI program, making it easier to filter the correct data and compile comprehensive tables and graphs.

This system ensures a robust database structure that supports efficient connections between orders, location information and time study elements across multiple databases. This structure is crucial for managing complex data relationships and ensuring accurate assembly time and parts tracking per order.

3.3.3 Isolation of Assembly Times

This analysis phase aimed to isolate pure assembly times from other workflow components, thereby assessing the efficiency of the assembly layout, including a scenario that incorporate a dedicated kitting operator. Initially, the distribution of various valves to specific sub-flows, primarily between sub-flow one and sub-flow three, was mapped. Using Power BI, step time elements and other kitting-related activities were removed from the total assembly time. This distinction was crucial to concentrate exclusively on the time dedicated to assembly tasks.

The results of this filtering process were compiled into a Power BI table that clearly presents the isolated assembly times, facilitating straightforward analysis and layout testing based on assembly time efficiency. This approach has enabled precise adjustments to the assembly line configurations and provided a comprehensive understanding of how different operational strategies impact assembly time. Fig. 3.4 illustrates the filtering of time elements using Power BI, highlighting the streamlined assembly times.



TimestudyElement

is not B., B7.211, B7.212, B7.21...

Filter type: Basic filtering

Search

☐	PS.	2
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☐	SD.	7
☐	B.	0
☐	B7.213	0
☐	B7.214	0

Figure 3.4: Interface for filtering of time elements in Power BI.

3.3.4 Variation in Assembly Times

PTS based process data constitute target times rather than actual assembly times [52]. The MTM analysis based times are expected to represent the mean assembly time for an experienced operator working in normal work speed (MTM100). Meanwhile, variation in the assembly time is to be expected, which has been shown in previous studies to potentially influence the results to a significant extent [17].

No statistical data covering the variations of the current assembly process could be located in the study. Furthermore, the variations of the redesigned process could potentially be different from the current levels of variation, due to the significant changes in cycle time. The study [17] show that application of a triangular distribution of MTM based process times can provide increased accuracy to simulation of a manual assembly process.

Previous simulation problems illustrating similar processes at Volvo were observed applying an estimated, triangular distribution of ±14%, based upon time standards established in the plant. Based upon discussions with process and data experts, this level of variation was deemed sufficient to cover the maximal levels of variation occurring. This estimation was also further validated in a time study.

3.3.5 Kitting times

The processing times for kitting are highly dependent on the amount of material to be kitted. To quantify and classify parts used in products in mixed-flow assembly, Bills-of-Materials can be used [22]. In order to classify the relevant material to be kitted and determine the material amount, an analysis was conducted based upon Bills-of-Materials for each order, filtered on the usage points of the assembly stations. A snippet from the Bill of Materials can be found in Tab. 3.3. The database used for this extraction was limited to only cover a few weeks of historical production data, resulting in a coverage of approximately one third of the total order list used in the study. In order to not impose a forced limit to the order statistics used for processing times and order generation, a linear regression of the material requirements was used as an estimation of the amount of material to be kitted for the orders.

Table 3.3: A table illustrating the connected information provided by Bill-of-Material per chassi filtered by the selected usage points for a selection of parts.

Order	Part	Qty	Description	Key	Variant	Location
AA336296	965534	1	KONSOL 1*9*72*3	7167509	FAA10, FSS-AIR	Fram\ECS fram
AA336296	977969	1	NIPPEL M12x1.5 4mm	6856648	TRBRAKE	Bak\TCM RIGID

In order to determine the material suitable for kitting, the data from the Bill-of-Material was combined with material storage location data from a logistics database. As a primary indicator for kitting material, the delivery position was used and the material was separated based upon deliveries to the material racks at the assembly tables, where primarily small and low value components such as bolts, swivels and connectors were delivered. A second review of the filtering was conducted based upon the container type. Here, smaller, low value components could be identified based upon delivery in cardboard boxes, whereas larger, high value material is delivered in blue boxes or pallets. In addition to the material identified in these two categories, the material delivered from other stations, such as the order specific pneumatic tubes, where included in the list of kitted material.

Based on the summation of the identified material, a linear regression of the estimated amount of material to be kitted based upon the total process times could be calculated. A scatter plot illustrating the linear relationship between the assembly times and estimated number of kitting components is presented in Fig. 3.5. Based upon this estimation, the approximate amount of kitted material could be calculated for all orders in the order statistics range.

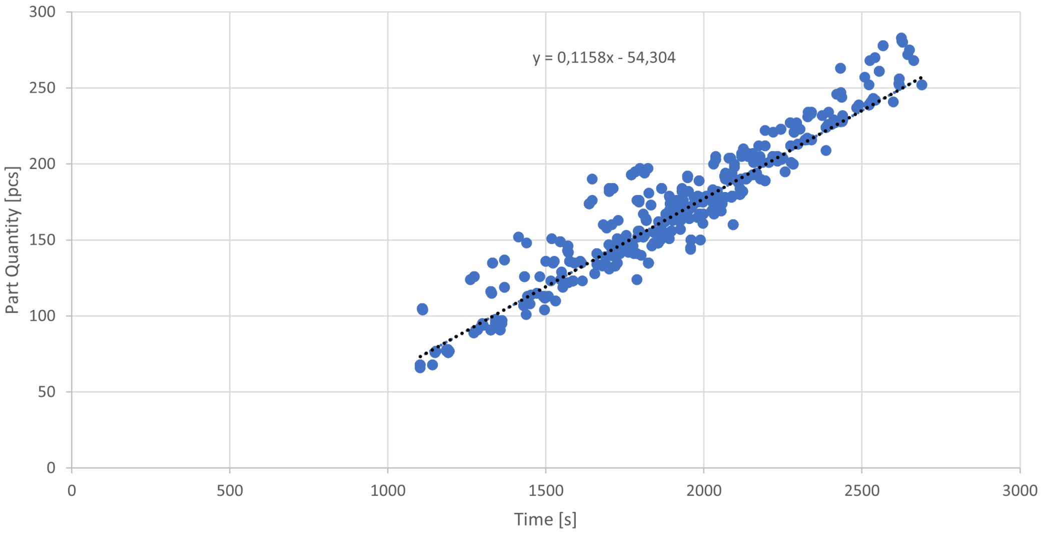


Figure 3.5: A scatter plot illustrating the samples and calculated linear regression for the number of kitted parts as a function of order process time.

Based on the estimation of kitting material amounts for each order, the total kitting time per piece was calculated using an MTM based time analysis. It was assumed that a pick-by-light concept would be used in the kitting process. For each component to be picked, time elements for picking and placing each component, moving the cart, and pushing the confirmation buttons of the pick-by-light system were included. The formula used to calculate the kitting time per order, $T_{kitTime}$ was specified as follows:

$$T_{kitTime} = (t_{AssemblyTot} \cdot k_{kitRegression} + m_{kitRegression}) \cdot t_{kitMTM} \tag{3.1}$$

where $t_{AssemblyTot}$ is the extracted total assembly time, $k_{kitRegression}$ and $m_{kitRegression}$ are given by the linear regression for kitted parts, and t_{kitMTM} is the time for kitting per component given by the MTM analysis. The kitting times were calculated for all orders in the order list.

3.3.6 Order Statistics & Variant Reduction

The orders on the main line constitute a central aspect of variation in the system, imposing process time variations across all assembly stations as well as the estimated kitting times (see Section 3.3.5). The range of possible product variants arriving at the line are given by a range of variant families, specifying the configuration of specific aspects of the order, such as the axle configuration, suspension system, etcetera. A total of more than 500 features, also referred to as variant families, exist, with an average of approximately six possible values/configurations for each feature, which results in a range of theoretically possible combinations in the size range of above 10^{300}. Several constraints apply to the combinations of specific configurations, but the specification of feasible solutions is not trivial.

To facilitate simulations with randomized orders, it is essential to base the simulations on statistical analysis of order data. Each order in the dataset contains a variant string that details the specifications for constructing the truck, see Tab. A.1. This string significantly influences the assembly times, as it determines the required materials and operations.

However, the variant string is typically extensive, containing much information that is irrelevant to the assembly of specific components, such as valves. To streamline this, the string was condensed to include only the pertinent information. This reduction was accomplished using an Avix simulation export report, which summarized all time study groups that interacted with the order strings over a six-month period. Each group's conditions were listed, comma-separated, and then compiled into a single-column list with duplicates removed, ensuring only relevant string conditions were retained.

These conditions were then matched to their corresponding variant families, resulting in a table organized into two columns: variant and variant family. Subsequently, using the engineering database, all variant families associated with the complete variant string were extracted. Non-relevant families and column headers were omitted, resulting in 35 essential parameter conditions specifically for valve assembly.

For the period of six months under review, the orders included variant strings with 35 parameters, leading to about 3300 distinct combinations that historically occurred. To manage this complexity, a frequency list of these combinations was compiled, see Tab. 3.4. This list now forms the foundation for the statistics used in generating random orders, ensuring the simulation model accurately reflects the historical data and variability.

It is important to note that these 35 parameters were initially subjected to a linear regression analysis to determine if the number could be reduced further, potentially focusing only on those parameters that most significantly affect assembly times. However, to maintain maximal accuracy, the decision was made to retain all 35 parameters. This analysis was performed using MATLAB's linear regression function with a categorical predictor through the *fitlm* command [60].

The MATLAB command *fitlm* was used in order to show the impact of each config-

Table 3.4: A table illustrating the calculated order frequency for a selected range of order archetypes.

Order Index	Calculated Frequency	Reference Order/Chassi
1	514.00	AA336296
2	394.00	AA336306
3	296.00	AA336297
4	268.00	AA336312
5	264.00	AA336405

uration on the assembly time of the valves. This result was stored in a structured table, as illustrated in Tab. 3.5.

Table 3.5: Example of Regression Analysis Results using MATLAB *fitlm*.

Term	Estimate	Standard Error	tStat	pValue
(Intercept)	47.977	3.8795	12.37	4.8957e-21
x1	-0.0065416	0.0011724	-5.8802	9.8742e-08
x2	-0.042943	0.024313	-1.7663	0.08078
x3	-0.011583	0.19333	-0.059991	0.95236

The resulting table provides several interesting values calculated for the linear regression. The *Estimate* column provides the coefficient estimates for each term in the model. The *Standard Error* column specifies the standard error associated with the coefficients. The *tStat* column provides the t-statistic for each coefficient, testing the null hypothesis that the coefficient is zero against the alternative hypothesis that it differs from zero, considering the other predictors in the model. Finally, the *pValue* column specifies the p-value for the t-statistic of a two-sided hypothesis test. A p-value greater than 0.05, such as for the term x2, indicates that the term is not statistically significant at the 5% significance level in the presence of other model terms.

Every configuration was explicitly linked to its respective variant family to assess the impact of each on assembly times. As shown in Fig. 3.6, some variant families significantly influence the assembly time of valves, while others have a minimal effect. This variability suggests the potential to simplify the model by disregarding variant families with negligible effects on assembly time. However, to maintain a high level of detail, all 35 variant families were retained in the analysis and the regression method was dropped.

3.3.7 Downtime calculation

The failure rate of the main line was calculated using availability and Mean Time To Repair (MTTR). A standard level of availability of 95% was applied, based upon specifications from process experts. The MTTR was calculated based upon an extraction of statistical production data from Volvo's production statistics database for a time period of 1 year. The MTTR was calculated as

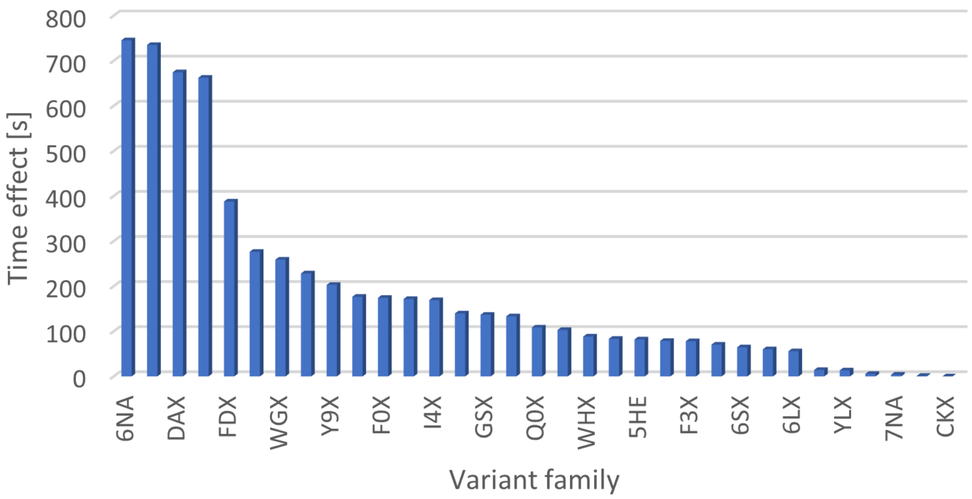


Figure 3.6: A graph illustrating the estimated influence on assembly time for a range of variant families, given by the regression model.

$$MTTR = \frac{\sum_{i=1}^{n} t_{stop}(i)}{n} \tag{3.2}$$

where $t_{stop}(i)$ is the stop time for stop i and n is the total number of stops at the main line in the given time period.

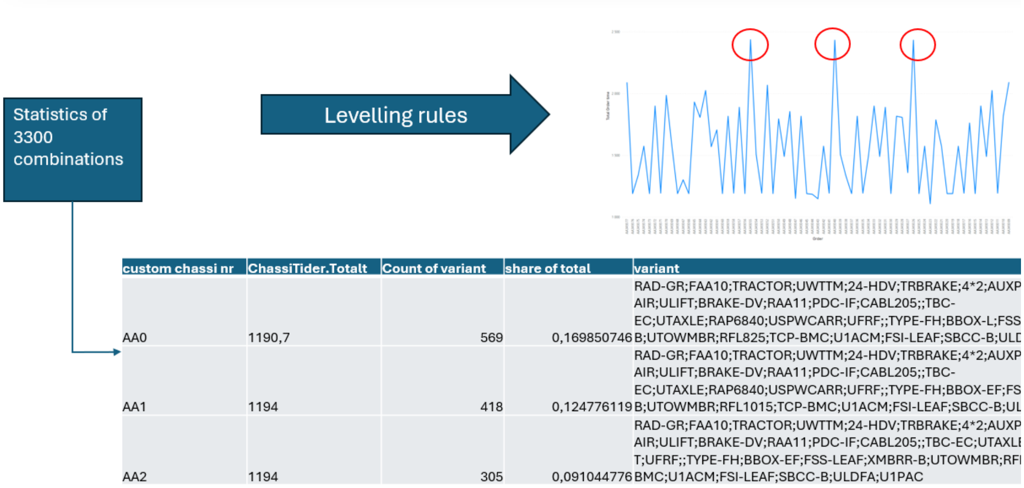
3.4 Model Construction

This section describes the work of simulation model construction, focusing on the central mechanisms and objects of the model. The model is based on the conceptual model and data extraction presented in Sections 3.2 and 3.3.

3.4.1 Random Order Generation & Levelling Adjustment

A mechanism for random order generation was included in the model to enable stochastic modelling without a forced time limit for the simulation, and to provide the user with the possibility to model different scenarios in terms of order statistics and changes in demand. In order to even out the variation induced by the significant differences in assembly time for different product variants, a set of levelling rules based upon variant specification are applied in production, creating a spread of the product configurations with the highest assembly times. In order to accurately simulate the process time variations applying to the valve assembly, consideration of these levelling rules is necessary. An overview illustration of the product variant based levelling is provided in Fig. 3.7.

Based upon the distributions calculated from extracted, historical order data from a six month time period, presented in Section 3.3.6, random orders are synthetically generated for each simulation run. These random orders are generated using a



custom chassi nr	ChassiTider.Totalt	Count of variant	share of total	variant
AA0	1190,7	569	0,169850746	RAD-GR;FAA10;TRACTOR;UWTTM;24-HDV;TRBRAKE;4*2;AUXP AIR;ULIFT;BRAKE-DV;RAA11;PDC-IF;CABL205;;TBC-EC;UTAXLE;RAP6840;USPWCARR;UFRF;;TYPE-FH;BBOX-L;FSS B;UTOWMBR;RFL825;TCP-BMC;U1ACM;FSI-LEAF;SBCC-B;ULD
AA1	1194	418	0,124776119	RAD-GR;FAA10;TRACTOR;UWTTM;24-HDV;TRBRAKE;4*2;AUXP AIR;ULIFT;BRAKE-DV;RAA11;PDC-IF;CABL205;;TBC-EC;UTAXLE;RAP6840;USPWCARR;UFRF;;TYPE-FH;BBOX-EF;FS B;UTOWMBR;RFL1015;TCP-BMC;U1ACM;FSI-LEAF;SBCC-B;UL
AA2	1194	305	0,091044776	RAD-GR;FAA10;TRACTOR;UWTTM;24-HDV;TRBRAKE;4*2;AUXP AIR;ULIFT;BRAKE-DV;RAA11;PDC-IF;CABL205;;TBC-EC;UTAXL T;UFRF;;TYPE-FH;BBOX-EF;FSS-LEAF;XMBRR-B;UTOWMBR;RF BMC;U1ACM;FSI-LEAF;SBCC-B;ULDFA;U1PAC

Figure 3.7: Illustration of the levelling rule application based on frequency of order archetypes and the resulting distribution of assembly times.

source in Plant Simulation. A Simtalk method [51] was constructed to account for the handling of levelling rules, which are implemented in the model using specified gap rules in a list. Once generated, orders are initially validated against the specified leveling rules. Orders that do not conform to the rules by regards to previous orders sent to the line are moved to a wait list. The wait list is then checked every cycle for potential orders to push to the main line. This ensures that the simulation accurately mimics the operational dynamics and constraints of the actual production environment, maintaining a realistic distribution and sequencing of tasks, while enabling the user to alter the applied levelling rules in order to conduct experiments.

3.4.2 Main Line Speed

The main line for the final assembly is operated by Automated Guided Vehicles (AGVs), whose velocities are calculated using a specific pace calculator and documented in the Pace Calculation document. This process considers various parameters, including speed, main line pace, maximum capacity, distance between trucks, working time, production time, line availability, and waste. The operational speed of the AGVs, the cycle time between producing one unit and the next, the maximum load each AGV can handle, and the required spacing between consecutive AGVs to ensure safety and efficiency are all taken into account. Additionally, the total operational hours of the AGVs per day, the time they are actively involved in the production process, the percentage of time the production line is operational, and any time or resources not effectively utilized during production are meticulously calculated.

These parameters help determine the optimal velocity for the AGVs, ensuring an efficient and effective production process. This calculated velocity is then replicated in the Plant Simulation software to mirror real-world operations of the final assembly line, providing a realistic simulation environment for testing and optimization. For example, at a main line pace of 70, the AGV speed would be approximately

2,3 meters per minute.

3.4.3 Walking Speed

As a replacement for the movement times filtered from the assembly process times, the required movements in the modelled solution are simulated using workers. The walking speed and length of steps for the workers is set to match the specified time study standards by Volvo. The time study standards of one step is 0,65 meters and the given time is 1,1 centiminute.

3.4.4 Model Parameters

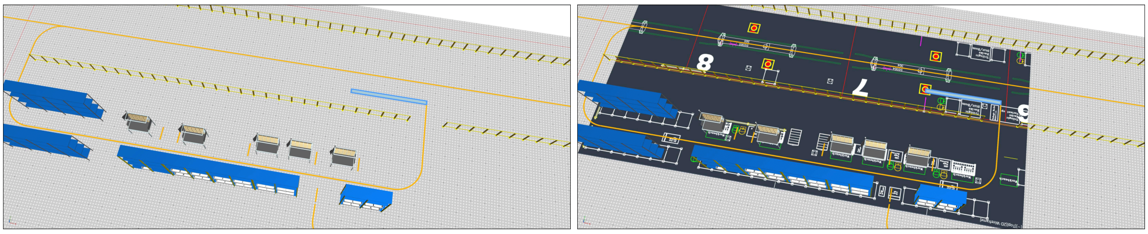
Plant Simulation offers the availability of a very wide range of attributes for objects in the model. Furthermore, parameters of the objects, such as processing time, distributions, and much more, can be controlled using methods. This enables a very high level of parametrization in the model, a feature which was used extensively in the model construction to facilitate experimentation and provide a simple user interface. An example of such use is found in the adjustments in the main line pace, which is also to affect the rate of order generation, as well as the time between exchanges of the kit rack for the sub-flow assembly. To enable this, a global variable representing the production pace was implemented, based upon which as dependant parameters could be calculated and subsequently adjusted.

As a primary priority, the parameters required for use as input and output variables during the experimental system analysis were prioritized. Additional variables were also added to support subsequent experimentation with the model after delivery to the project owners. A list of implemented input and output parameters in the model is presented in Section 4.3.1.

3.4.5 Layout Alignment & Scaling

The current layout in 2D graphics was obtained to achieve an accurate representation in the Plant Simulation environment. This accurate scaling is necessary not only for simulating correct step distances, but also to facilitate the correct positioning and accurate reconfiguration of objects in the model, especially when planning layout changes in a 3D simulation environment.

Initially, a 1 meter line was marked on the layout to serve as a reference scale within the simulation. A 2D CAD file of the layout was imported into Plant Simulation and implemented as external graphics within the simulation tool, allowing for the option to visually toggle the layout on or off as desired. To ensure fidelity to real-world dimensions, the drawing was up-scaled within the simulation until the reference length matched precisely with the scale of the simulation. Appropriate scaling adjustments were made to the objects applied in the simulation model to achieve a 1:1 ratio, ensuring that the simulated layout accurately represents the actual dimensions. An overview image of the simulation model with and without the toggling of the 2D drawing is presented in Fig. 3.8.



(a) Without drawing filter

(b) With drawing filter

Figure 3.8: An overview image of the simulation model with and without the inclusion of the 1:1 scale CAD layout drawing.

3.4.6 Customized Objects

In addition to the standard objects included in the object library, Plant simulation offers the possibility to construct customized objects with changes in both design and features. The following custom objects were constructed for use in the simulation model as an adaptation of the visual features and functionality of the studied process:

WorkBench Two different versions were constructed for main flow and sub-flow respectively. The functionality was based on the standard Assembly Station object, but adapted to visually appear like the actual workbenches at the assembly.

Kitting cart A custom object of the type Container was created and designed using a CAD visual of a cart, adjusted to appear similar to the type of cart currently used at the assembly. The Container object type enables internal storage of parts and other containers, while simultaneously enabling the ability to be stored on the main line and moved by workers.

AGV Made graphically to mimic the real one. The AGV speed is calculated according to Section 3.4.2.

Line Buffers Store objects were modified implementing @.*move* control in the entry as store objects do not have an exit method. Store obects are used to be able to store carts on ground level and not stack them vertically.

Poka Yoke Gate A representation of lights, gates or a similar application guiding the operators in picking from buffers. Controlled by hide/show of red/green graphic groups. The pre-line buffer connected to the Poka Yoke gate was based on the PlaceBuffer object in order to be able to visualise updating sequence of a row of carts.

Kit cart & MU:s Operators carry a kitting cart, on it is a kitting box, and in that are representations of the parts. The part types correspond to the actual parts from that order.

3.4.7 Visual Resources per Order

For each order, a variety of parts are required, and capturing this complexity in the simulation involves several steps. Different CAD parts were imported into the Plant Simulation software (see Tab. 3.6), and a library of these parts was established. Given the vast number of part variants, and considering that each 3D CAD import into Plant Simulation is a manual process, simplifications were made to streamline the process by importing only one type of configuration for each product type and by grouping the parts involved into singular part representations. Tab. 3.6 shows the parts included in the model and illustrates the level of detail for the parts implementation.

Table 3.6: List of CAD based parts and assemblies included in the customized part library of the simulation model.

Index	Included CAD Parts	Included CAD Assemblies
1	ABS_parts	ABS_assy
2	AVAS_parts	AVAS_assy
3	Diffinterface_parts	Diffinterface_assy
4	EBS_1kanal_parts	EBS_1kanal_assy
5	EBS_parts	EBS_assy
6	ECS_2kanal_parts	ECS_2kanal_assy
7	ECS_parts	ECS_assy
8	LastkannandeSensor_parts	LastkannandeSensor_assy
9	Nippelkonsoler_parts Nippelkonsol_parts	Nippelkonsoler_assembly
10	OverstromningsVentil_parts	OverstromningsVentil_assy
11	ParkInterface_parts	ParkInterface_assy
12	PusherInterface_parts	PusherInterface_assy
13	RLVentil_parts	RLVentil_assy
14	Solenoid_parts	Solenoid_assy
15	Tagaxelinterface_parts	Tagaxelinterface_assy
16	Trailerbrake_parts	Trailerbrake_assy
17		Slangnippel_assy
18	KittaKonsoler_parts	

Each order is linked to a specific group of parts (see Tab. 3.7), and when this group is included in an order, a visual representation of it is automatically generated in the simulation using a method block connected by components per order. The CAD library was constructed to include both individual parts and their fully assembled counterparts, as detailed in Tab. 3.6. One of the assemblies does not have a corresponding part in Tab. 3.6 due to the inability to retrieve CAD files for that type. Additionally, one part does not have a matching assembly because it is included in multiple assemblies.

Initially, all parts are presented as single, separate items, and after assembly, they are depicted as fully assembled units. This transition from separate parts to assembled units is handled by an exit method programmable block in Plant Simulation,

Table 3.7: Components and Their Descriptions – List of Resource Information per Order.

Index	Order/Chassi	Involved Resources
1	AA336296	Nippelkonsoler
2	AA336296	EBS-modulator fram
3	AA336296	ECS ventiler bak
4	AA336296	ABS framvagn
5	AA336296	Park/service-nippel
6	AA336296	EBS ventiler bak
7	AA336296	Park interface
8	AA336296	Reläventil Park bakre krets

simulating the assembly process at a workbench, as shown in Fig. 3.9.

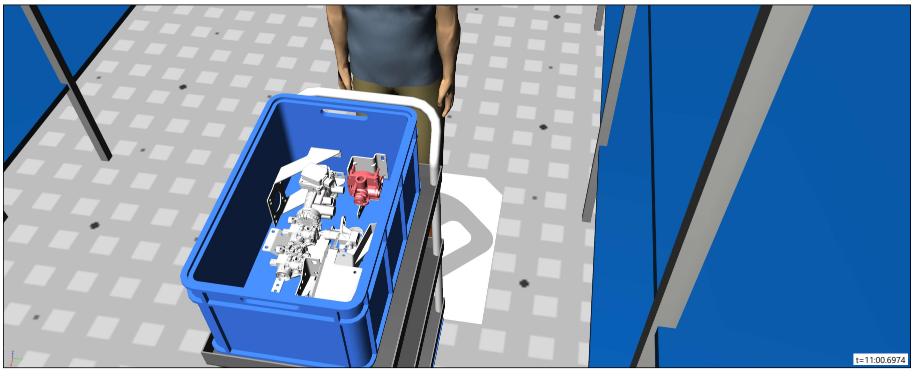


Figure 3.9: Picture from the simulation model showing CAD based representations of parts in a kit box, placed on a kit cart and transported by an operator.

3.5 Verification & Validation

The purpose of verification and validation is to determine the suitability of a model and its results for a specific, intended purpose [49]. Model verification concerns the correctness of the constructed computer model as a representation of the model concept, while validation instead concerns the confirmation that the model delivers results of sufficient accuracy to be used for the intended purpose. The approach of verification and validation applied in the project is based on the simplified structure suggested by [49], consisting of four main categories: conceptual model validity, model verification, operational validity, and data validity.

The aspect of verification within the study was considered in several steps of the project conduction, mainly in the phase of model construction. Verification of the elements of the simulation model was conducted continually throughout the model construction phase. Continuous testing of each added mechanism was applied to ensure that the functionality followed the specified or desired behavior. Verification of the model construction as well as the implemented process design was also a part of the reoccurring consultation and model screening meetings with process and data experts, and additional stakeholders. The functionality and performance of the simulation model were examined through a series of pilot runs, where the behavior of the model was examined. A central factor of support in this phase was the visual features of the constructed simulation, enabled by the software platform used, which enabled examination of several specific aspects of the constructed model for verification, such as the movement of operators and flow of products through the system.

Regarding the validation of data employed in the model, several aspects of the project provided challenges limiting the possibilities of quantitative evaluation. Most significantly, since no physical representation of the process modelled in this project exists to be used as reference in the validation phase, no direct comparisons could be made with regards to statistics from the actual process, thus limiting the possibilities of quantitative evaluation for many aspects of the model and the data used. In such cases, it is commonly recommended to base the central aspects of validation upon consultation with operators and similar experts with significant experience of the operations in the studied system [44]. The accuracy of the reconstructed time data from variant code queries was verified by comparing summarized assembly time totals with assembly times exported from Avix for each order in the six-month sample range.

The assessment of conceptual and operational model validation was mainly ensured by consultation with process and data experts in reoccurring meetings of model screening and studies of pilot runs. The validity of input data or assumptions made in the model were also validated through consultation of process and data experts in these meetings.

3.5.1 Summary of Key Model Assumptions

A number of assumptions were made in the model construction which affect the system performance in comparison to the real system. In all such cases, discussions with the project stakeholders were conducted regarding the effects of these assumptions, and approval of these assumptions were given.

Firstly, while an additional setup time was implemented for each of the assembly stations representing the handling of material cartons, the material availability for the assembly stations was assumed to be 100 %, meaning that material would never run out. This assumption was based on the project delimitation that the detailed processes of material delivery would not be studied in the project. While occurrences of material shortage were indeed observed once during the studies at the Gemba, it was stated that such occasions were rare as material buffers were to be inspected frequently by logistics personnel. Furthermore, the potential effects of such occurrence would likely be reduced in a parallel setup, since all stations would keep buffers of the same material, and could thus obtain material from each other if necessary.

Another assumption of the model based upon the above mentioned project delimitation concerns the exchanging of the kit rack for the sub-flow, which is assumed to be exchanged in accordance to the specified interval. A risk of this exchange being delayed occasionally was pointed out by operators, which would risk giving the assembly operator very little time to refill the new kit rack before the next exchange. This risk is assumed to be reduced by incorporation of a second cart at the station.

In the cases of kits not delivered in time, the model assumes that the assemblies are still completed, and that the assemblies are removed and kit cart returned upon delivery to the main line. Since the primary purpose of the simulation model is to identify the risk of such cases, with the aim of avoiding this risk in the real system, the detailed performance of the system in the state where failure occurs is not of central relevance.

3.6 Experiments & Analysis

Subsequent to the model construction for the final model concept, a series of experiments were designed and conducted with the aim of quantifying the system performance. Firstly, a steady-state analysis was conducted in order to enable removal of misleading statistics from the transient state of the process. A detailed description of this analysis is presented in Section 3.6.4. Secondly, a system pace threshold analysis was conducted to identify the feasible ranges of pace for different levels of manning, which is described further in Section 3.6.5. Subsequently, a buffer minimization analysis was conducted based upon the manning thresholds identified in the previous experiments. This analysis is described in detail in Section 3.6.6.

3.6.1 Model Performance Indicators

System throughput is a commonly applied metric to evaluate system performance [13]. In the case of the valve assembly, the required throughput is given by the pace at line, which is also used as an input variable in several experiments. Instead of throughput, one central performance metric relevant for this process is given by the delivery precision for prepared kits to the main line, given by the OTD rate defined as:

$$r_{OTD} = \frac{n_{OTD}}{n_{tot}} \tag{3.3}$$

where n_{OTD} is the number of on-time deliveries and n_{tot} is the number of total deliveries. The similar metric is also applied to evaluate the performance of the sub-flow assembly, where the number of kit racks exchanged before completely filled are studied in relation to the total amount of exchanged racks. Using this metric, any occurrence of failure to deliver components to the main line can be immediately indicated by a decrease in On-Time Delivery Rate, and a further decrease will indicate a higher rate of failure. In a successful system configuration, the aim is to maintain a value of $r_{OTD} = 1$, indicating that all deliveries were made on time.

A second performance indicator is given by the lead time for replenishment of assembled kits used in the calculation of Kanban safety margin of the assembled kits buffer, which is discussed further in Section 3.6.6. The cumulative average Lead time is given by 3.4.

where t_i represents the time between the arrival of empty cart number i at the end of the line and the kitted cart arriving at the final buffer, and n is the total number of carts arrived at the final buffer. A metric calculating the cumulative average Lead time described in Eq. (3.4) was implemented in the simulation model to support the evaluation of minimal buffer safety factor.

$$CA_L = \frac{\sum_{i=1}^{n} t_i}{n} \tag{3.4}$$

3.6.2 Selection of Simulation Time & Number of Observations

The simulation time and number of repetitions for each experiment are crucial to ensuring the quality of the results by providing sufficient output data from the simulations [1]. Multiple replications in simulations are analogous to collecting multiple samples in statistics, while increased runtime is akin to gathering one large sample. Generally, higher simulation times and more repetitions improve accuracy and certainty but also increase overall simulation times, contributing to issues discussed in Section 3.6.3. Therefore, it's necessary to limit simulation runtime and the number of observations.

A recommended simulation runtime is significantly longer than the system's transient state, ideally at least 10 times longer [13]. Section 3.6.4 analyzes transient times, suggesting that typical input parameters should not result in transient times exceeding 4 hours, implying a minimum runtime of 40 hours. However, to account for rare extreme cases, a substantial safety margin is required, leading to a recommended runtime of 240 hours, which is approximately equivalent to one shift over 30 working days.

To determine a sufficient number of observations, the graphical method was applied suggested by [1]. Since the OTD, the main performance metric, does not reflect system variation under balanced input parameters, cumulative assembly worker workload portions were used instead. Experiments were conducted with a step-wise increase in the number of observations, and the cumulative mean workload was plotted against the number of observations. The graph for the main line pre-assembly worker is shown in Fig. 3.10.

In the experiments, each observation's simulation time was set to 15 days, totaling 360 working hours, which is significantly higher than the model's required ramp-up time. Fig. 3.10 indicates a stabilization of the cumulative mean after approximately

9 observations. A similar trend, showing slightly lower levels of variation, was also observed for the assembly operator in the sub-flow assembly.

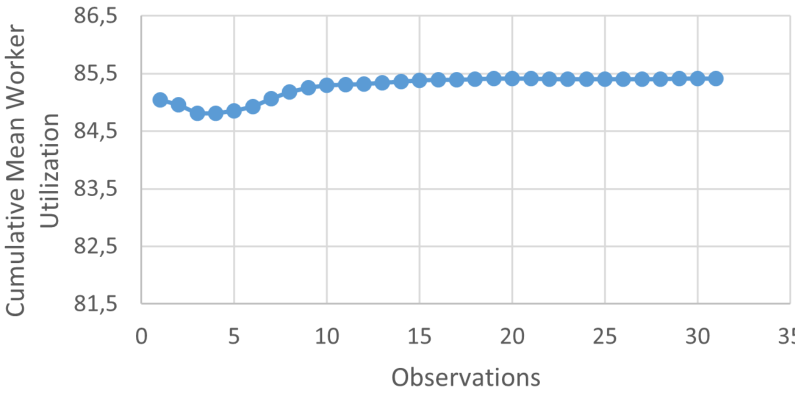


Figure 3.10: Simulated cumulative mean of main line pre-assembly worker utilization (percentage) as a function of an increased number of observations.

3.6.3 Limitation of Variable Combinations & Ranges

The possible combinations of input parameters and parameter ranges to test for each experiment risk leading to an exponential increase in the number of experiments that need to be run, resulting in what is commonly known as combinatorial explosion [61]. Running experiments with several observations for each possible combination of input values is not feasible, as this would require significant amounts of computational time to run the simulations. It is therefore necessary to limit the combinations studied in each experiment. To tackle this problem, the initial system analysis was initiated with overview experiments, where broader ranges, based upon static calculations and estimations, were tested in shorter simulation times and using only a single observation for each combination. This provided an overview of the relevant ranges of interest for more detailed studies. Detailed experiments were then conducted within these ranges with longer observation times and an increased number of observations. The experimental boundaries were extended slightly beyond these limits to ensure the capture of observations around the edges, thereby enhancing the robustness of the data and providing understanding of the system's behavior at its limits.

3.6.4 Steady-State Analysis

There are three main factors that affect how well a simulated average based on a finite simulation length correlates with a long-term average of a simulation: the system state at the beginning of the simulation, the time when the data collection is initiated, and the length of the simulation run [14]. The time for the system to approach a steady-state is therefore of central relevance to ensure sufficient results.

Due to the pull flow generated by the kitting trolleys in the system, the transient time of the system is dependant on the pace of the main line, which is also used as an input parameter in subsequent experiments. In order to align with the model parametrization, the required time before initialization of the data collection in the model needs to be scalable by regards to the pace. In the initial state of the simulation, the workers also need additional time to fill up the buffers before the orders arrive at the line, which is handled by a delay time $t_{startLine}$ before the start of the main line. The value of $t_{startLine}$ is based on the time required for assembly operators to prepare enough assembled kits to reach a sufficient buffer level between them and the main line.

The transient phase of the system t_{rampUp} is given approximately by the time for the first three kit trolleys to return from the line, which is given by the Eq. (3.5).

$$t_{rampUp} = t_{startLine} + \frac{d_{line}}{v_{line}} + 3 \cdot d_{truck} \tag{3.5}$$

where $t_{startLine}$ is the time for the delay before the start of the line, l_{line} is the length from the start of the line to the return point of the carts at the end of the line, v_{line} is the line speed and d_{truck} is the distance between chassis at the line.

A chart illustrating an example of the transient phase for the kitting worker in a simulation run at pace 65 is presented in Fig. 3.11.

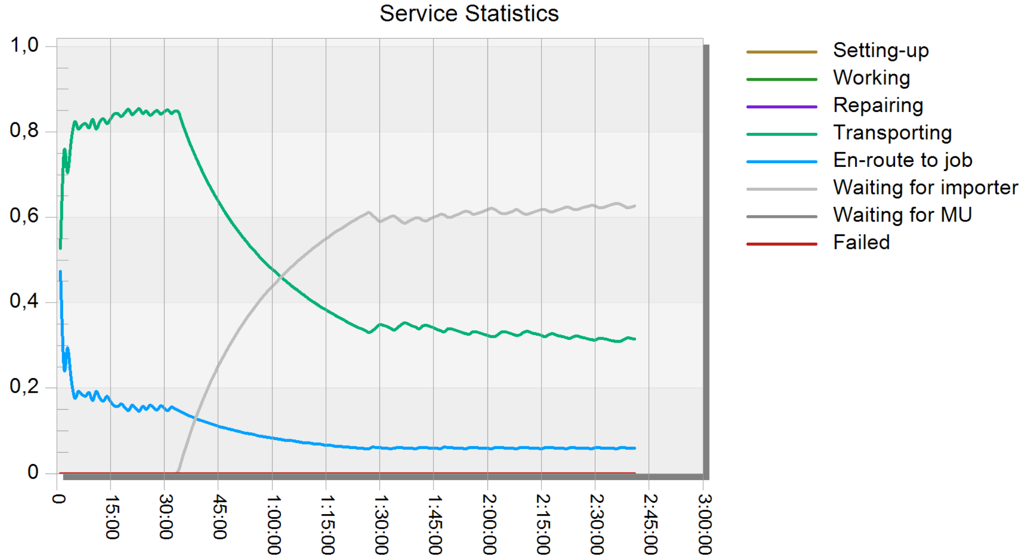


Figure 3.11: Service statistics chart for the kitting worker in the simulation ramp-up phase at pace 65, illustrating the ramp-up phase of the system.

3.6.5 Analysis of Pace Requirements

The two critical aspects of this project were determining the required number of assembly operators and kit carts for various paces, i.e. orders to process per day. The range of this analysis covered paces 20 to 90, which was the range requested by stakehodlers at the company.

To appropriately define the experiments, multi-level experiment design techniques were employed using plant simulation software. This method proved invaluable for systematically creating a list of experiments by setting upper and lower bounds with incremental adjustments across several factors. Specifically, these factors included the pace, number of kit carts, and number of operators in the main flow, as shown in Tab. 3.8.

The comprehensive application of multi-level experiment design indicated the need for a total of 2,982 experiments, which would necessitate a 15-day simulation period. Such a duration implies a considerable computational demand. To manage and reduce the computational load, it was necessary to decrease the number of experiments. The approach to achieve this reduction involved performing preliminary rough estimations as outlined in Section 3.6.3. This strategy allowed for a more focused and efficient experimental setup, reducing unnecessary computational time while still capturing essential data.

Table 3.8: List of input variables for the conducted experiments in Experiment Manager.

Input Value	Pace	No. Kit Carts	No. Operators main flow
Lower level	25	5	1
Upper level	90	18	3
Increment	1	1	1

In addition to the system performance given by the OTD rates for the main flow and sub-flow of the process, additional output parameters were recorded during the simulations to enable subsequent analysis. The worker workload, given by the total percentage of time were workers have assigned tasks, was recorded for all workers. Furthermore, the empty rates of the buffers with assembled kits was included as an additional measure of the safety margin towards the main line. A complete list of output parameters used in the experiments is presented in Tab. 3.9.

Table 3.9: List of constructed Output variables for analysis of Pace, worker utilization and kit cart requirement experiments in Experiment Manager.

Output Variable	Description
∼.RatioPassedDel1	OTD Rate for sub-flow (Del 1)
∼.RatioPassedDel3	OTD Rate for Main flow (Del 3)
∼.Mainline.NonWaiting1	Workload, Main flow assembly Op 1
∼.Mainline.NonWaiting2	Workload, Main flow assembly Op 2
∼.Mainline.NonWaiting3	Workload, Main flow assembly Op 3
∼.Mainline.NonWaiting4	Workload, sub-flow assembly Op 1

3.6.6 Evaluation of Kanban Safety Factor

The number of carts circulating in the system could be viewed as a so called Kanban system. Kanban is a principle of material replenishment authorization based upon visual signals, commonly referred to as Kanban cards, circulating in a closed loop between the supplying and consuming unit [29, 30]. The purpose of Kanban is to control a minimized level of local stock, as the stock is limited by the number of cards included in the system. The number of Kanban cards n required in a system is given by 3.6.

$$n = \frac{D \cdot L \cdot (1 + \alpha)}{a} \tag{3.6}$$

where D is the demand per time unit, L is the lead time (in number of time units), α is a safety factor, and a is the capacity per delivery unit (card). The safety factor α represents the percentage of safety stock, which is given by the uncertainty in demand during the lead time. As a reference value, the manufacturing plants of Toyota have commonly used an established aim of $\alpha = 0.1$. While the demand per time unit does not vary significantly in the valve assembly process, due to the constant Pace at the main line, the lead time itself is affected by the variation in assembly time given by the different product variants. An evaluation of the suitable value of α thus requires an evaluation of this variation.

In order to determine the minimum level of safety stock, a series of experiments were run at Pace levels around the thresholds identified in Section 3.6.5. The number of carts included in the system were lowered step by step, and the level of successful deliveries to the main line was studied as output.

Based upon the minimum number of kitting carts n_{min} identified in the experiments, a minimum safety factor α_{min} could be calculated as in 3.7.

$$\alpha_{min} = \frac{n \cdot a}{D \cdot L} - 1 \tag{3.7}$$

The calculated value of α_{min} can be used as a quantitative evaluation of the simulated minimum levels of safety stock required in the Kanban system.

4

Results

4.1 Present State Analysis

This section presents the results of the present state analysis conducted in the initial phase of the project, with the purpose of mapping the central aspects of the current process, the losses and potential problems and factors of improvement.

4.1.1 Process Mapping

An overview illustration of the process, its included activities, buffers, flows, and work division, is presented in Fig. 4.1.

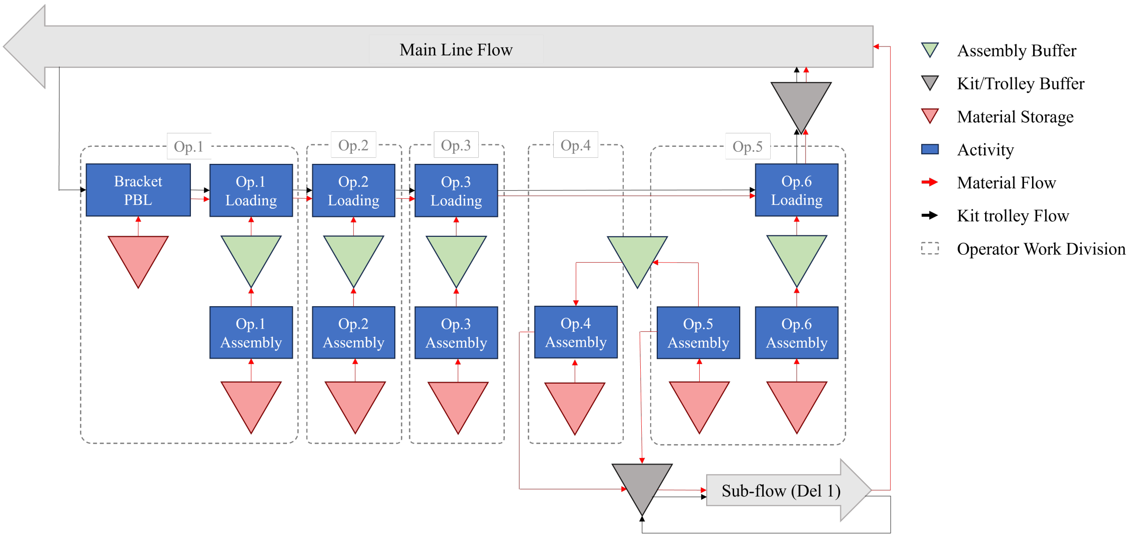


Figure 4.1: Process Flow diagram illustrating the activities, flows and buffers of the Valve Assembly Process.

The main demand of the process is given by the main line flow, which is considered an external activity in the context of this project, and is therefore not illustrated in detail. The line is provided material through moving kit trolleys, which are fed back to the valve assembly when emptied on the line. The flow of the moving kits is controlled by the flow of the main line, which is also the source of demand for the process.

The valve assembly activities are handled by five operators that fill the returning kit trolley in a serial flow. The flow of each valve assembly station involves several buffers that decouple the different activities from each other, which means that the valve assembly activities are not controlled by the demand of the line. The valve assembly activities are instead run as independent push flows, controlled mainly by the buffer levels or knowledge regarding the amount of valves to process each day. Each station has its own status in relation to the order list, while they handle the loading in a sequence synchronized with the main line.

4.1.2 Improvement Factors

Several factors of improvement were identified in the Present State Analysis. A presentation of the main factors identified is provided below.

One primary aspect of waste in the process is the unnecessary movement of the assembly workers, who are required to fetch material from storage behind them. This adds non-value adding time in the process, resulting in waste. Furthermore, the same material is commonly used by several stations, which results in the same material being stored in multiple places, consuming unnecessary levels of space and resulting in larger material buffers.

Another central factor is the combination of the moving kit trolleys and the buffers of each station. The five trolleys included in the current flow essentially function as a Kanban system providing a physical pull signal to the assembly, signaling that a new order should be loaded and sent to the line. Because of the buffers however, the pull signal does not control the actual assembly activities, only the loading. The valve assembly activities instead function essentially as a push flow that continuously pushes the next order to their buffer, allowing for overproduction and losses in unnecessary tasks of material handling.

According to operators, the kit trolley flow used to contain six trolleys, but when one broke, they discovered that the system worked well with only five. This, however, could mean that a higher buffer level is instead required at each station. The amount of trolleys, functioning as cards in a Kanban system, are to be adapted to be able to handle the variation of the system. If enough buffer levels to cope with tolerance is not included in this system, the variation will instead need to be handled by each individual station, where the valves must now be loaded as soon as the valve arrives rather than when the valve is finished. The assembly stations thus need to keep a buffer of finished valves from which they can load the valves directly. This results in waste in terms of unnecessary material handling.

Another significant problem concerns the workload balancing of the stations. Due to the wide range of product variants imposing different assembly times at each station and for each cycle, balancing is not a trivial task. However, several factors indicate that the current balancing is not sufficient. Primarily, the operators have taken initiatives to change the balancing themselves, indicating a lack of trust towards the given structure and standards.

Yet another factor is the placement of the sub-flow assembly. While this assembly serves to feed a separate flow, the stations supporting this process are positioned in the middle of the process, which results in the processes interrupting each other. Due to the workload of the sub-assembly requiring more than one operator, some pre-assembly tasks have been added to an assembly worker of the main line flow, which requires this operator to handle two separate stations. This results in waste in terms of movement between the stations and increases the mental load for the operator that has to monitor and manage two separate buffers. This also requires the operator to build large buffers at one station in order to be free to work at the other.

4.2 Future State Conceptual Model

Based on the basic process redesigns to include kitting and parallel workflow at the assembly stations, a range of different solutions were generated to tackle the sequential problem in the kit delivery at the end of the line. A process flow diagram illustrating the activities, buffers and process interrelations of the final conceptual design is presented in Fig. 4.2.

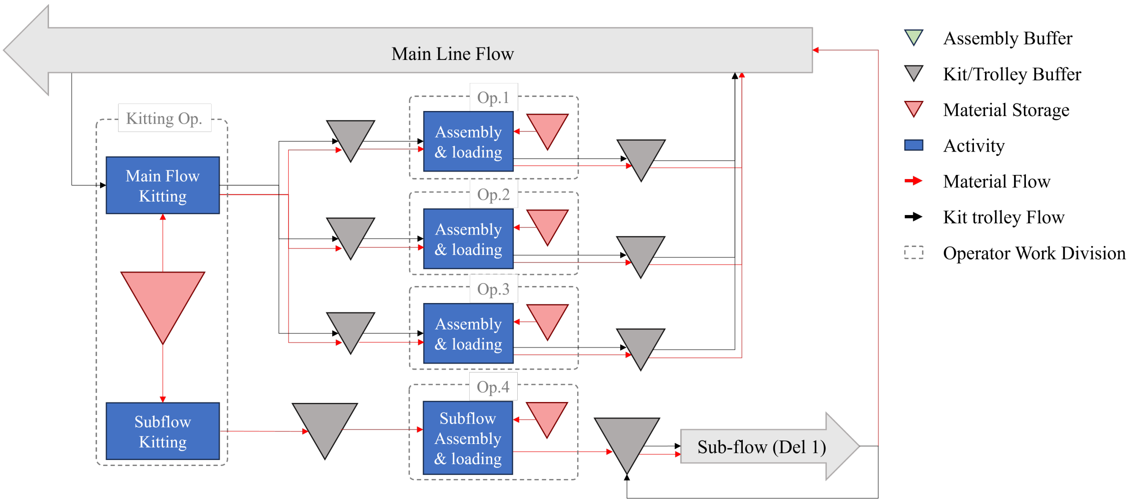


Figure 4.2: Process Flow diagram illustrating the activities, flows and buffers of the Future State Model.

4.3 Simulation Model Overview

An overview image of the final simulation model highlighting its main components is presented in Fig. 4.3. The explanation of each part of the model is provided below.

> **1-2: Main line** The main line (1) is the receiving and consuming unit for the kits assembled by the assembly workers of the main line flow. The line handles the consumption of parts and transports the carts from the assembled kits buffer (5) to the empty carts buffer (2), where the carts are dropped off.
>
> The beginning of the main line handles the order generation based upon statistics of variant configuration statistics for six months, and applies specified

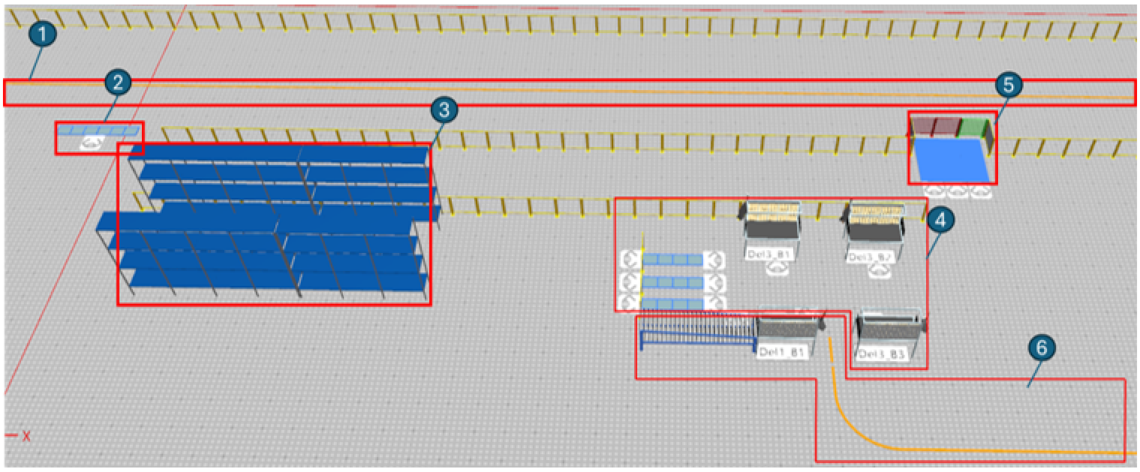


Figure 4.3: Overview of the simulation model and main components.

levelling rules in accordance with a specified list, described further in Section 3.4.1.

AGVs are generated step-wise in accordance with the specified distance between trucks at the line and pick the next order in the generated sequence from a buffer. The AGVs then move the chassi forward on the line in accordance with the specified speed, which is calculated based on the selected pace. The AGVs are stopped based upon randomized failures generated on the basis of failure rates and MTTR. Upon arrival at the assembled kits buffer (5), a request is sent to the buffer based upon the Order number of the transported chassi, and if available, the correct kit cart is loaded on the AGV. If the corresponding order is not available, the order is added in a list, and deleted upon arrival, after which the late delivery cart is moved directly to the empty carts buffer (2). After emptying and returning of the kit cart at the end of the line, the AGV and the loaded order are both sent to drains. If the AGV has not received an order, this is noted in the counter of the drain and used to adjust the OTD rate (see Section 3.6.1).

3: Kitting The kitting process (3) represents a pick-by-light system where the material for the next order is collected in the returned kit cart and sent to the next-in-sequence buffer before the main flow assembly (4). Simultaneously, the kitting also handles the picking of the next order for the sub-flow, which is delivered to the buffer before sub-flow assembly (6).

The kitting is manned by a dedicated kitting worker who handles the movement of the cart. When an empty cart is received, the worker moves the cart to the workplace for kitting. The next order is picked from a source, which in its turn bases the orders from the generated order list in (1). A process time is applied, representing the pick-by-light kitting time based upon the estimated amount of material to kit for the received order. In this process, parts (MU:s) illustrating the parts to pick are generated and placed on the kit cart. After finished kitting process, the worker moves the kit to the buffers before assembly.

4: Main line assembly The assembly of kits for the main line flow (4) is handled by an adjustable number of workers and stations from 1-3. Each worker picks a received cart with prepared kits upon arrival in their dedicated buffer and moves the cart, loaded with MU representations of their kitted parts, to their dedicated workstation. A processing time, based upon the order number for the received kit, is applied at the station. A triangular process time distribution, based upon the specified upper and lower limits given by the input variables, is applied. In this process, the MU:s on the cart, representing the kitted parts, are deleted, and new MU:s, representing the finished assemblies for the specific order, are placed on the cart. After finished assembly process, the worker moves the cart, loaded with the finished assemblies for the current order, to their dedicated buffer before line (5).

5: Poka Yoke The workers have dedicated buffers for the finished assemblies delivered to the main line, which results in three available buffers for the operators to retrrieve carts from. This selection is handled automatically by the simplified main line implementation (1), but in practice, the risk of picking errors was identified in the system. The simulation implements gates as an illustration of a Poka-Yoke system, with the purpose of ensuring that the kits are picked from the buffers in the correct sequence. The next buffer to pick from is marked by a green colored gate, while the rest of the gates are red. The green gate switches only between the active buffers, given by the number of active assembly workers for the main flow.

6: Sub-flow The sub-flow assembly handles the separate assembly of valves, which are collected in batches and sent to a usage point earlier on the main line. The sub-flow assembly is handled by one operator receiving kitted material in a gravity flow buffer connected to the station. The worker moves the kit from the buffer to the station and handles the assembly, with a processing time based upon the order number provided by the kitted parts. A process variation based upon the same input settings for triangular distribution limits used for the main line operators is applied. After finished assembly, the worker moves the prepared kit to a buffer, representing kit racks. The size of the buffer is adjustable, but a required size representing three kit racks was found necessary in the simulation experiments, corresponding to a buffer size of 18 orders. After a specified amount of time corresponding to the passing of six chassis at the main line, calculated based upon the given pace setting, a forklift arrives at the station and removes six assembled orders from the buffer. If less than six orders are available, the amount missing is counted in a variable used in the calculation of OTD rate (see Section 3.6.1), and the missing orders are removed from the buffer upon arrival.

4.3.1 List of Adjustable Parameters

The following parameters were included in the model to enable subsequent input adjustments.

1. Main line pace (orders per day)
2. Distance between trucks
3. Number of assembly operators for main flow
4. Number of kit carts
5. Line Availability
6. Max and Min limits for triangular process time distribution
7. Worker Efficiency (MTM Workspeed) for each worker
8. Simulation Runtime
9. Size of sub-flow kit cart

Furthermore, the order generation system provides the user with the opportunity to make adjustments in the order statistics, for example to promote the probability of specific truck configurations, and test the outcome of such changes in the model performance. The order generation also provides to add, withdraw and change the gap rules applied for levelling of the production.

It is worth noting that in addition to the parameters mentioned above, a wide range of additional attributes are also available for adjustments. The above mentioned parameters have been included to ensure correct interaction between related, internal parameters in the constructed model.

A number of parameters were also implemented to simplify access to specific model output. A list of output parameters constructed for the model is presented below.

1. OTD rate of Main Line Flow
2. OTD rate of sub-flow
3. Worker Occupancy Rate for main line flow
4. Worker Occupancy Rate for sub-flow
5. Cumulative Lead time for kit cart replenishment

In addition to the manually constructed parameters presented above, objects in Plant Simulation feature a wide range of object attributes and statistics that can be accessed by the model user in subsequent experimentation.

4.4 Experiment Results

This section presents the results of the conducted simulation experiments and subsequent analysis of the future state process model. Section 4.4.1 presents the identified manning thresholds of the system and illustrates the achieved levels of worker workload based on the conducted simulations. Section 4.4.2 presents the identified kit cart requirements identified based upon the different levels of pace and manning.

The combined results of the two analyses are summarized and discussed in Section 4.4.3. Finally, Section 4.4.4 presents an evaluation of the Kanban safety factor based upon the simulated lead time and minimized kit carts, illustrating the levels of minimum safety stock required in the system.

4.4.1 Pace Thresholds for 1-3 Main Flow Workers

The pre-assembly process is critical for its ability to deliver on time, measured by the OTD rate. This pre-assembly stage delivers pre-assembled valves to two distinct flows, necessitating separate OTD metrics for each.

Fig. 4.4 illustrates the OTD rates for both the main flow and the sub-flow, using a color-coded system to differentiate between the number of operators. The shaded area in the graph represents the maximum and minimum values of the observations. The line represents the lower bound of the 95% confidence interval, indicating that there is a 95% probability that the true OTD rate will fall above this line.

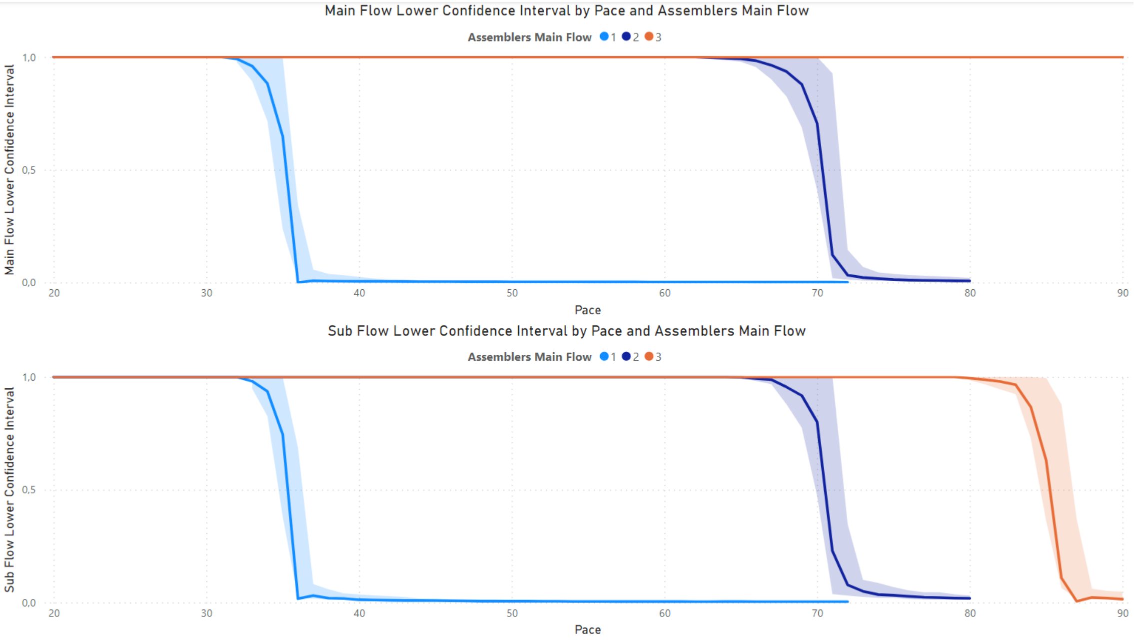


Figure 4.4: Lower Confidence of Pass ratios due to pace limitations. The upper graph illustrates the main flow assembly without regards to the subassembly, lower graph illustrates the constraints influenced by the sub-flow assembly.

The figure reveals that while the main flow can sustain the entire range of production pace with three workers, it struggles with only one or two. Conversely, the sub-flow is unable to meet the pace range requirements with any number of workers (1-3) and begins to exhibit performance issues at an earlier pace than the main flow, marking it as the more constraining factor in the sub-assembly setup. In the figure, the amount of kit carts is set at a high level so the only affecting factor will be the pace and not amount of kit carts.

The graph in Fig. 4.4 highlights specific production paces where the configurations of 1-3 workers result in an OTD rate below 1, with a rate of 1 indicating that all orders are successfully processed and rates below 1 indicating a decline in performance, where assembled kits are no longer delivered to the main line in time. This analysis is crucial for identifying the levels of pace at which the current workforce is inadequate, signaling the need for an increase in the number of workers to maintain efficiency.

By separating the performance thresholds for both the main and sub-flows, Fig. 4.4 serves as a valuable tool for pinpointing where improvements are necessary to prevent bottlenecks and enhance the overall system throughput.

A central aspect to study within these ranges is the resulting levels of workload for the assembly workers. A chart illustrating the simulated levels of worker workload for different levels of pace and amount of workers is shown in Fig. 4.5. The minimum and maximum levels observed in the simulation runs are illustrated with bars and shading for each line.

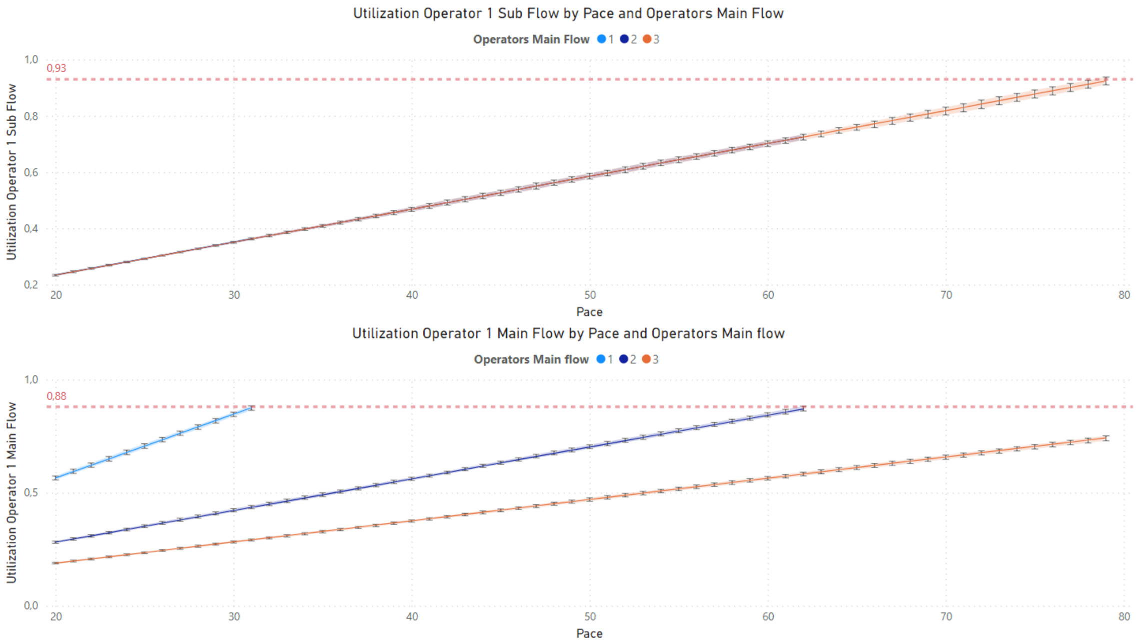


Figure 4.5: A line plot illustrating the average Worker Utilization rates for an assembly worker at the main flow and sub-flow as a function of pace.

As could be expected, a linear increase of the average workload based upon an increase in pace can be observed in Fig. 4.5. An interesting observation can be made in the end points of each line, indicating the levels of pace where failure occurred. As illustrated by the red line in the upper parts of Fig. 4.5, the average workload of the worker does not reach above 88% before failure, despite added carts in the buffer.

The graph illustrates the main flow with separate lines representing different numbers of workers, while the sub-flow lines coincide. This occurs because the number of workers varies only for the main flow, whereas the number of operators in the sub-flow is always kept constant at one. Consequently, the graph for the main flow shows a steeper increase in worker utilization as the pace increases with just one worker.

As more workers are added to share the total assembly workload, the increase in utilization becomes more gradual.

For a given level of production pace, a difference in utilization rate can be observed for the operators of the main and sub-flow, given by the upper and lower graphs of Fig. 4.5. An illustrative example of the imbalance in workload is presented in Fig. 4.6, illustrating the difference workload for the different workers, based on a simulation run at production pace 70 and three assembly workers for the main flow.

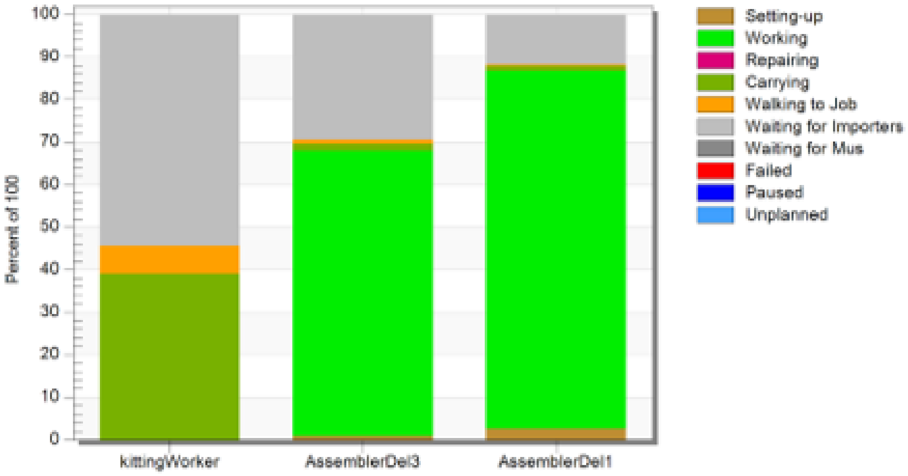


Figure 4.6: Utilization rate and distribution between different tasks for kitting worker (left), main flow assembly operator (middle) and sub-flow assembly operator (right)in a simulation run at pace 70.

At the pace applied in Fig. 4.6, the sub-flow assembly worker is shown to have a significantly higher workload than the main flow assembly operator. The notably low utilization observed for the kitting worker suggests that this worker could potentially be allocated additional tasks, such as the kitting of additional processes

4.4.2 Kit Cart Requirements for 1-3 Main Flow Workers

After analysis of the system limits provided by the pace and number of workers, the minimized number of kit carts for the feasible ranges of pace and manning can be determined. The amount of kit carts works as a buffers in the system as the it will reduce the waiting time and increase the utilization of the workers caused by the main line flow bind up a amount of carts before the valves are assembled at the main line.

A plot illustrating the minimal required number of kit carts in the system for different levels of production pace and number of operators is presented in Fig. 4.7. The upper graph illustrates the results based upon the main flow assembly and the lower shows the results when including the sub-flow assembly, ie. for the complete system.

The simulation results show exponential increases in the required number of carts when approaching the production pace limits for each level of manning (1-3 workers)

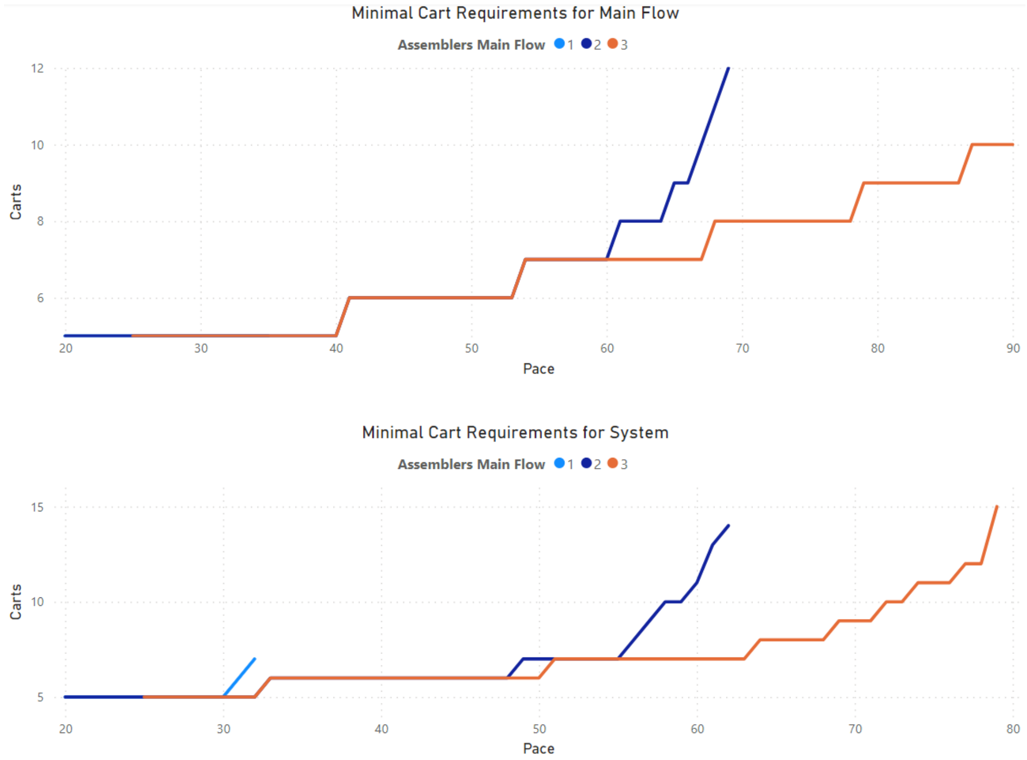


Figure 4.7: Simulated minimum kit cart requirements for various levels of production pace, based upon main flow assembly (upper) and the complete system, i.e. including sub-flow assembly (lower).

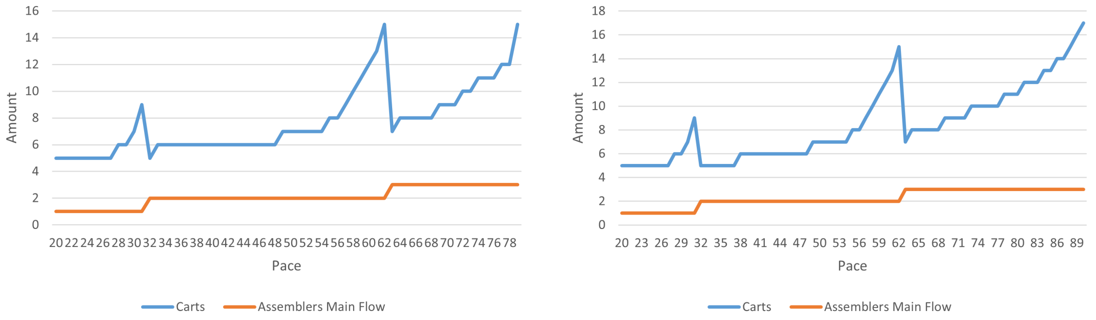
for the main flow assembly. It also shows that the sub-flow requires more carts at a bit lower pace levels.

The sub-flow requires a greater allocation of buffers and carts because the valves pre-assembled at this stage are retrieved by material handlers every sixth order. This schedule contrasts sharply with the main line, where valves are fetched at every pace. This discrepancy necessitates distinct logistical strategies to efficiently manage each flow's unique requirements.

4.4.3 Summary of Minimization

This section shows the summarised part of the experimental results. If the new setup were to be implemented this would be a chart for decision when manning the station at different levels of production pace. Fig. 4.8 shows a summary of the data of minimal number of workers and buffers required for that amount of operators in order to not require a pass rate below 100% according the the simulation observations.

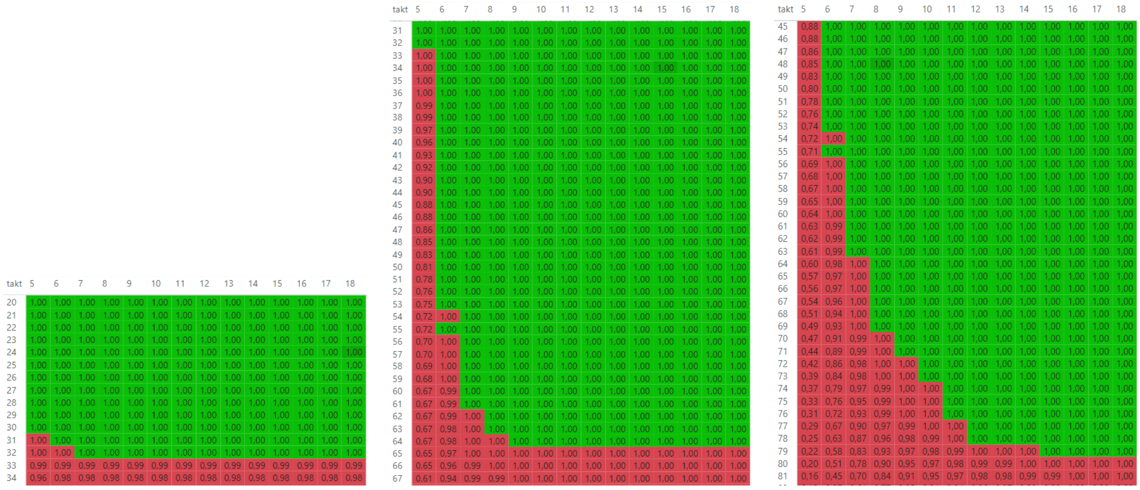
Fig. 4.8 displays a summary of the minimum number of workers required per level of production pace, highlighting it as the critical factor. It also details the minimal number of kitting carts needed for that specific levels of manning at each corresponding pace. The same data is also displayed in Fig. 4.9 as a heat map, divided by amount of workers.



(a) Complete system **(b)** Isolated main flow

Figure 4.8: Simulated mimimum requirements of operators and kit carts, by regards to the isolated main flow and the complete system, i.e. including sub-flow assembly.

Fig. 4.8a illustrates the complete system requirements, while Fig. 4.8b depicts the requirements for only the main flow. The difference between the figures suggests that the sub-flow constrains the system. This constraint arises because the sub-flow is processed in batches and is more heavily utilized than the main flow.



takt	5	6	7	8	9	10	11	12	13	14	15	16	17	18
20	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
21	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
22	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
23	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
24	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
25	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
26	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
27	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
28	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
29	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
30	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
31	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
32	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
33	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99
34	0,96	0,98	0,98	0,98	0,98	0,98	0,98	0,98	0,98	0,98	0,98	0,98	0,98	0,98

(a) 1 worker

takt	5	6	7	8	9	10	11	12	13	14	15	16	17	18
31	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
32	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
33	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
34	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
35	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
36	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
37	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
38	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
39	0,97	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
40	0,96	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
41	0,93	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
42	0,92	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
43	0,90	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
44	0,90	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
45	0,88	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
46	0,88	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
47	0,86	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
48	0,85	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
49	0,83	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
50	0,81	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
51	0,78	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
52	0,76	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
53	0,75	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
54	0,72	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
55	0,72	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
56	0,70	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
57	0,70	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
58	0,69	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
59	0,68	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
60	0,67	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
61	0,67	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
62	0,67	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
63	0,67	0,98	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
64	0,67	0,98	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
65	0,65	0,97	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
66	0,65	0,96	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
67	0,61	0,94	0,99	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00

(b) 2 workers

takt	5	6	7	8	9	10	11	12	13	14	15	16	17	18
45	0,88	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
46	0,88	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
47	0,86	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
48	0,85	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
49	0,83	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
50	0,80	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
51	0,78	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
52	0,76	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
53	0,74	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
54	0,72	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
55	0,71	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
56	0,69	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
57	0,68	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
58	0,67	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
59	0,65	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
60	0,64	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
61	0,63	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
62	0,62	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
63	0,61	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
64	0,60	0,98	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
65	0,57	0,97	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
66	0,56	0,97	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
67	0,54	0,96	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
68	0,51	0,94	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
69	0,49	0,93	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
70	0,47	0,91	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
71	0,44	0,89	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
72	0,42	0,86	0,98	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
73	0,39	0,84	0,98	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
74	0,37	0,79	0,97	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
75	0,33	0,76	0,95	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
76	0,31	0,72	0,93	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
77	0,29	0,67	0,90	0,97	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
78	0,25	0,63	0,87	0,96	0,98	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
79	0,22	0,58	0,83	0,93	0,97	0,98	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00
80	0,20	0,51	0,78	0,90	0,95	0,97	0,98	0,99	0,99	1,00	1,00	1,00	1,00	1,00
81	0,16	0,45	0,70	0,84	0,91	0,95	0,97	0,98	0,98	0,99	0,99	1,00	1,00	1,00

(c) 3 workers

Figure 4.9: Heat maps illustrating the simulated OTD rate for the tested combinations of production pace (vertical axis) and number of kit carts (Horizontal axis) for 1-3 main line assembly workers.

The assembly operator for the sub-flow was found unable to fill the rack in the given time in some cases of high assembly time, indicating the need for additional buffers here.

Fig. 4.8 demonstrates that the sub-flow is constraining the overall system flow. To fully leverage the benefits of the new layout changes, which include parallel work and kitting, it is preferable to separate the kitting processes for the main flow and sub-flow. Currently, both flows are kitted based on the main line Kanban system, where the kitting for both flows is triggered by the entry of an empty cart from the main line. This setup causes the main flow to be constrained by the sub-flow. Therefore, the kitting for the sub-flow should be independently triggered, not reliant on the main line.

4.4.4 Evaluation of Kanban Safety Factor

An example of the Kanban safety factor α was calculated based upon the cumulative average lead time, for a simulation configuration implementing the simulated minimum kit cart requirements for pace 62 and three workers. The demand rate D is given by

$$D = \frac{n_{kits}}{t} = \frac{2836}{15 \cdot 24 \cdot 3600} \approx 0.002188 \text{ kits per second}$$

where n_{kits} is the total number of kits demanded in the specified time period t_{tot}. Adding this to Eq. (3.7) for a number of Kanban cards $K = 7$, a container capacity $C = 1$ corresponding to one kit per delivery, and a simulated, cumulative mean lead time $LT = 1036$ results in a Kanban safety factor α_{min} calculated as

$$\alpha_{min} = \frac{7 \cdot 1}{0.002188 \cdot 1036} - 1 \approx 2.09$$

This calculation illustrates the simulated minimum safety factor α_{min} necessary to consider in the Kanban system to account for uncertainties and variation in the simulated assembly process. The safety factor of 2.09 suggests a buffer stock that is slightly more than double the calculated need based on the demand and lead time. The buffer helps manage risks associated with fluctuations that are not captured by average or expected values. This can be compared to the Kanban levels of Toyota, where an aim of $\alpha = 0.1$ is commonly applied [28].

It is worth noting that the very high value of α calculated here would be lower if only the main flow were to be considered as the sub-flow requires a higher amount of buffers. However, the value provides an indication of the levels of variation in the system, which serve to inflate the buffer requirements. Note that the required levels of safety stock will increase further at production pace close to the identified system thresholds, following the increase in kit cart requirements shown in Section 4.4.2.

5

Discussion

In this chapter, the collected literature presented in Chapter 2 and the results of the conducted DES case study are analyzed in combination, providing a basis for the answering of the established research questions. Section 5.1 discusses the use of DES as a support tool in studies of assembly processes, especially in terms of visual support and the use of PTS process time data as a data source in manual assembly, answering the question *How can DES support studies of assembly processes featuring high levels of product based variation*? Section 5.2 elaborates on the theoretical framework for kitting and parallelization of processes, and provides an overview evaluation of the simulated redesign based upon simulation results, thus answering the question *What are the effects of parallelization & kitting on a manual assembly process*? Limitations of the study are discussed in Section 5.4, together with recommendations for future research. Finally, the study is discussed from the perspective of sustainability in Section 5.6.

5.1 RQ1: How can DES support studies of assembly processes featuring high levels of product based variation?

The use of DES has proven beneficial in supporting the redesign and evaluation of mixed-model, manual assembly processes. The iterative and detailed nature of DES allows for detailed modelling and analysis of complex systems, providing insights that can be critical for effective decision-making. In this study, DES enabled a structured and systematic approach to concretization of ideas for redesign the assembly process by simulating different scenarios and analyzing the outcomes.

The findings illustrate that DES can help identify inefficiencies in design, facilitating the exploration of various redesign strategies in collaboration with process experts. For instance, the low utilization observed in kitting work indicated potential areas for reallocating tasks to improve overall efficiency. Additionally, DES provided a quantitative basis for determining the resulting buffer requirements and worker workload in a redesigned process, thereby supporting optimization of resource allocation and reducing waste.

The capability of DES to model parallelization and kitting processes was particularly useful. By simulating the effects of these changes, it was possible to predict their impact on operator utilization and OTD rates. The simulation results highlighted the importance of balancing workloads and adjusting the number of operators to meet production pace requirements, ensuring that all orders are processed timely without overburdening the workers. The experimental results also indicate the importance of using multiple output parameters as a means of process evaluation, underlining the theoretical claims that no single measure can be used to capture the performance of a process [18].

5.1.1 Visual Detail Level in Simulation

The literature study showed that DES is a commonly used tool in studies of manufacturing system design improvements and optimization. In practical work in industry however, the work of process improvement may often be conducted by, or in close collaboration with, operators and other process experts, whose knowledge and expertise in advanced simulation and optimization tools may be limited. This, in its turn, could also contribute to limit the use of the advanced tools and methodologies applied in research. DES literature commonly recommends work of model design and development in close collaboration with process experts and in an iterative fashion [1,12,13], and here, visual support was identified as a potentially central enabler of cross-disciplinary collaboration, a factor which was also used as a guideline for the DES study covered in this report.

The visual details of the model have proven highly useful both in the phases of process design development, and verification and validation, especially in the cooperative phases involving project owners and process experts. However, implementation of visual details, such as CAD models of parts and products, increase both the development time and simulation runtime. Plant Simulation offers functions to reduce details in the graphic structure to reduce the computational load for graphics, but this optimization is also time consuming when it needs to be done for a wide range of parts. Additional time is also required to configure the CAD parts in terms of size and position. Furthermore, visual details have at times been found to impose problems in the logical structure of the simulation model, which can be time consuming and difficult to solve, and may risk contributing to a less comprehensible simulation model. For manual assembly processes like the one in this project, the visual representations may still be unsatisfactory for stakeholders. This is because the actual work of assembly is not illustrated, and including such detail would be too demanding in terms of both simulation complexity and project duration.

5.1.2 Use of Predetermined Time System Data in DES

Another limiting factor in DES modelling of manual assembly processes is the lack of statistical data for use in the modelling. Where machine based processes may provide the opportunity to study production logs or similar data, manual assembly does not necessarily provide such opportunities. In less product variant rich environments, stopwatch time studies or similar techniques could be a solution. In mass customization environments, such as mixed-model assembly processes, including significantly broader product variant ranges and high levels of product based variation, the approach of detailed and thorough time studies may likely be too time consuming to be feasible. As an alternative source of data, PTS data such as MTM analyses may be the only available source of process time data. Use of such data increases the time demanded for data handling [45], but enables high accuracy modelling featuring the level of detail commonly required for process redesign tasks such as line balancing [57].

In this study, detailed MTM time data was successfully used in the calculation of manual assembly times in the simulation of a redesigned assembly system. The detailed time element handling enabled removal of non value-adding tasks such as steps, unnecessary material handling and other tasks that were to be removed or changed in the redesigned flow. The significantly reduced times for material handling after implementation of kitting could then be added subsequently as setup, loading and unloading times in the model. The reduced amount of steps required in the redesigned process could be implemented based on simulation with workers in the model, without the need of additional calculations of MTM analyses, and could thus also be used as a flexible parameter in the detailed redesign of the layout in the simulation.

While beneficial in terms of the detailed modelling capabilities described above, implementation of detailed MTM based time data in the simulation model has demanded a significant portion of the project conduction time, aligning with claims in literature [45]. The handling of detailed MTM data increases both the complexity of the model and the time required for data extraction, processing and model implementation. In order to lower the required time and decrease model complexity, the PTS process times were filtered and calculated externally, and implemented as summarized assembly times in the model, which enabled highly accurate assembly times while allowing for relatively simple mechanisms of time allocation in the model. While this approach allowed for simplifications in the modelling phase, the detail level required in the data extraction and processing phase remained highly time demanding.

While the simplified approach in modelling of assembly times and handling of variant flora was found beneficial for the experiments to be conducted in this study, it is expected that a more substantial implementation of the logical structure behind the generated time elements and their variant logic could provide several useful characteristics in a more advanced model. By using the detailed product variant based process time variations in a simulation, future order lists could be tested and evaluated for feasibility for the modelled process, estimated resource requirements, and more. In context of an Industry 4.0 and the work towards predictive and digital twin capabilities, this level of detail could be considered a necessity in order enable mirroring of the mechanisms of the complex and product variant rich environment of Volvo. However, it increases the requirements for computational capacity during experiments and may not be suitable for use with high levels of visual detail.

The iterative methodology applied in the project effectively supported communication with stakeholders. This approach allowed for early identification, discussion, and resolution of potential problems in the intended process redesign, which might not have been possible otherwise. However, it significantly increased the model construction time. Although an iterative increase in complexity is recommended in several parts of the literature [1,12,13,44], the generated code and parts of the object structure created during the model construction phase often become unusable after increasing detail, necessitating substantial rework with each iteration.

5.2 RQ2: What are the effects of parallelization & kitting on a manual assembly process?

Kitting is an increasingly popular method for material feeding in the industry, particularly beneficial in environments with a wide range of component variants. It helps reduce space requirements, picking time, cognitive load, and the risk of assembly errors [25, 62]. Kitting aligns with Lean principles of waste elimination and supports Poka Yoke by providing only the correct materials to the operator. It also aids Kanban by allowing operators to initiate assembly only when necessary [28]. Additionally, kitting reduces non-value-adding time in assembly operations by providing nearby access to materials, thereby reducing walking time.

The effects on parallelization of manufacturing processes, as opposed to the moving line concept made popular by Ford, has been researched historically, with ambivalent results. While research around the early 2000's, influenced by ideas from the Human Relations Movement and Socio-technical theory [20], advocated beneficial work cycles of up to two hours [23, 24], more recent literature advocates principles based on serial flow and shorter work cycles [22, 27, 28]. While benefits of increased work satisfaction were pointed out as a central motivators for implementing long cycle times and parallel, stationary assembly [23], recent literature points out that despite these positive effects, long cycles commonly result in an even stronger influence of negative factors, such as increased risk of errors and dependence on skilled and experienced workforce [22].

The results of the simulation based process improvement study show that implementation of parallelization and kitting in a redesigned assembly process is feasible, and can provide several benefits. While kitting serves to reduce the assembly times significantly, it is shown that the parallelization still results in work cycle times of above 15 minutes, which could be considered long cycles and imposes risks [22]. By concretizing the implementation in support of Kanban, buffer levels can be kept at a controlled minimum. However, it is also shown that the product based process variations still impose significant safety stock requirements on the process. The variation also imposes limitations in the utilization of resources, where the simulation results indicate that mean worker workloads can not reach higher than approximately 88% in the suggested configuration, without an unrealistic increase in the required buffer levels to cope with the variation.

5.2.1 Comparative Evaluation of Process Redesign

A matrix illustrating the main aspects of comparison between the current assembly process and the redesign generated and tested in the project is provided in Tab. 5.1.

Table 5.1: An overview comparison of the Present State and Redesigned Layout.

Comparison Factor	Present State	Redesign
Buffer Levels	High, unregulated	Lower, regulated
Quality	OK	Increased risk
Cognitive load	Medium	Increased
Push/pull	Push	Pull
Manning flexibility	Lower	Higher
Rebalancing	Complex	Only manning changes
Learning period	Shorter	Longer
Work satisfaction	Lower	Higher
Required manning	More	Less
Waste	More	Less

The overview comparison in Tab. 5.1 reveals both positive and negative impacts of adopting this new solution over maintaining the old one. The most significant advantages of implementing the new system are increased efficiency, through implementation of a pull system, reduced buffer levels and not least reduce movement time for assembly operators. The study shows that fewer operators are needed for the process than what is currently the case, resulting in reduced labour costs. However, it necessitates additional measures to reduce cognitive load, such as implementation of visual instructions, and potentially requires enhancing quality control, due to concerns about potential declines in quality. This was also found to be the case in another plant, where similar levels of work cycle times per operator could be found in the corresponding valve assembly process. As a may to cope with the issues of quality, the assembly at this plant had initialized implementation of a vision based quality inspection system, which could be worthy of consideration for future implementation.

Another interesting factor here is work satisfaction, which several studies underline as a potential increase in a parallelized flow with longer cycles [22–24]. While the required learning period of the workers is very likely to increase, the work satisfaction can be significantly improved at the stations, and there is also a significant increase of possibilities for cooperation between the stations, providing increased flexibility and tolerance to cope with the most time demanding product variants. Furthermore, the flexibility also extends to cover the factor of balancing, which is not required at all in a parallelized flow. There are, however, only limited ranges of production pace where the workload levels are feasible at the main flow assembly, and an even more narrow span where workload is also balanced between main and sub-flow assembly.

While the workload balance between the main and sub-flow assembly could be difficult, it is worth underlining that the study shows that an implementation of kitting enables complete separation of the sub-flow assembly, with all tasks added to only one operator. This provides significant levels of flexibility regarding this sub-process, which could, for instance, be moved closer to the usage point of the assemblies, thus further reducing waste in terms of additional material handling.

An interesting aspect regarding the identified problems of the suggested redesign is that the most central problems identified, i.e. the long cycles and the risks of decreased quality, are factors which can not, in fact, be captured solely by the DES model. In this setting, there is instead risk that the simulation model provides a misleading image that processes are feasible, just because the simulation model shows them to be. This underlines the importance of involving the process experts, such as operators and team leaders, in the development and evaluation of processes, as also recommended by DES literature [1, 12, 13].

Due to the time constraints of the project, a delimitation was established stating that the processes at the main line were not to be studied in detail in the project. As a consequence, it was determined necessary to keep the current interface between the main line and the valve assembly process intact, meaning that the kit cart system was preserved in the redesigned system. By studying the potential to redesign this interface with the line and remove the kit carts while preserving the Kanban principles, for example through implementation of a Karakuri material delivery solutions [63], as used in the corresponding process in Curitiba, it is likely that several additional factors of waste could be eliminated.

An example of such waste can be found in the handling of the kit carts, which includes the necessary movements to and from the delivery and return points of the kit carts at the main line. By replacing the kit carts, these factors of non value adding time could potentially be removed. This, in its turn, could also contribute to reduce the lead time for the replenishment of assembled kits in the Kanban system by excluding the material kitting process from the card circulation. As indicated by the relationships shown in Eq. (3.6), this could contribute to an even further reduction of Kanban cards than indicated in this project, thereby resulting in even further decrease of buffer levels and WIP. However, it is expected that a significant safety margin is still to be required in this system due to the high levels of product variant based variation.

5.3 Generalizability of Study Findings

While this study mainly provides insights specific to the context of the studied case, several implications could be found applicable to a broader context of manufacturing industry. Most central here is the conclusions relating to RQ1, as discussed in Section 5.1, where the results of the study serve to showcase a potential use of DES in mass customization environments in general. The type of variation affecting the performance of such systems could be considered special cause variation, which is a central aspect of process analysis and improvement [18]. Data-driven analysis of this variation, which could be supported by DES, can enable adaptation of all processes and systems subject to this variation. It could also be possible to quantify the effects of this variation, which could support companies in balancing costs and benefits of expanding or restricting their product flora.

Many aspects of the evaluation of effects of kitting and parallelization on the assembly process, as discussed in Section 5.2, could also be applicable in a general setting, but the extent of these results would likely depend significantly on the setting of the application. In the case studied in this project, kitting enabled both the implementation of a pull flow and a potential reduction of the space requirements for storage. Meanwhile, other studies have found that while space requirements near line can be reduced, the total required space of the entire process may instead increase [62]. For parallelization, the results could be found largely dependant on the length of the process work cycles, as well as aspects regarding the work tasks of the cycle. The general effect of significantly increased cycle times in parallelized workflow and the resulting risks could however be considered applicable in a generalized setting.

5.4 Study Limitations & Recommendations for Future Research

The simplified modelling of material supply and subsequent operations was a necessary project limitation due to the project time constraints. This simplification means that the study might not capture all the nuances of these processes, potentially affecting the model's accuracy and the applicability of the results. Additionally, the focus on historical order data for product variation, rather than forecasting future variations, limits the model's ability to predict future performance under different conditions. These limitations highlight the importance of contextualizing our findings within the scope of these assumptions.

As pointed out in Section 1.4, the detailed aspects of material delivery were not examined in detail in the project, nor included in detail in the model. The modelling of these mechanisms was simplified to only mimic the relevant main characteristics of these processes. The material supply to the valve assembly was assumed to never run out, meaning that material would always be available. The study also illustrated the implementation of kitting using a highly simplified approach based on the storage location of the kitted material. The detailed design of the containers for delivering kitted parts was not considered, and it was assumed that kitted material would be delivered in containers that support easy access without additional handling. Literature underlines the importance of considering the exact material to be kitted, as well as the design of kitting containers, in order to ensure beneficial kitting implementations [22,62]. Thus, additional studies of these aspects and their potential effect on the results presented in this study should be conducted before eventual implementation.

The data used for model construction were based upon pre-collected statistics, historical production data, PTS based process times, and similar data provided by the company. Where no data was available, the implementation relied on recommendations from the literature and made assumptions in collaboration with process and data domain experts at the company. It has been assumed in this project that the MTM analysis based process times for the present state system are both correct and sufficiently accurate These assumptions, while necessary due to time constraints, could cause inaccuracies in the model, potentially impacting the study's findings.

The extracted and filtered MTM based process times were applied in a redesigned process featuring updated methods for material supply using kitting. This was achieved by filtering of the movement times in the MTM data, and reapplication of new movement times through simulations of worker movement. An interesting feature provided by the simulation is that the walking distances and times can be extracted from the simulation based upon the layout, which could enable support for validation, and potentially even updating, of the PTS time data by regards to changes in the layout. Research of how this can be used in support of conduction and validation of MTM analyses could provide significant value for the company, as MTM analyses are highly time consuming to conduct, leading to the data not being updated on the basis of smaller layout or process changes.

Another potential aspect to pinpoint in further studies could be the possibilities of involving real-time database communication in the model. This could serve to improve both the detail level and maintainability of the model, and take the concept one step further towards the development of a digital shadow of the process.

5.5 Use of Generative AI

This master's thesis was supported by generative AI tools in several steps, including brainstorming and refining project structure ideas, suggesting elements for the project methodology, support for programming and troubleshooting. Additionally, generative AI improved the quality of this report by locating grammatical errors, suggesting reformulations for better readability, and generating structural suggestions which were considered during the writing process.

5.6 Project Ethics & Sustainability

Sustainable development is commonly defined as *development that meets the needs of the present without compromising the ability of future generations to meet their own needs* [64]. The subject of sustainability is commonly divided into the three central factors of social, economical and environmental sustainability, commonly referred to as the three pillars of sustainability [65]. Efficient, optimized use of resources is a central aspect of sustainability and also a common motivator for the use of DES, as is also the case in this project. The methodology and results of the project indicate the potential for DES as a tool to study multiple aspects of complex manufacturing systems, in order to evaluate and support improvement of resource utilization. The results contribute to the substantial research of DES as a potent tool in both inventory management and process optimization, both underlined as key factors in the transition towards sustainable manufacturing [66].

The project further contributes to the aspect of sustainability through the involvement of Lean manufacturing principles. Lean manufacturing and the focus of waste elimination and value addition is to be viewed as a predecessor in the long term transition towards green and sustainable manufacturing [67]. In this context, green manufacturing could be specified as a holistic orientation towards what is known as the 3R factors: reduce, re-use, and recycle. The further transition towards sustainable manufacturing involves a transition towards inclusion of three additional factors of recovery, redesign, and remanufacturing, resulting in a 6R orientation. Previous studies have shown how a combined implementation of Lean practices and sustainability go hand in hand [68]. As shown in Section 2.1.4, modern Lean frameworks commonly also underline the factor of environmental waste, relating to the subject of environmental sustainability, as a key factor of waste to be eliminated [27].

A potentially sensitive subject involved in this study is the studies that involve optimization of manning, which could risk being perceived as a basis simply for reducing manning. It is important, however, to point out that the opposite view would be just as relevant in this case. One of the central perks of using DES in the way used in this project is the possibility to assess workload of manual assembly personnel, which would also ensure that personnel are subjected to a reasonable level of workload and reduce other disturbances in the work, causing unnecessary stress and problems for human personnel. Decent work is a central factor of social sustainability, and involves factors of both labor rights, security, and productivity [69]. This type of overburdening is also underlined as one of the major factors of waste in Lean theory [27].

6

Conclusion

DES is a highly useful tool to enable analysis of complex assembly systems, such as the assembly process of Volvo GTO. The DES model developed in the project provides the user with the opportunity to predict the workload of operators, levels of manning and number of Kanban cards in the valve assembly, with regards to changes in order distributions and/or application of production levelling rules (Heijunka). The use of PTS process time data enables detailed determination of process times in manual assembly, also taking the variant range of the mixed-model assembly into consideration. The results show that application of PTS data can support a high detail level in the work of process redesign and re-balancing, but at the cost of significant time requirements for data handling. The complexity level of the simulation model can be kept low through external data handling.

The results of the study indicate that kitting can reduce the cycle times of the assembly process significantly, which could provide opportunities of re-balancing between the stations. This reduction allows for the sub-flow assembly to be separated entirely from the main flow in regular spans of production pace, which enables flexibility in future redesigns, where this assembly could be moved closer to the usage point at the main line or moved elsewhere to further reduce material handling. The cycle time reduction increases the potential to implement parallelization of the assembly. Through implementation of small, parallel buffers and a Poka Yoke system, it is possible to handle deviations in the order sequence without a significant increase in buffer size requirements. Furthermore, by enforcement of a Kanban signal to initiate the assembly operations, overproduction could be prevented and WIP could be kept to a minimum.

While the reduced cycle times provided by kitting improve the conditions for parallelization, the study results indicate long cycles, a factor which literature underlines as a risk. This could potentially result in less efficient assembly due to lower level of repetition, and an increased risk of assembly errors. In order to mitigate these risks, an increased focus on cognitive support for the assembly operators, for example using digitized, visual support for the assembly instructions, is recommended. Here, the study underlines aspects of process design which are not possible to evaluate using simulation, but may instead risk being hidden by simulation. This risk clarifies the importance of involving process experts in the development and evaluation of process redesigns.

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A

Transformed Process Data

Order	Date	Variant String
order1	date1	24-HDV,FH 42 T,UXFUEL,ULADDER,USPOTP,UTMP..
order2	date2	24-HDV,FM 84F R,UXFUEL,ULADDER,USPOTP,UTMP..
order3	date3	24-HDV,FH104FTR,UXFUEL,ULADDER,SPOTP-R..

Table A.1: Example of transformed data: Order Data including variant strings to every order

B

Pseudo Code for Data Processing

The following pseudo code outlines the steps taken to read data, apply filtering rules, and save the results:

```
1. Import necessary libraries

2. Define function to escape SQL special characters:
   - Input: string
   - Output: string with '%' and '_' escaped

3. Define function to transform rule into SQL WHERE clause:
   - Input: rule as string
   - Output: SQL WHERE clause as string
   - Add space around parentheses and logical operators
   - Split rule into elements
   - Initialize list for SQL WHERE clause elements
   - For each element:
     - If logical operator (AND, OR, NOT):
       - Add to list
     - Else if parenthesis:
       - Add to list
     - Else:
       - Convert to SQL LIKE clause with escaped special characters
   - Join elements into SQL WHERE clause
   - Return SQL WHERE clause

4. Define function to filter DataFrame and add Timestudy Group and Workstation:
   - Input: DataFrame, rule, timestudy_group, workstation
   - Output: Filtered DataFrame
   - Convert rule to SQL WHERE clause
   - Construct SQL query to select rows matching rule, add Timestudy Group and Workstation
   - Execute SQL query
   - Drop 'Variant' column
   - Return result

5. Load DataFrame from Excel file
   - Convert 'Variant' column to string

6. Load rules and Timestudy Groups from Excel file

7. Define range for processing

```

```
8. Define function to process a single rule:
   - Input: index
   - Output: Filtered DataFrame for the rule
   - Get rule, Timestudy Group, and Workstation for index
   - Return filtered DataFrame with Time study Group and
   ↪ Workstation

9. Initialize list to store results

10. Use parallel processing:
    - Submit tasks for each rule
    - For each completed task:
      - Get result
      - If result is not empty:
        - Add to results list

11. Combine all results into one DataFrame
    - If results list is not empty:
      - Concatenate into single DataFrame
    - Else:
      - Create empty DataFrame

12. Save combined DataFrame to new Excel file, excluding 'Variant'
   ↪ column

13. Print confirmation message with output file path
```

Listing B.1: Pseudo Code for Data Processing