A discrete event simulation framework for flexible job-shops with re-entrant flows

A case study at RUAG Space AB Gothenburg, a satellite component manufacturer

Master's thesis in Production Engineering

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Gothenburg, Sweden 2018

MASTER'S THESIS 2018

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Master's Thesis 2018
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Cover: Visualization of a satellite in orbit.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2018

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Abstract

The space industry is on the verge of entering a new era, with an increasing number of commercial actors. The recent technology advancements, which have lead to reduced launch costs, are paving the way for a whole new type of businesses. The increase in commercial actors is creating a more dynamic and faster changing market for space product manufacturers. RUAG Space AB Gothenburg, a company manufacturing components for satellites, is expecting that this change in the market will require them to adapt their production system to more efficiently handle the expected fluctuation in demand. To do this, they have initiated a collaborative research project with Chalmers University of Technology. To complete the project a simulation model, on which experimentation can be performed, is required. This thesis deals with the development of said simulation model.

The production system at RUAG is identified as a flexible job-shop (FJS), characterized by re-entrants flows, predominantly manual work, low production volume and high product variance. Developing a simulation model for such a complex system, a well-designed methodology has to be created and followed throughout the project. FJS with re-entrants flows is a non-traditional production system in terms of simulation. Therefore, a framework is developed to deal with the complexity and uniqueness of such a system. This thesis presents the framework in theory and application.

The application of the framework shows its suitability for use in the creation of a simulation model of an FJS production system with re-entrant flows. Following the framework steps, a strategy for validation of the simulation model is designed and successfully executed, showing that it is possible to validate such complex models. Possible improvements to the framework are also discovered during its application which strengthens the robustness. In conclusion, the developed framework sheds light upon the development and validation of a DES model of an FJS production system.

Keywords: discrete event simulation, flexible job-shop, engineer-to-order, re-entrant, space, manufacturing, validation.

Acknowledgements

The authors of this report would like to take a moment to thank all the people who have participated in the project in direct and indirect ways.

First of all, a big thanks to Chalmers University of Technology and RUAG Space AB Gothenburg which made this project possible and provided the tools and resources we needed to complete our thesis. More specifically:

From Chalmers, we would like to thank Björn Johansson, our examiner, for his constructive feedback and support on the report. A big thank you to Daniel Nåfors and Maja Bärring, our supervisors, for your continuous contribution and support during all the phases of the project. Without your guidance this project would not have been the same.

From RUAG, we would like to thank Mats Wahlström, our supervisor, and Camilla Malmer, our brief hero, both of whom provided immense help towards the completion of this project. Moreover, we would like to thank all of the employees at RUAG whom have taken us on tour of the facilities, participated in the validation, or generally been available to help us with any queries.

Last but not least, we want to say a huge thank you to our families and friends for their selfless support and unlimited love that they showed to us during the whole two years of our master program.

Georgios Papaioannou
Markus Fransson
Gothenburg, June 2018

Contents

Glossary

ATO	Assemble-To-Order, a production strategy where modules of products are prepared and placed in stock, and assembled to a final product once an order is received.
DES	Discrete Event Simulation, a simulation type which only progresses the simulation model when an event occurs
Entity	Can either be a digital representation of parts that flow across the simulation, or represent the flow of information in the system
ERP	Enterprise Resource Planning (system), is a company database which manages and supplies information for many different functions within the company
ETO	Engineer-To-Order, a production strategy where the product is designed and produced according to the customers specifications
Event	A change of state in a discrete simulation model
FJS	Flexible Job-Shop, a production type, suitable for ETO, where resources are organized in a functional layout. Resources are multipurpose and can process many types of products
MDT	Mean Down Time, the mean time a certain resource is down (broken/unavailable)
MTBF	Mean Time Between Failure, the mean time between failures of a certain resource
MTO	Make-To-Order, a production strategy where no production is performed until an order has been received
MTTF	Mean Time To Failure, the mean time to failure for a non-repairable resource
MTTR	Mean Time To Repair, the mean time it takes to repair a certain resource
Resource	In a simulation, represents anything that has a constrained capacity
Simulation	The imitation of a real-world process or system over time
SMT	Surface Mounting Technology, a printer-like machine which places components on circuit boards
System	A collection of parts organized for some purpose

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Introduction

The chapter presents current developments in the space industry and how that will affect the case-company. The rest of the chapter describes the aim of the thesis, the research questions to be answered and the project's delimitations.

1.1 Background

The commercial space industry is on the brink of drastic change. During 2017 SpaceX demonstrated their ability to reuse launch rockets by achieving re-flight with their Falcon 9 rocket (SpaceX, 2015). This means that they launched the Falcon 9 into space, released a payload, returned the rocket safely back to earth, and then did the same thing again, with the same rocket. The ability to reduce launch costs by reusing rockets creates opportunities for projects that were previously not financially feasible. One such project that is now becoming feasible is suggested by SpaceX themselves. They have presented a plan to the United States Senate (Cooper, 2017) to have launched 4425 satellites by 2024. Another company, OneWeb, have presented a plan to launch 900 satellites by 2027 (Wyler, 2016). This can be compared with the approximately 1700 operational space objects, satellites, telescopes, space stations etc., that are currently orbiting the earth (Committee on the Peaceful Use of Outer Space, Office of Outer Space Affairs, 2018). Both companies satellites are to be used to provide internet access anywhere in the world.

Companies manufacturing space products/components belong to the engineer-to-order (ETO) operating environment which is characterized by low volumes of products produced per year, complex functional requirements, high technical risks, long delivery times and unpredictable demand (Vellmar, Gepp, & Schertl, 2017). Since indications have shown that an increase in space products is imminent, companies in this sector must react quickly and master uncertainty and unpredictability, cope with customer requirements and standards, and finally decrease lead-times and cost of products.

A trend in businesses is Industrie 4.0 (Zhou, Liu, & Zhou, 2015). Industrie 4.0 refers to the emerging industrial revolution which aims to connecting the digital world with the physical, but there does not exist an official description. Hermann, Pentek, and Otto (2016) made an attempt to create a set of design principles for Industrie 4.0, and found that decentralized decisions, interconnection, information transparency and technical assistance were the main pillars. This industrial revolution offers a wide variety of tools and technologies with great benefits for industries, such as better decision making, lower costs and better integration of systems. However, ETO businesses have only taken a few steps towards this direction (Vellmar et al., 2017). Space products manufacturing companies might be ready to deal with increased demand, however adopting Industrie 4.0 concepts and tools, will certainly ease the challenge.

1.2 Case company

RUAG Space is a branch of the Swiss company RUAG Group. RUAG Space (hereafter simply referred to as RUAG) Swedish headquarters are located in Gothenburg, Sweden, housing approximately 350 employees. The company specializes in manufacturing communication modules for satellites, such as transceivers, converters and antennas. The production is divided into three units, going under the names Microwave, Digital and Antenna respectively. The three production units are completely disconnected from each other, apart from some shared machines (ovens, testing equipment, etc.). The production is utilizing a functional layout, where highly skilled operators, to a large degree manually, perform work on the products. The production type is described as a flexible job-shop (FJS) (Pinedo, 2009). The production is characterized by extremely high-quality demands, high product variability, long lead times and low production volume, characteristics that are found mainly in ETO operating environments (Olhager, 2003).

Because of the reduced launch costs achieved by SpaceX, RUAG is predicting a drastic increase in the demand of their products in the near future. Realizing that change was needed, RUAG initiated a project together with Chalmers University of Technology to evaluate what changes are needed. Simulation models were requested to experiment on different volume scenarios, but the large product variance, where each product is different in terms of customer specifications, meant that some compromise in level of detail had to be made. It was deemed infeasible to create a simulation model supporting hundreds or even thousands of individual product flows. A thesis was then performed, where the most representative products in each production unit were identified (Olsson & Henriksen, 2017). Using the representative products, another project was performed on a high-volume scenario, but without considering dynamic changes in the system.

A simulation model will be developed for this thesis, which will attempt to increase the accuracy by allowing a greater number of products in the model, rendering the use of representative products obsolete. The developed simulation model will be used in the future to accommodate experimentation on flexible volume scenarios.

1.3 Aim

The thesis will utilize a combination of simulation project methodologies and apply them to a non-traditional production type, an FJS. The complexity that comes with job-shop, such as high product variance and re-entrants flows, presents many challenges when it comes to model translation, verification and validation. The thesis aims to present a framework of how a simulation model of such a complex system can be developed, and later validated.

1.4 Goal

The goal of the thesis is to develop an accurate simulation model of the production system of RUAG Space that can be used for experimentation in flexible volume scenarios. The simulation model should be built to support many product variants since RUAG Space operates in an ETO environment.

1.5 Research questions

Based on the difficulties developing a simulation model of an FJS production system described in section 1.3, the thesis intends to answer the following research questions:

RQ1: How can a flexible job-shop production system with re-entrant flows be simulated?

RQ2: How can a simulation model of a flexible job-shop production system with re-entrant flows be validated?

1.6 Delimitations

RUAG's facility in Gothenburg includes three units where manufacturing of different product families takes place. If there is not enough time to complete all simulation models, a prioritization order will be kept: Microwave Unit → Digital Unit → Antenna Unit. The order was decided by RUAG, based on their internal needs.

The simulation project will stop after the validation step due to expected development times. Analysis and experimental design of the models are not included.

The simulation models will be displayed using the basic 3D graphics of the software and not 3D scans of the facilities. It was decided that validity of the models is more important than their visual fidelity.

The simulation models will not use mannequins to display operators' movement, instead significant transportation times will be considered in the logic as delays.

2

Frame of reference

The chapter begins with explaining what a production system is, and presents several types of production systems. Next, the concept of simulation is covered, and some of the major advantages and disadvantages of simulation are presented. The rest of the chapter is dedicated to simulation project methodology.

2.1 Production systems

Production systems can be explained as a transformation of input to output. A commonly accepted description of a transformation system is the black-box principle, see figure 2.1 (Bellgran & Säfsten, 2010).

Figure 2.1: Black-box principle, transformation of input to output.

The major elements of a transformation system are: a process, an operand, and an operator. It has the goal of transforming an applied operand from an existing state to a desired, predefined state. This change process is what defines production systems, meaning the transformation of raw material into components or complete products, using existing resources. Depending on the purpose of a production system, different classifications can be used. Table 2.1 presents some of these classifications.

Table 2.1: Classification of production systems depending on their purpose (Bellgran & Säfsten, 2010).

System classification	Classification description
Physical and conceptual	Physical systems consist of real objects, such as machines and equipment, whereas conceptual systems consist of models, diagrams, flowcharts, etc.

Table 2.1: (continued)

System classification	Classification description
Continuous and discrete	These types of systems belong to the category of dynamic systems which variables change over time. This change can happen continuously (continuous system) or step-by-step (discrete system).
Stochastic and deterministic	Deterministic systems are systems that for a given input will always give the same output. On the other hand, stochastic systems are characterized by random properties and the output can only be statistically analyzed.

Common notions of production systems are workshop, line, factory and plant. The different notions are used to describe the differences as well as the scale of a system. Whatever the notion, the main elements of a production system are the same: premises, machines, equipment, humans, procedures and software (Bellgran & Säfsten, 2010). Production processes that handle the change of input material to output products vary to a large extent and their architecture is based on their purpose and the types of resources used to perform the activities (Anupindi, Chopra, Deshmukh, Van Mieghem, & Zemel, 2014). By process architecture, the physical layout in a processing network is meant and how processes and activities are organized, which is also linked to the production volume and number of product variants. Volume and variants are parameters that define the type of a production system in terms of process type, layout arrangement, technology level, personnel and level of automation (Bellgran & Säfsten, 2010).

2.1.1 Types of production systems

Production systems can be categorized in three general types: projects, job-shops and flow-shops. However, two more categories arise by combining attributes of the general types, namely production cells and batch-shops, which have similar characteristics (Pappis, 2006).

Projects
Project production systems are used when producing one-of-a-kind products, which are usually large in size and value, to be delivered to one customer. The product is being produced according to the customer's requirements, which require higher flexibility to the production method. The production has low level of automation and is arranged around the product.

Job-shops
Job-shops' production is characterized to be suitable for a large number of product

families and product variation, and small production volumes (Bellgran & Säfsten, 2010). The production is organized in a functional layout fashion. Product specifications are usually defined by the customer.

Flow-shops
In flow-shops, production is limited to a few products with low variance, which are offered for mass use by customers. The production is organized in a linear fashion with high level of automation, and every production flow is the same for its respective product type.

Production cells
A production cell is a collection of machines, physically organized in close proximity, where groups of products with similar requirements in materials, equipment, personnel and process flows are produced.

Batch-shops
Production in batch-shops is performed in batches of products that use similar material and equipment. The layout is organized either in production lines or "cells". Products are stored and later offered for commercial use. The production runs in consecutive cycles during a year, meaning that different products are produced in different time intervals.

For comparison, the various production types and their characteristics regarding layout requirements, volume, variants, flexibility and level of automation are presented in table 2.2.

Table 2.2: Production types and their respective characteristics, adapted from descriptions by Pappis (2006).

	Projects	**Job-shops**	**Flow-shops**	**Batch-shops/Cells**
Layout	Fixed position	Functional	Line	Group
Volume	Very low	Low	High	Medium
Variants	Very low	High	Low	Medium
Flexibility	High	High	Low	Medium
Automation level	Low	Varying	High	Medium

Aspects influencing decisions regarding production systems and production types are usually volume, variants, available space, existing systems, supply and demand and other relevant competitive factors (Bellgran & Säfsten, 2010). According to Olhager and Wikner (2000), customers, products and processes constitute a system and their links are what define, in a large degree, how different production types relate to product volume mix and demand patterns. This relationship can be seen in figure 2.2. If for example demand requires an ETO operating environment, where low-volume-many-variants production takes place, then job-shop seems to be the right choice. The same logic applies to the rest of production types. Positions on the diagonal have been concluded to be appropriate and would give the necessary production competence (Olhager & Wikner, 2000).

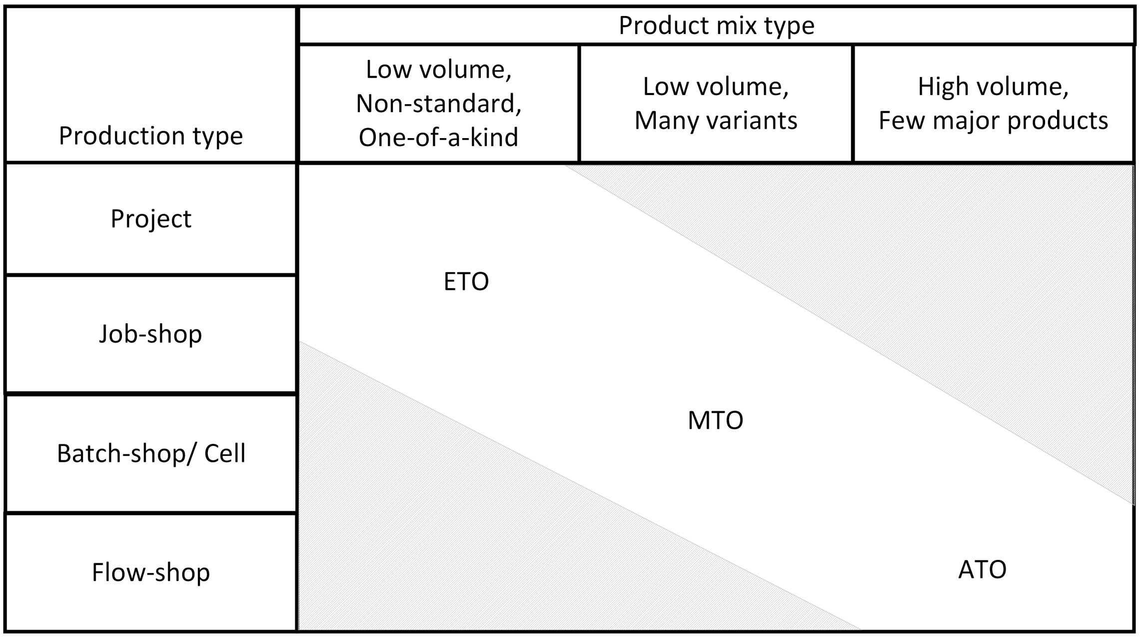


Figure 2.2: Relationship between product volume and mix, and choice of process type. Adapted from Olhager and Wikner (2000).

2.1.1.1 Job-shop

In a job shop, machines or workcenters are organized depending on their type and purpose and grouped together. Jobs (products) can take many different routes in the flow. There are different types of job-shops based on the route a job takes. A FJS is considered as the general type of job-shops, where machines and workcenters are grouped together in parallel, meaning that parallel resources are capable of performing the same operation, and a job can choose which resource to occupy (Pinedo, 2009).

According to the literature, a constant problem with job-shops is the scheduling of jobs and resources (machines, workcenters, operators). A variety of scheduling algorithms and solutions exist that deal with different types of settings, and can be found in the literature (Banks, 1998; Law, 2007; Pinedo, 2009; Kulkarni & Venkateswaran, 2016; Borreguero-Sanchidrián, Pulido, García-Sánchez, & Ortega-Mier, 2018). Job-shop scheduling usually refers to a strict machine environment where most of the necessary data is already available, however it can also be applied in more complex production environments, where re-entrant flows, process-type operations and high sensitivity to due dates are some of the characteristics that define the system (Banks, 1998). "Re-entrant" refers to the case where a job is required to use the same resource more than once. According to Pinedo (2009) a FJS with re-entrant flows is one of the most complex production types to control optimally, and this type of production is common within the semiconductor industry.

From a simulation perspective, a job-shop is considered as a queuing network, where an order may pass through different resources or may wait in different queues until there is space to enter the resource. In simulation terms this type of job-shop is referred to as dynamic job-shop (Banks, 1998).

2.2 Simulation

When studying a system, a collection of parts organized for some purpose, it may be necessary to create a model of the system, due to unpredictable variations of the system and dynamic complexity of the relations between the system's components (Robinson, 2004). Creating a model requires an abstraction level to be decided on, and assumptions to be made about how the system functions. If the relationships within a system are simple enough, it may be possible to analyze the model with mathematics, *analytically* (Law, 2007). Li and Meerkov (2009) describe several approaches of how mathematical models are applied to analyze systems. If the relationships are so complex that they can not be evaluated mathematically, it may be necessary to simulate the system (Law, 2007).

Banks (1998) defines simulation as the "*imitation of a real-world process or system over time*". The simulation is performed by evaluating the model *numerically*, which provides an estimation of the characteristics of the real system (Law, 2007). In addition to providing a better understanding of a real-world system, simulation is often used to evaluate changes to the system. In this way the effects of e.g. investments or external changes can be estimated. Simulation models and their accompanying software's are designed to run the simulations at high speeds, so that many experiments can be performed, and a suitable solution can be found (McGregor, 2002). If the experiments were performed in the real system, it might take years instead of minutes or hours to analyze the long-term effects of the changes. Simulation can therefore be seen as a decision-making tool (Robinson, 2004).

Systems are often categorized into one of two types, continuous or discrete. The difference between these types is explained in the following subsection.

2.2.1 Continuous vs. Discrete

A system is considered continuous if the state of the system is continuously changing, e.g. the fluid system at a chemical plant. Systems with a high volume of items moving quickly, e.g. automated productions of food, may also be considered continuous. While it is not possible for computers to model continuous changes in state, the simulations are instead progressed in small (Δt) discrete time-steps (Robinson, 2004).

If the state of a system changes instantaneously, it is categorized as a discrete system (Law, 2007). Some examples of these kinds of systems are: Patients moving throughout wards at a hospital (Ferrin, Miller, & Mcbroom, 2007; Sinreich & Marmor, 2004; Ruohonen, Neittaanmäki, & Teittinen, 2006; Günal & Pidd, 2010), packages or products moving in a warehouse (Gagliardi, Renaud, & Ruiz, 2007; Peixoto, Dias, Carvalho, Pereira, & Geraldes, 2016), or travellers and baggage moving in an airport (Dorton & Liu, 2012; Wu & Xie, 2017). While a continuous simulation progresses the simulation model in small steps, discrete simulation only progresses the model when the state of the system changes. A change of state in a discrete simulation model is often referred to as an *event*, and the commonly used name for simulation of discrete systems is therefore discrete event simulation (DES).

Systems are rarely completely continuous or completely discrete. When determining which category fits best, it is important to consider why the system is being modeled, as that may affect which type is the best fit (Law, 2007). If a production system is to be modeled to evaluate the output, a discrete model may be appropriate. If instead the dynamics of how the forklifts inside a factory interact with each other is of interest, a continuous model may be more appropriate.

2.2.2 Discrete event simulation

Discrete event simulation concerns the changes of a system's state on different points in time (Robinson, 2004). This changing of the system's state is caused by events that are happening while the system is evolving over time (Law, 2007). Fishman (2001) describes DES as a collection of techniques that, when applied, generates sample paths(sequences) which characterize the behavior of a DES dynamical system. It is its ability to mimic the dynamics of the real system, that makes DES a powerful tool (Ingalls, 2011), used for the purpose of understanding the modeled system or analyze and evaluate various strategies.

DES models share a common structure and components, which supports coding, debugging and future changing of the model, even though different software packages may be used (Banks, 1998; Law, 2007; Ingalls, 2011). There are different notations for the structure and components of a DES model, however, notation by Ingalls (2011) will be used for this section. Below, the structural components of a DES model are explained.

Entities cause changes in the state of the simulation. They can either be a digital representation of parts that flow across the simulation (e.g., a component that moves from machine to machine in a factory flow) or represent the flow of information in the system (e.g., a customer order). Entities have attributes which are characteristics unique for that entity (e.g., the cycle time of a certain entity on a certain machine).

Activities are processes in the simulation. *Events* are conditions that if occurred will change the state of the system. Entities react with activities and create events.

The *calendar* holds events that are scheduled to happen in the future.

Resources, in a simulation, represent anything that has a constrained capacity. For example, number of operators, machines and buffers.

Global variables are variables of the system that are available to anything in the system at all times during a simulation run. Changes in these variables can be used to analyze their effect to the system.

A *random number generator* generates random numbers between 0 and 1 that are used in sampling random distributions. For example, the generator is used to assign values to random delays in the system.

System state variables are variables that vary depending on the simulation software. One system state variable that is always available is the current time of the simulation. This variable is updated each time an entity creates a new event.

Statistics collectors collect statistics on certain events, for example about the state of a resource, its utilization or the time that an entity has stayed in the system.

DES has applications in various fields and industries, from health care to service systems, and from automobile production lines to more complex production systems, for example, at the semiconductor industry (Banks, 1998).

2.2.3 Randomness in simulation

Any real world system has some source of randomness. In manufacturing systems, randomness may stem from inter-arrival times of material, processing times, machines breakdowns or repair times (Law, 2007). Randomness makes production systems unpredictable, which means that the system is stochastic, as described in table 2.1. To mirror this randomness, simulation models can utilize random number generators and statistical distributions, as described in subsection 2.2.2.

Robinson (2004) proposes that randomness in a simulation model should be represented by using either of the following four methods: traces, empirical distributions, bootstrapping, or statistical distributions. Whereas it is in the hands of the simulation expert how to model randomness in a simulation model, fitting data to statistical distributions requires extra caution, since the probability of failing to interpret and choose correct distributions is high and depends solely on the gathered data and the expertise of the simulation modeller (Law, 2007). The same author also suggest that all methods have their uses depending on the situation that the simulation model is used for.

According to Law (2007), a trace driven simulation, uses data values directly in the simulation. This means that there is no randomness involved in the model and the simulation can only reproduce passed events. Moreover, empirical distributions may have certain irregularities that will affect the overall model, if for example applied to a small number of data values. That way, randomness in the model will only be limited within a certain range of values, excluding extreme events that may be interesting or important to analyze (Law, 2007). Statistical distributions, on the other hand, "smooths out" the data (Law, 2007), and include values from their whole spectrum, enabling the analysis of all kinds of events that can happen during a simulation run. Finally, (Robinson, 2004) explains that bootstrapping is to re-sample a set of data with replacement so a value might appear more or fewer times compared to the original simulation run. Both Law (2007) and Robinson (2004) agree that in most cases, statistical distributions are preferable to be used since they provide higher flexibility to the simulation model.

Statistical distributions can be used for a variety of purposes in a simulation model. The most common distributions, described by Robinson (2004) and Law (2007), are presented in the following list:

- Beta: Time to complete a task, proportions
- Erlang: Time to complete task, inter-arrival times
- Gamma: Time to complete task, inter-arrival times
- Lognormal: Time to complete task
- Negative exponential: Time to complete task, inter-arrival times
- Normal/truncated normal: Errors
- Uniform: Used to assign randomness when data is absent
- Triangular: Used to assign randomness when data is absent
- Weibull: Time to complete task, time to failure, inter-arrival times

While most of the distributions presented in the list above require historical data to fit the randomness of the real world to a statistical distribution, availability of data is not guaranteed. The absence of reliable data presents a challenge when preforming a simulation project. Banks (1998) suggests that, in the absence of data, the first approach is to acquire the help of an expert of actual or expected behaviour of the system. The expert would need to perform probability assessments, which according to Banks (1998) often leads to unreliable results. If no expert is available, Banks suggests to use uniform, triangular or beta distributions. Although, it should be noted that Banks (2004) refers to the uniform distribution as the "distribution of maximum ignorance", as it assumes every possible value is equally probable.

However, fitting data to statistical distributions might not always be applicable. A lack of data is a particularly tough problem when developing a simulation model of a system with mainly manual labour, as Knott and Sury (1987) explains that manual work can not be reliably represented by any standard statistical distribution. To be more specific, during a work time sampling, Knott and Sury (1987) showed that none of the obtained distributions had a significant correspondence with any of the standard statistical distributions.

2.2.4 Advantages and disadvantages of simulation

Simulation models can provide great benefits if applied correctly, but they can also have drawbacks. The major advantages and disadvantages proposed by Robinson (2004) and Law (2007) are presented in tables 2.3 and 2.4. As seen in the tables, some of the advantages are the same as the disadvantages. Before performing a simulation project it is therefore imperative to establish that it is the best approach to the problem in question.

Table 2.3: Advantages of simulation (Robinson, 2004; Law, 2007).

Advantages	
Cost	It can be costly to interrupt daily operations to perform experiments in the real-world system. It will cost even more if the experiment turns out to be unsuccessful. The cost for performing an experiment with the simulation model is only the salary for the simulation expert.
Time	It is time consuming to perform physical experiments on a system, and the effects of the experiment may take a long time to stabilize. A simulation expert can perform an experiment, and have an estimation of the effects of the change on the system in the long-term, in a matter of minutes or hours.
Estimation of performance	Simulation models only provide an estimate of the performance of a system, and are therefore best suited for comparing results of different experiments on the same system.
Control of experimental conditions	In a simulation model better control of the experimental conditions is possible than when experimenting with the real-world system.
No real system	A simulation project can be performed when there is no real-world system to perform experiments on. The simulation model can then aid in the design of the new system.

Table 2.4: Disadvantages of simulation (Robinson, 2004; Law, 2007).

Disadvantages	
Cost	Simulation software can have expensive licenses, and the development of simulation models can result in high labour costs.
Time	Simulation models can take a lot of time to be developed and validated, which means that the benefit from the investment is delayed.
Estimation of performance	Simulation models only provide an estimate of the performance of a system, and are therefore not well suited for optimization.

Table 2.4: (continued)

Disadvantages	
Data hungry	Simulation models often require large amounts of data, which is not always available. The data that is available often requires significant analysis before it can be used for the simulation model. Collecting the missing data requires time and money.
Requires expertise	Simulation modelling is a multidisciplinary task, requiring knowledge within project management, programming, conceptual modelling, validation and statistics. Finding someone with all these skills can prove difficult.
Overconfidence	The large amount of data that can be extracted from simulation models can give the impression that the simulation is very accurate. It is important that the user of the simulation model is aware of all the assumptions and simplifications made.

2.3 Simulation project methodology

Robinson and Bhatia (1995) propose that there are four phases in a simulation project, presented in figure 2.3. The first phase starts with understanding the problem and gathering of necessary information, and continues with building the model and testing its validity. Experimentation, as the third phase, looks into the model's behavior if parameters are changed, and produces results that need to be communicated and documented in the final, fourth phase before the conclusion of the project.

The model in figure 2.3 serves as a baseline to the simulation project methodology that Banks (1998) created, which is presented in figure 2.4. The simulation project methodology proposed by Banks includes approximately the same activities (steps) as the methodology suggested by Robinson and Bhatia (1995), but presents the steps in a more detailed flowchart, including important decision loops.

Phase I - Problem definition

Formulating the problem to be addressed means to understand why simulation modeling is needed. That suggests the setting of project objectives, as well the creation of a well defined project plan. After these two steps are completed, the third step includes model specification and agreed level of detail, and conceptual modeling of the system, which is mainly how the model should look and be structured. Model conceptualization is explained further in section 2.3.1. The fourth and final step of

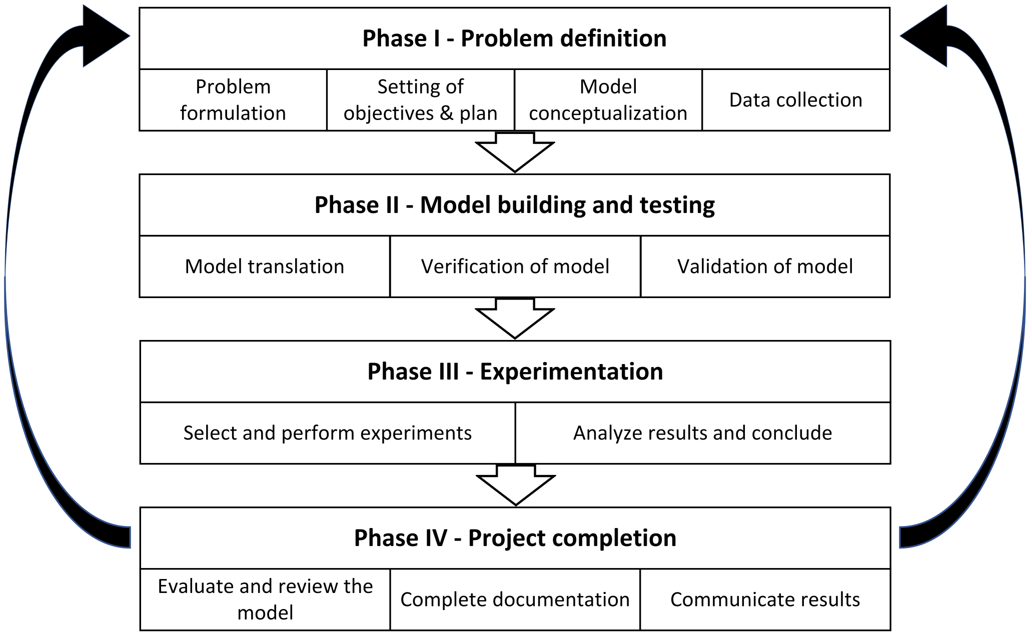


Figure 2.3: Overview of a simulation project's phases and their respective activities. Adapted from Robinson and Bhatia (1995).

the first phase is the identification of required data that the model will use, as well as the classification and collection of the data. This step is presented in more detail in section 2.3.2. Although data gathering could be an ongoing process, after the fourth step is completed Phase I is finished.

Phase II - Model building and testing

Phase II starts with the transformation of the conceptual model into a computerized model using some software or programming language, explained in more detail in section 2.3.3, and then verifying the code using verification techniques. If the simulation model is verified, the next step is to validate it using established validation methods, ensuring that the translated model represents, to a large extent, reality. Verification and validation is explained in more detail in section 2.3.4 and 2.3.5.

Phase III - Experimentation

Phase III consists of experimentation on the simulation model. This includes the experimental design, where experiments are selected and performed, and the analysis of the results produced by conducting production runs. The phase ends when conclusions upon the results are drawn and recommendations are made.

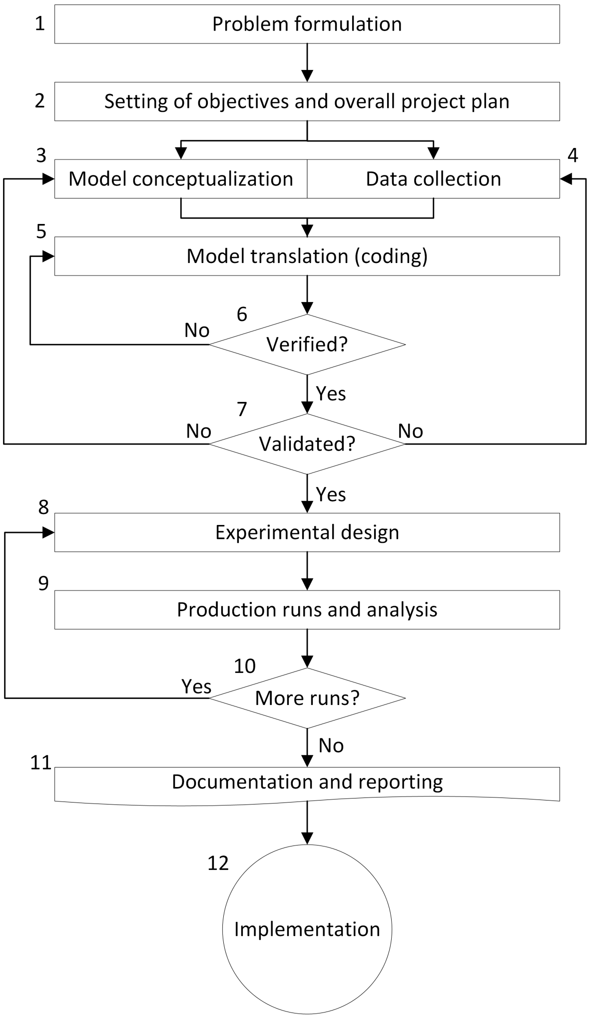


Figure 2.4: Adaptation of Robinson and Bhatia (1995) simulation project methodology, as proposed by Banks (1998).

Phase IV - Project completion

Phase IV is the final phase of a simulation project. It starts with communicating the results to stakeholders and continues with finalizing documentation of the project. The important step in this phase is the model evaluation and review. Decisions are made on potential changes of the model that will lead to future actions for improvements. Finally, and depending on the results, an implementation plan is developed.

2.3.1 Model conceptualization

When the problem to be solved is defined and the objectives are set, the next major step in a simulation project is to conceptualize the model. The goal of this step is to create an abstract representation of the real-world system, a conceptual model (Banks, 1998). In the literature it is not defined how a conceptual model should be represented, and it is therefore up to the practitioner to decide on a design. The requirement is to be able to represent the logic of the real-world system (Banks, 1998). Figure 2.5 illustrates a basic graphical example of what a conceptual model of a small production flow might look like.

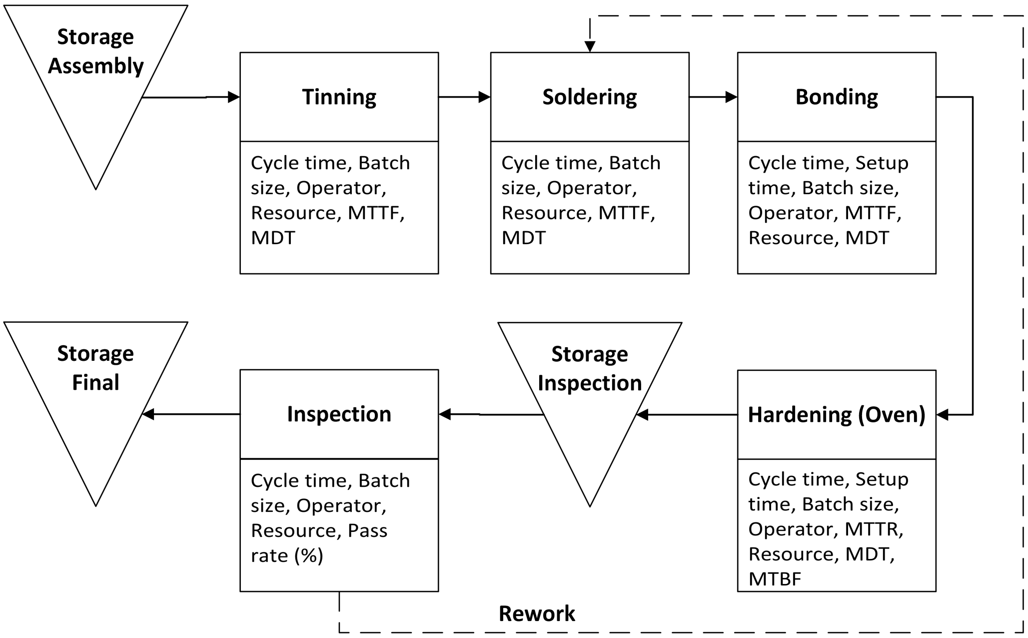


Figure 2.5: An illustration of how a conceptual model of a production flow might look.

Banks (1998) explains that it is appropriate to begin with a basic representation at first, and then add any further complexity that is required to meet the objectives of the project. If superfluous complexity is added, it will cause the cost of the project to increase, without necessarily providing a better result. Robinson and Bhatia (1995) explains that setting the complexity to an appropriate level is more of an art than a science.

2.3.2 Input data management

DES models can imitate the dynamics of a real system, aiming for understanding the behavior of the system or evaluating various scenarios within limits imposed by different sets of criteria (Ingalls, 2011). This means that high quality input data is necessary in order to allow a simulation model to produce desired results, and therefore providing high quality data determines in a way the outcomes of a simulation project (Banks, 1998). Robinson and Bhatia (1995) mentions that data collection and analysis require time and should be performed in parallel with other activities when developing simulation models. Empirical studies have shown that only data collection may consume more than 30% of the total time of a simulation project and it is not always certain that the collected data will be used in the model (Skoogh & Johansson, 2008).

Reasons for this high time consumption arise from the availability and form of the data. There are three categories of data specified by Robinson and Bhatia (1995) and presented in table 2.5.

Table 2.5: Classification of data based on availability (Robinson & Bhatia, 1995).

Category	Availability
A	Available
B	Not available but collectable
C	Not available and not collectable

Category A data can be found in a company's corporate and production tools (ERP, MPS, MES, etc.), other data collection systems (order handling, maintenance systems, etc.), and from previous studies analysis and projects (process documents, technical reports, etc.) (Skoogh & Johansson, 2008).

Category B data refers to data that exist in a quantitative form but have not been collected and require additional effort in their gathering during the simulation project. Conducting time studies (stopwatch, video analysis, MTM), interviews, etc., are ways of collecting this type of data and depending on the detail level of the model, the appropriate tool should be chosen (Skoogh & Johansson, 2008).

Category C data refers to data that are new for the company, for instance, data of new processes or equipment, which is not collectible and instead relies on reasonable estimations that would not compromise the quality of the simulation model. Ways of obtaining category C data can be, for example, focus groups, interviews, historical data and machine vendor information (Skoogh & Johansson, 2008).

Several methodologies have been produced to assist with input data management in DES projects that suggest various ways for the simulation practitioner to reduce time consumption of the data collection process. Skoogh and Johansson (2008) propose a methodology that covers the identification, collection and preparation of data that are to be used in a simulation project. However, data quality plays a crucial role in the credibility and acceptability of simulation results (Bokrantz, Skoogh, Lämkull, Hanna, & Perera, 2017). Balci et al. (2000) define 11 dimensions of data quality that need to be evaluated so high-quality simulation data can be collected. Table 2.6 presents the different dimensions, along with a brief description of each.

Table 2.6: The 11 data quality dimensions as defined by Balci et al. (2000).

Dimension	Description
Accessibility	The degree to which data are available or easily and quickly retrievable.
Accuracy	The degree to which data possess sufficient transformational and representational correctness.

Table 2.6: (continued)

Dimension	**Description**
Clarity	The degree to which data are unambiguous and understandable.
Completeness	The degree to which all parts of the data are specified with no missing information.
Consistency	The degree to which (a) data are specified using consistent measurement unit, uniform notation, and uniform terminology, and (b) any one data value does not conflict with any other.
Currency	The degree to which the age of the data is appropriate for the use of the data in the simulation model.
Precision	The degree to which data possess sufficient number of significant digits in their numerical values.
Relevance	The degree to which data are applicable for use in the simulation model.
Resolution	The degree to which data possess sufficient level of detail.
Reputation	The degree to which data are trusted or highly regarded in terms of their source or origin.
Traceability	The degree to which data are easily attributed to a source.

2.3.3 Model translation

After the conceptual models have been developed, and the required data gathered, they need to be translated into digital representations, so that they can be executed by a computer (Banks, 1998). The strategy of the translation depends on which simulation software is used and the structure of the system itself.

If the system being modeled contains operations that are similar to each other, e.g. work stations that only vary in process time, it can be beneficial to create modules, also referred to as *building blocks* by Valentin and Verbraeck (2002), that can be reused (Johansson, 2006). A simulation model is rarely either completely modular or completely non-modular, but increasing the degree of modularity can reduce the time needed to develop the model. Verification and validation also becomes less time consuming when the degree of modularity increases, as it first can be performed on module level, and then on system level (Johansson, 2006).

2.3.4 Verification

Verification of the computerized model is done to ensure that it behaves as described by the conceptual model. The verification can be divided into two approaches, static and dynamic testing. Static testing includes steps such as structured walkthroughs, correctness proof, and examination of the structural properties of the program. When performing dynamic testing, the program is executed with various input parameters, and the data generated by the program are used to determine the program's correctness. Data that can be investigated include, but is not limited to, tracing of entities and input-output relationships (Sargent, 2013).

2.3.5 Validation

Whereas model verification deals with the computerized model and its accuracy over the conceptual model, validation of simulation models is defined as the determination that the simulation model can substitute the real system for the purpose of experimentation (Banks, 1998). See figure 2.6 for an illustration on the difference between verification and validation. The procedure is iterative during the execution of a simulation project to ensure whether the model is on the right track of representing reality or must be modified.

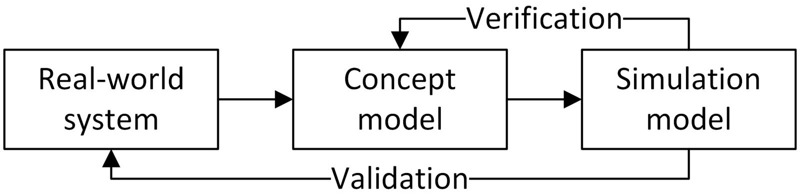


Figure 2.6: Illustration of the difference between verification and validation.

Sargent (2013) mentions that a simulation model is developed for a specific purpose and its validity is determined with regards to that purpose. Moreover, since validation reflects on the accuracy of the model, an acceptable range of the latter should be specified prior to the development of the model. Although, it might be time and cost consuming to define a model's absolute validity on its intended applicability, tests and evaluations should be conducted until a certain level of credence is acquired that the model is valid (Sargent, 2013). On the other hand, Banks (1998) supports that to ensure success in a simulation study, there is an accuracy quality characteristic that needs to be assessed by conducting verification, validation and testing (VV&T) of the model throughout the life-cycle of the project.

Deciding upon a model's validity, Sargent (2013) claims that there are three approaches with different decision makers, each of them offering a different level of credibility. The first approach uses the project team to decide on validation by analyzing the results of experimentation on the model, however this approach might be biased. A second approach involves the users of the model to decide on validity. This means that the users participate from the beginning of the model's development, making sure that the model is valid in each phase of the project. This second approach helps in model credibility. Finally, a third approach is having an external team, a third party, to perform the so called "independent verification and validation" (IV&V) (Sargent, 2013). This approach is generally accepted in large scale simulation projects that involve several development teams.

As mentioned, Banks (1998) suggests VV&T during the life-cycle of a simulation project. He claims that over 75 techniques, divided into four categories (i.e., informal, static, dynamic, and formal) exist, however it is up to the developers' judgment and skills what techniques to use depending on the circumstances of the study. Sargent (2013) focuses on validation methods which categorizes into objective (mathematical procedures or statistical tests) and subjective, based on the developer's expertise and other general information. Table 2.7 presents a set of validation methods:

Table 2.7: Validation methods (Banks, 1998; Sargent, 2013; Robinson, 2004).

Method	Description
Animation	Examining the model's operational behavior over time when running the simulation.
Black-box	Validation of the accuracy of the model compared to the real world and the projects' objectives.
Event validity	Occurred events in the simulation are compared with actual event of the real system.
Extreme condition test	Testing extreme combination of levels of factors in the system to determine the behavior and outputs.
Face validity	People who are knowledgeable about the system are asked whether or not the model's input – output relationships are reasonable.
Historical data validation	Historical data are used to determine whether the model behaves as the real system.
Sensitivity analysis	Changing sensitive parameters in the model to test the effect on model's behavior or output.
Trace	Tracing a specific entity in the model to determine if necessary accuracy is obtained.
Turing test	Discrimination between system and model outputs by individuals who know the system and its operations extremely well.

3

Methodology

The chapter presents the methodologies that the thesis utilized to produce results. Methods have been used from different research angles and have been tailored to suit the thesis context. The chapter starts with an explanation on research methodology according to literature. Then, the topic of research ethics is covered. Lastly, the methods used are presented, along with descriptions of how the project was executed.

3.1 Research methodology

The research methodology that the thesis followed involves three methods, namely literature review, qualitative data and quantitative data, which according to Denscombe (2010), can be called triangulated mixed research method. How this methodology results in key findings, can be seen in figure 3.1.

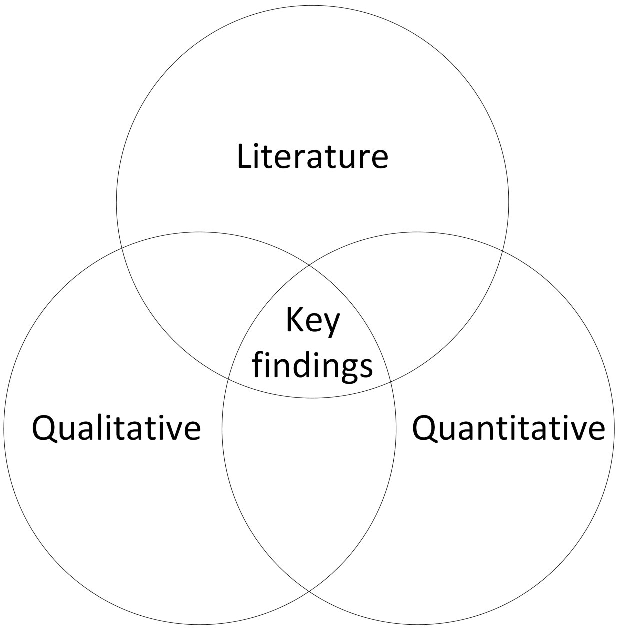


Figure 3.1: Illustration of the research methodology explained by Denscombe (2010).

3.1.1 Literature review

In research projects, a literature study is often performed to reveal areas that require further research and to help formulate research questions. Ideally, it will provide necessary insights of the research area, key ideas and themes, current theories and trends, methodologies used and implications involved, and further investigation needs. It will give answers as to why this area needs to be studied further, but also how the research project will contribute (O'Gorman & MacIntosh, 2015). The literature study should also support the aim of the project (Denscombe, 2010).

3.1.2 Qualitative data collection and analysis

Qualitative data takes the form of words and visual images. According to Denscombe (2010), qualitative data is associated with research methods such as interviews, observations and documents. O'Gorman and MacIntosh (2015) suggests that qualitative data research focuses on investigating occurrences in different environments, and by using different "actors" the phenomena are understood. There are various ways to analyze collected qualitative data, with common techniques been grounded theory, content analysis, and discourse analysis (Denscombe, 2010; O'Gorman & MacIntosh, 2015).

3.1.3 Quantitative data collection and analysis

Quantitative data takes the form of numbers. According to Denscombe (2010), quantitative data is associated primarily with questionnaires, in the form of scales, and observations of experiments. However, interviews and documents can produce quantitative data, depending on the design of the study and analysis of the data. Quantitative data can also be found in business data, content analysis of reports and content analysis of interview transcripts. Ways to analyze numerical data are defined by what types of data should be analyzed, e.g., statistical techniques (O'Gorman & MacIntosh, 2015).

3.1.4 Mixed research methods

The use of many different research methods in a research project is referred to as a mixed methods approach, and according to Denscombe (2010) the use of this approach checks how accurate the findings are, provides a more complete picture of the research area and helps with the research analysis. On the other hand, O'Gorman and MacIntosh (2015) state that using mixed method approaches would only provide confusion and misunderstanding of results.

However, there is an approach that would view research problems from a variety of perspectives, but also successfully combine different components of a research project without confusing the results, and is called triangulation of methods. Derived from trigonometry, its main idea is that three perspectives are enough to verify key findings. Triangulation offers improved accuracy by validating findings in terms of authenticity and checking bias in research methods (Denscombe, 2010).

As mentioned in section 3.1, the thesis followed a triangulation of methods, combining literature findings relevant for the case with qualitative and quantitative data that were gathered and analyzed throughout the project using various collection methods. In most cases, both types of data were collected using the same method. More specifically, figure 3.2 presents the data collection methods that were used in the thesis.

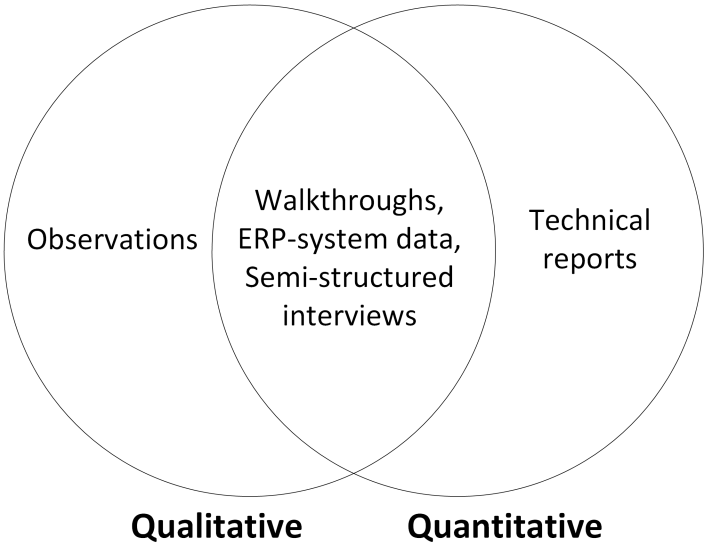


Figure 3.2: Collection methods for qualitative and quantitative data used in the project.

3.2 Research ethics

When performing qualitative research the participants in the study can be affected in numerous ways. While there are no legally enforced ethical regulations, it is still important to apply ethical guidelines to protect participants from being affected negatively due to their participation. (Wiles, 2013) explains that there are three major concerns when performing a qualitative study, informed consent, confidentiality and anonymity, and risk and safety. Firstly, the participant must be informed what participation in the study will involve, i.e. what the study is about, why it is needed, who is funding it and what will happen to the results. After being informed, the participant is free to not participate in the study, if they so choose. Secondly, with regards to confidentiality and anonymity, the participant is informed what will happen with the information they share, if it will be possible to identify the participant from the data and what the effect of identification may result in. Lastly, the safety of the participant is considered. Potential risks, often in the form of sensitive personal or taboo issues, are discussed and the potential benefits of the research are, together with the participant, weighed against the risks. While it is good practice to be open and share information with the participant, it may sometimes be necessary to deceive the participant. Denscombe (2010) states that it in certain scenarios is justified that the researcher deceives the participant, but that it should be avoided if possible.

Regarding quantitative data used in research, there are two basic criteria that needs to be fulfilled (Denscombe, 2017). These are *validity* and *reliability*. Validity refers to the relevance, accuracy and precision of data, in relation to internal and external factors (Denscombe, 2017). As the author explains, internal factors refer to the integrity of collecting the data by asking the right questions and receiving the right answers, but also to the management of data and elimination of errors during data translation to inputs. External factors refer to the generalization of data and how they compare to other similar studies or phenomena, but can also refer to how the identified and collected data can be applied to similar situations. Concerning reliability of data, Denscombe (2017) explains that reliability refers to the possibility that someone achieves the same results, if they perform the research study again using the same methods and instruments. Concerning ethics of quantitative research, Denscombe (2010) explains that no documentary data should be assumed to be correct, and their quality should be claimed by the researchers who are responsible to agree on common grounds and persuade the audience for their research (Denscombe, 2017).

3.3 Project execution method

The execution of the project followed a method which was adapted from the methodologies suggested by Robinson and Bhatia (1995), Banks (1998) and Denscombe (2010). By combining the three methodologies, a method could be tailored to fit the specific problem at hand. The project started with a thorough introduction to the problem, followed by the beginning of a literature study around the subject, that were ongoing until the conclusion of the project. Preliminary findings initiated the problem formulation and setting of objectives. The last step in the used method was the development of the simulation model. Figure 3.3 illustrates, in chronological order, the steps of the project.

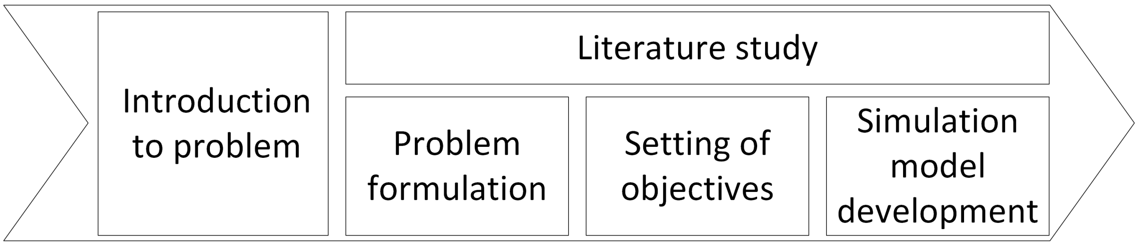


Figure 3.3: Illustration of the activities, and their order, that were performed towards the completion of the project.

3.3.1 Introduction to problem

To gain an understanding of the problem to solve, several presentations and tours were held by the company. The current state of the production facilities, product lineup and global market were explained by the Chief of Operations, as well as how these were expected to change in the future. Discussions were held with the Microwave Production Unit Manager, project managers and academic supervisors regarding the needs and wants of both the company and project members, and an understanding of the project's value was acquired by both parties. The knowledge gained during this step, the current state of the company, is presented in chapter 4.

3.3.2 Literature study

With a better understanding of the problem, an extensive literature study was performed. The study covered a wide range of topics, but the main focus was to find literature on five topics: general DES methodology, DES of ETO businesses, validation of such DES models, simulation of FJS, and modular programming in DES. The findings are presented in chapter 2. While the literature study was most intense in the early phase of the project, it was ongoing during the whole project to provide answers to any problems and inquiries that arose. Databases that were used in the search were: Scopus, IEEE Xplore, Summon and Google Scholar.

3.3.3 Problem formulation

The preliminary findings from the literature study together with the introduction from the company formed the basis for the problem formulation. The problem formulation was conducted through discussions with the direct stakeholders. These were the company's representatives (upper management of the Microwave production unit), the project's supervisors and the project team members. An understanding of the system to be modeled and the problems to be tackled was obtained.

3.3.4 Setting of objectives

With the problem formulated, the objectives were set together with the upper management of the Microwave production unit. The Unit Manager and project managers were first presented with preliminary objectives, which were then adapted to fit their requests. Questions such as what kind of usage the model would have, who the user of the model would be and what the company's expectations are, were inquired in order to set the business value of the project. Although in a regular simulation project the only important party to agree on objectives is the "customer" (Robinson & Bhatia, 1995), the academic value of the project was also included in this stage mainly from discussions with university supervisors.

3.3.5 Simulation model development

When the problem had been defined, literature had been studied and the objectives had been set, it was time to begin the development of a simulation model. However, due to the lack of literature on the area of development and validation of simulation models of FJS production facilities, a framework had to be developed to provide sound guidelines during the simulation model development. During this phase of the project, it was deemed necessary that a structured methodology had to be followed in order to deal with the complexity of such a production facility. Combining key steps from the established simulation project methodologies of Banks (1998) and Robinson and Bhatia (1995), the developed framework focuses on four areas that need to be dealt with caution, namely data collection, conceptual modelling, model translation and validation. The methods applied in the development of the simulation model are dependant on the current state of the company, presented in chapter 4. How these methods were used, is presented in chapter 5.

4

Current state

The chapter presents the current state of the production of the studied company, aiming to give an understanding of its structure and answering questions on production setup, work and personnel, product families and types, and organization.

4.1 Production

Production at RUAG Space is considered complex in terms of product variance and configurations. Being in an ETO environment requires a shop-floor that can support constant changes in products and provide high flexibility to process changes. RUAG's production system can be defined as a FJS where many operations in one flow recirculate in same processes and there are many re-entrant flows in the system.

The production is structured in six functions depending on their purpose. These functions are Microwave, Digital, Antenna, Surface Mounting Technology (SMT), Micro-Circuit-Model (MCM), and Supply.

Microwave, Digital and Antenna, apart from being product units, are also the main functions where assembly and testing of products take place. Part of the production is dedicated to SMT, which is a function that supplies circuit boards to the Microwave and Digital units. There is an MCM unit which, although it belongs to Microwave, is considered as an individual function which supplies products to Microwave using MTS strategy, but also has external customers. Finally, there is the Supply function that consists of the Inspection of incoming goods, that are stored and distributed, and Kitting which supplies kits to Microwave and Digital. Antenna is differentiated from the other units in terms of the Inspection of incoming goods and Kitting which are performed directly at Antenna by Antenna personnel. Lastly, the main product units have their own Packaging process of completed products which is performed at the same location but by different personnel. Figure 4.1, provides a visualization of how production is structured and how the functions relate.

4.1.1 Shop-floor setup

Each function has its own dedicated space in the shop-floor with their own stations, equipment and personnel. However, if required by demand, product units share resources and people between them. For example people situated at Microwave unit

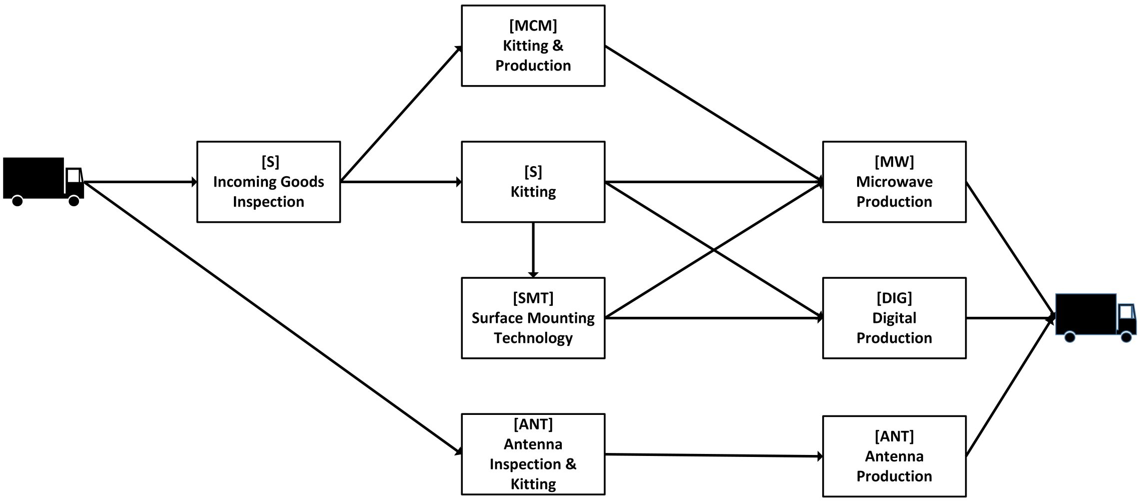


Figure 4.1: Process map displaying production's structure. Adapted from Olsson and Henriksen (2017).

can work on products from Digital unit and vice versa.

Workstations are arranged in a functional layout fashion which is suitable for the company's low-volume-high-variance products. Many stations are grouped together and represent one process category. In total there are six process categories and operations are divided among them. The process categories are presented in the following list:

(i) Kitting
(ii) Assembly
(iii) Inspection
(iv) Quality assurance
(v) Testing
(vi) Automated processes

For simplicity, the process categories are indexed with the same roman number as in the above list. In following sections, the process categories will be referred as per index.

Workbenches are well equipped to support a number of operations and tests so the product does not have to move after each task. Some processes are similar and utilize the same station in different parts of the production flow. All operations require high skills and precision due to fragility and high quality demands. There are testing machines and rooms that are shared between all units for various environmental and acceptance tests. Some operations, such as bonding and cleaning, have their own dedicated space and can be used by all product units. Finally, each unit has its own storage rooms and cabinets which are divided depending on the state of the component or product (e.g., assembly cabinets, testing cabinets, inspection cabinets, etc.).

4.1.2 Work and personnel

Production consists mainly of manual work, however some machines are used, such as ovens for the baking of circuit boards and testing machines. SMT is the function which is the most automated, with state-of-the-art surface mounting assembly machines. However, in all automated processes, loading and unloading of parts or products is done manually by the operators.

Production personnel is divided as the six process categories described in subsection 4.1.1. There are operators for assembly operations, other for testing, etc. Most operators have the same competence on their specific process category, which means that almost everyone can perform required tasks on different products, flows and even product units. However, operators have their own workbenches which means that they do not rotate around, but instead work on different products at the same place. There is the exception of shared resources that were mentioned earlier, where personnel within the different product units can use them at any time. If there is congestion in the shared resources, priority rules determined between the product units takes place and sort the order. A more detailed description of the different roles and disciplines involved in production is presented below, in table 4.1.

Table 4.1: Roles and responsibilities associated with the production units.

Title	**Description**
Production Unit Manager	Orderly preparation and coordination of the respective production unit
Object Manager	Initiates orders and reserves the material needed. Also, decides on to what components to be assembled and when.
Project Manager	Owner of production orders. Performs scheduling to meet deadlines, and keeps in contact with customers.
Quality Control Engineer	Quality assurance of parts/units. This can be done either with the customer (MIP) or the customer delegates the task to the quality engineers.
Inline Inspector	Inspection of parts/units in various stages during manufacturing and/or administrative tasks.
Test Engineer	Test operations on parts/units. These can include simple tests performed at the workbench or advanced testing using testing machines.

Table 4.1: (continued)

Title	Description
Assembly Operator	Assembly operation on parts/units. These can include assembly, soldering, tinning, bonding, etc.
Kitting Operator	Preparation of kits before and during manufacturing.

4.2 Product units

The three product units at RUAG, Microwave, Digital and Antenna, do not only produce different product families, but each unit produces many variants of products within these families, establishing a second layer of product families, which is unit specific. The three product units are described in the following subsections.

4.2.1 Microwave unit

The Microwave product unit produces receivers, converters, low-noise amplifiers (LNA's) and solid state power amplifiers (SSPA's) for communication satellites, and produces the largest volume of products compared to the other two units. All of the products in Microwave are composed of a similar product structure, shown in figure 4.2. The production consists of approximately 35 employees that work with process categories (ii)-(v) that were described in section 4.1.1. There are several different products being manufactured which are customized according to customer specifications. Product variance does not stem from new products being developed, but from different variants on existing products. Microwave products also include MCM modules which are considered sub-components, and are used in all products.

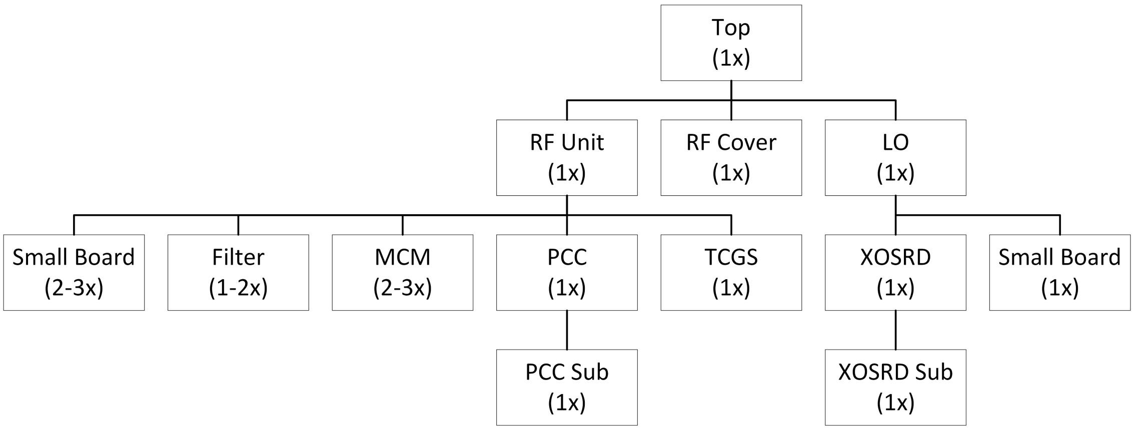


Figure 4.2: Generalized structure of a Microwave product.

Each type of component represented in the product structure has its own dedicated production flow, except PCC Sub and XOSRD Sub which are both produced by the SMT function. In total there are 10 production flows in Microwave: Top Assembly, RF Unit Assembly, RF Cover, LO Assembly, Small Board, Filter, PCC, TCSG, XOSRD and SMT, with MCM being considered a separate function.

4.2.2 Digital unit

The Digital product unit produces satellite and launch computers, payload electronics and data handling systems, and is the unit that brings in the most revenue. There are approximately 20 employees in the Digital production, and the employees are divided into 3 categories, Assembly, Testing and Inspection, as these require different skill-sets. As in the Microwave unit, all products have similar product structures. However, the structure of the Digital products is much more straight forward, only consisting of 3 levels, with one type of component per level (see figure 4.3). As for Microwave, each component in the product structure has a dedicated production flow, with the exception being PW Sub which is built by the SMT function.

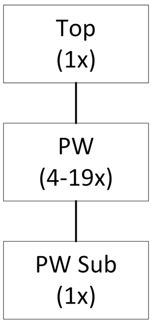


Figure 4.3: Generalized structure of a Digital product.

4.2.3 Antenna unit

Antenna product unit is the smallest, both in regards to volume and revenue, of the three units, and produces a wide range of antennas. Since the unit is so much smaller than the other two, it has been decided that it should be disconnected from the rest of the production. The Antenna unit is therefore responsible for their own kitting and incoming goods inspection. The kitting, assembly and inspection of the antennas is done by 4 employees, while 4 employees are responsible for testing. Unlike with the Microwave and Digital products, the Antenna products vary a lot in structure. Because of this there are no dedicated flows apart from testing.

4.3 Planning and control

Production runs during one shift which is approximately 7 hours of net production time per day. There are cases where equipment works for longer periods of time, usually overnight, but that falls under automated processes and refers to ovens or testing chambers. Working time includes both value and non-value adding activities that are necessary to proceed with manufacturing.

Product units have their own production schedules which are not correlated with each other. People in charge of handling customer order and plan production are called Object Managers. They are responsible to start the order, do the necessary administrative tasks, and organize the personnel with production activities. They also send orders to Kitting to start preparing kits for each flow. However, not all production flows are initiated simultaneously. Object managers possess the knowledge and the tools to initiate specific flows at certain time intervals so production is synchronized. A production order is initiated according to the product structure and the respective lead time of each production flow. That way, object managers guarantee on time delivery to the customer but also save resources and space at the shop-floor.

Finally, communication takes place in many levels. Regarding production, morning meetings are held every day between object managers, project leaders and operators where the state of production is discussed and teams are assigned tasks.

5

Developed framework

The chapter presents the framework for creating a simulation model of an FJS production system with re-entrant flows that was developed to deal with the challenges mentioned throughout the thesis. The framework is built based on existing theory, and the case company's current state and specific needs.

5.1 The framework

The developed framework continues to build on the simulation project methodology suggested by Banks (1998), but goes into more detail about how steps 3-7 could be approached in the development of a simulation model, for an FJS scenario. The main problem when creating a simulation model of an FJS production is the large number of product variants (ETO environment, explained in subsection 2.1.1), and the complexity that comes from those many routings, which are flexible with re-entrant flows (explained in subsection 2.1.1.1). A proper strategy is required, especially for the data collection and model translation steps, to manage this complexity. Figure 5.1 illustrates the 3 steps of the developed framework, *Initialization*, *Model building* and *Validation*, that were designed to deal with these problems. The rest of the chapter will explain each step further, by first presenting a theoretical background based on the literature, followed by the methods, suited for the company's context, applied by the project members.

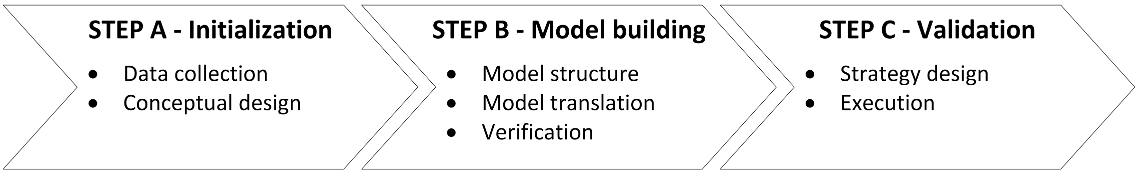


Figure 5.1: Illustration of the framework that was developed to manage the complexity of developing a DES model of FJS.

5.2 Step A - Initialization

Initialization refers to steps 3 and 4 of Banks (1998), although while Banks suggests to perform these steps in parallel, the developed framework approaches the steps in a sequential manner, meaning that collection of data precedes conceptual modeling.

5.2.1 Data collection

Data collection is an important step, not only for the model's development using the right input, but also to understand the system, its processes and resources and how components of the system interact and correlate together (Robinson & Bhatia, 1995). In this thesis the data collection was performed in three phases. Starting with walkthroughs in production to understand how the system works and how its components interact, continuing with a data management process where the data needed to build the simulation model was identified and classified, and ends with the collection of data that was defined as important for the correct functionality of the model. Since components in an FJS flow through plenty of processes that may use the same resources and are of the same nature, it can be beneficial to map all operations and categorize them to find similarities in order to support modularity during model translation. However, in an ETO environment, mapping of processes may prove to be challenging since products come in plenty of variants and different specifications that may require different processing even though products belong to the same product family. This framework suggests selecting a limited number of products for mapping.

5.2.1.1 Production walkthroughs

To understand how the products were routed through the production, an introduction was held by a representative from the specific component flow, assigned by upper management based on expertise, who explained each of the production processes required towards the completion of this component. A set of questions was asked to the representative during the walks, in the form of a semi-structured interview. Before each walkthrough, the representative was presented with the questions, and the project aim and potential results were explained, as per the qualitative research ethics presented in section 3.2. Questions such as number of operators/stations, responsibilities, shared resources with other units, transportation times from process to process, etc. were asked. The complete list of questions asked can be found in appendix B. The production walkthroughs along with the semi-structured interview lasted between 30 to 60 minutes, depending on the complexity of the flow, and were performed solely on the production floor. The results were later used in both the creation of the conceptual models and the simulation model.

5.2.1.2 Input data management

Input data management as explained in section 2.3.2 was applied and is presented below. While production walkthroughs provided with primary data, data management was utilized to identify all needed data for the development of the model and classify them based on availability.

Identification of needed data
A list of required data was compiled based on previous experience of the project members and was complemented using the information gathered during the production walkthroughs. The list was presented to the manager of each production unit, so that they could investigate what data was available.

Since in an ETO environment there may be hundreds of different products in terms of variants, the scope of data collection had to be shrunk. In order to narrow down the scope, the eight products with the highest production volume of each production unit, one of which was previously identified by Olsson and Henriksen (2017) to be the most representative product, were selected. Data regarding these products would be the main focus of the data management efforts.

Identification of available data
The available data was provided by, or found with the help of, the managers of the production units. This data was available in the company ERP-system, but was difficult for someone from outside the company to locate, as the names of products had to be translated into the correct product numbers.

Identification of missing data
The data that could not be located was declared missing, and was classified according to the theory presented in section 2.3.2. The data that was classified as category C, not collectable, introduced limitations to the model's detail. Some data was expected to become available in the future, which was considered for the later model translation, in terms of facilitating simple updates of such data. Category C data were determined to be impossible to collect within the time frame of the project, and therefore they were neglected from the collection process.

5.2.1.3 Collection of data

Cycle and setup times, routing data and product structure for selected products were extracted from the ERP-system. Data connected to the operations, such as number of operators/stations and their roles, shared resources, batch sizes, rework loops, prioritization rules and buffer capacity were collected during the production walkthroughs and from discussions with operators and managers. The complete compilation of collection methods applied to obtain the needed data is presented in table 5.1.

Table 5.1: The main data collection methods utilized for the collection of each data type.

Collection method	Data type	Comment
Observations	Buffer sizes	Visual inspection of storage buffers
	Production floor layout plans	

Table 5.1: (continued)

Collection method	Data type	Comment
ERP-system	Cycle times	
	Product structure	
	Routings	
	Setup times	
Interviews/ Walkthroughs	Batch sizes	
	Changeover times	Mainly for calibrating testing equipment
	Control rules/Prioritization	
	Number of operators	
	Number of stations	
	Rework rates	Estimations based on operator experience
	Shared stations	
	Transportation times	
	Working times	
Technical reports	Arrival frequency of orders	Internal company reports

5.2.2 Conceptual design

The knowledge gained from the production walkthroughs, combined with data extracted from the company ERP-system were used to create conceptual models. Conceptual modeling is an abstract way to describe elements of the system, their characteristics and their interactions (Banks, 1998). The conceptual models were designed in the form of flowcharts, as described in subsection 2.3.1, to represent the flow of a product or component in the system. The conceptual models where prepared for each flow separately, according to the product structures presented in section 4.2, and were created in close connection to the production walkthroughs, as to minimize the risk of losing knowledge.

5.3 Step B - Model building

This step represents steps 5 and 6 in simulation project methodology presented by Banks (1998). Having collected required data and developed the conceptual models, the next step of the project, the building of the simulation model, could start. Taking advantage of knowledge gained during step A, a strategy for the model´s structure was first developed. The next task was to translate the conceptual models into code, while applying the structure strategy. Lastly, verification was performed to ensure that the translated model in-fact was a correct representation of the conceptual models.

5.3.1 Model structure

The conceptual models created in step A provided a foundation for the development of the strategy of model translation, as explained in 2.3.3, including model structure. The strategy, which addresses the complexity and variability of the system, enables a deliberate transition to model translation. Parameters to be considered are the characteristics of the system and how they can be modeled in the software that is being used for the simulation (Robinson & Bhatia, 1995). In this thesis, by analyzing the conceptual models, patterns with regards to logic and resource requirements were identified. These emerging patterns were leveraged when designing the model structure, to increase modularity, reduce logical repetition and make the future translated code more compact. The goal of the strategy is to make the model as modular as possible, taking advantage of the similar operations. Since only process flows of selected products are mapped, it is likely that there will be a need to add more products and processes to the model in the future, to increase its accuracy. Therefore it is required to keep in mind the adding of new products when deciding on the model structure. While not part of this framework, future experimentation needs to be considered in this step as well. The final model structure required logical verification to be performed, as it utilized several new concepts that had not previously been tested by the project members. Once these concepts were proven to be functional, the translation of the model could commence.

5.3.2 Model translation

The model translation was performed by applying the model structure strategy that was developed previously. In this thesis, the conceptual models were translated into a digital representation of the production by means of programming. The simulation software used was AutoMod, which was chosen based on previous experience of the project members and external requests.

5.3.3 Verification

It is necessary to perform verification constantly during the translation (Robinson & Bhatia, 1995; Banks, 1998; Law, 2007), to ensure that the simulation model behaves as described in the conceptual models. When the logic for a flow was translated, it was verified by tracing the products in the simulation model and comparing it with the conceptual model. When an error was found, AutoMod's debugger was used extensively to identify the root cause of the problem. Since the production facilities are large, model translation and verification were performed iteratively for each flow in the production. The connection between the flow and its related flows was also verified using tracing and input/output relations. To make this easier, a floor-plan was obtained from the company, and the buffers/resources were placed at their respective locations. Every error that was found was corrected until the whole model functioned as described by the conceptual models.

5.4 Step C - Validation

Validation refers to step 7 of Banks (1998) simulation project methodology. The methods used for the validation are project specific and a strategy must therefore be designed. But, whichever methods are used, they will all benefit from the modularity that was achieved in step B. The first goal of the validation is to ensure that all processes are modeled correctly. Since similar processes are using the same logic they only need to be validated once, if modularity is properly implemented. Once all different types of processes are validated, the routings and product/component specific process data that is used can be validated. Lastly, after all processes and input data have been successfully validated, the overall behaviour of the system is left to be validated. This approach to validation could be denoted as *bottoms-up validation*.

5.4.1 Strategy design

As explained in subsection 2.3.5, there are plenty of validation methods that can be used during the validation phase of a simulation project. These methods can be tailored to suit each project needs and characteristics. Due to time restrictions and the unreliability of the quantitative data, the choice was limited to few methods which were combined in two approaches, inspired by Sargent (2013). The first approach included the application of validation techniques by the project members, whereas the second approach included knowledgeable representatives from the company and was divided in two parts, validation with operators knowledgeable of the processes and flows in production, and with managers knowledgeable of the system and its input/output relations.

Approach I
Validation by the project members was restricted to two methods: *trace* and *extreme condition testing*, explained in section 2.3.5. This decision was taken based on

the limited knowledge of the real-world system. However, the methods chosen are powerful to indicate abnormalities of the simulation model that are easy to understand and fix even for people with no prior knowledge of the system. For example, if all operators are removed from the system there should be zero output. This approach was chosen to be executed first to minimize the risk of unwanted flaws surfacing during the following validation approaches.

Approach II - Part 1
The first part of the second approach involved the use of *trace* and *face validity* to validate the production flows one-by-one. By using *trace*, process owners could distinguish whether the logic is correct and accuracy is achieved. For example, if a specific component passes through the correct processes at the correct place and time. Thanks to the modular design, each module (process) only needs to be validated once. The component that passes through the largest variety of processes was traced, and additional tracing was performed for operations that were not part of that component's routing.

Combining this method with *face validity*, the system's behavior can be determined as reasonable and according to the conceptual models, which are also validated for their consistency. Moreover, during *face validity*, data validation, regarding the data fed from the conceptual models to the system took place. However, due to unreliability of the data extracted, data validation focused mainly on the routings and processes and not on quantitative measures. In an attempt to avoid a situation where no flaws were found, which would make it difficult to deduct whether the cause was a perfect model or a poor validation strategy, some flaws were introduced on purpose. This way, if the intentional flaws were not found, it would be possible to deduct that the validation strategy was poorly designed. The project members considered this deception of the validation participants as necessary an non-harmful, in accordance with the research ethics presented in section 3.2.

Approach II - Part 2
The second part of the second approach was performed by applying *black-box validation* with the help of upper management. In this way input/output relations and overall behaviour of the system could be validated and an insight on the model's accuracy compared to the real world could be gained. Measures that were considered for comparison were the capacity of the system, average lead times of products, bottlenecks, and resource utilization. The measures were obtained by analyzing the model using the AutoStat package in AutoMod.

5.4.2 Execution

Execution follows the validation strategy that was designed and the application of the suggested methods is presented here.

Approach I
By applying the first validation approach, involving *trace* and *extreme condition testing*, the project members attempted to "break" the model by means of changing parameters. Parameters that were changed included:

- Batch size
- Buffer capacity
- Number of operators
- Number of orders
- Number of resources
- Product mix
- Process time

Approach II - Part 1

The first part of the next validation approach was performed by the project members and 1-3 participants of different positions and disciplines, depending on the extent of the flow and the processes involved. From the Microwave production unit, positions that participated in the validation sessions were assembly operators and test engineers, whereas the validation session of the Digital production unit was performed with the help of the Production Unit Manager who validated all of Digital's flows. Due to lack of input data and interest from the Antenna production unit, Antenna was not part of the validation process.

The participants were first introduced to the problem, over email, and what would be expected of them during the validation session. The introduction to the validation session can be found in appendix C.1. Again, all participants were kept anonymous. After accepting to take part in the validation, the participants were provided with the conceptual models, that contained intentional errors, ahead of the meetings. This was done to allow them a greater amount of time to reflect and analyze what they were presented with. At the meetings the conceptual models and the routings extracted from the ERP-system were provided in printed form, and the participants were encouraged to point out any flaws they could identify. For every operation in the conceptual model, the same operation was displayed in the simulation model so that the participants could confirm that it reflected the real world. The flaws that had been planted included:

- Additional/missing processes
- Order of processes
- Faulty batch sizes
- Faulty cycle/setup times
- Wrong operators
- Wrong resources

Approach II - Part 2

The last part of the second validation approach was performed with the assistance of the production unit manager and object managers from the Microwave production unit. The Digital production unit was not qualified for this step since only one product was mapped and included in the simulation model, due to the lack of input data. As mentioned in part 1, the Antenna production unit could not be included in the validation process.

Statistical analysis of the simulation model was performed using AutoStat, and lead times, utilization of resources and the maximum capacity of the production system were obtained prior to the validation session. Lead times of each product type were obtained by using equations in the simulation model. Running AutoStat provided with averages of lead times after 1 year of production. To increase the statistical significance of the results, 30 replications of a single scenario were run. Bottlenecks were identified by looking at the utilization of the resources provided by the same single scenario analysis. To approximate the maximum capacity of the production system, a single factor analysis that was gradually increasing the total number of orders per year was performed. Once again, the analysis was run for 30 replications, and the results revealed the needed measure.

Once again the participants were introduced to the problem and what it will be asked from them during the validation session in advance. The introduction to this validation session can be seen in C.2. After the introduction the participants were presented with relevant data that were used in the model, seen in the list below:

- Product orders per year
- Production time (hours per year)
- Number of production employees per process category
- Product types to be produced

With the data used in mind, the participants were asked to make estimates about the performance of the system in terms of the aforementioned measures. After they presented their estimates, the results from the simulation runs were revealed.

6

Framework application results

The chapter presents the results of the application of the developed framework. The results are presented in the same order as suggested by the developed framework. Results regarding model translation may not be directly applicable to other simulation software. Due to confidentiality the results presented here have been modified or fabricated as to comply with company policy.

6.1 Step A - Initialization

Applying the methods presented in section 5.2.1, the results obtained for Step A of the framework, namely data collection and conceptual design, are presented below.

6.1.1 Data collection

Identification of needed data
As explained in section 5.2.1.2, a list with the needed data for the simulation model was compiled, based on the project members' experience and the production walkthroughs, and handed in to the production units managers. An early indication of what data the managers thought was available was obtained. The list of the needed data is presented below:

- Arrival frequency of orders
- Arrival times of raw material
- Batch sizes
- Buffer sizes
- Changeover/setup times
- Control rules/prioritization
- Cycle times
- Disturbances:
    - MTBF-MTTF
    - MTTR-MDT

- Number of operators
- Number of stations
- Product structure
- Production floor layout plans
- Repair/rework rates
- Routings
- Scrap rates
- Shared stations
- Transportation times
- Working times

Classification of data

The needed data was classified in accordance with the input data management methodology presented in section 2.3.2, based on its availability. The result of the classification is presented in table 6.1.

Table 6.1: Classification of data to A/B/C categories based on availability.

	Category	
A	**B**	**C**
Cycle times	Arrival frequency of orders	Arrival times of raw material
Product structure	Batch sizes	MTBF/MTTF/ MTTR/MD
Routings	Buffer sizes	Repair/rework rates/times
Setup times	Changeover times	Scrap rates
	Control rules/prioritization	
	Number of operators	
	Number of stations	
	Production floor layout plans	
	Shared stations	
	Transportation times	
	Working times	

Collection of data

The quantitative data collected from the ERP-system was known to be of poor quality and unreliable, but it was complemented with the help of experienced personnel. However, there was no historical machine data available to be fit in statistical distributions or enough data from manual work to create empirical distributions. Due to the long lead-times and the large variety of products and operations it was deemed infeasible for the project members to collect such data. Hence there is no randomness associated with times in the simulation model. The only cause of randomness in the model stems from the approximations of rework-rates that were obtained with the help of operators. Moreover, due to insufficient availability of assistance from the Digital and Antenna production units, the data management efforts were limited to Microwave production unit. However, data for some products of Digital and Antenna could still be collected.

6.1.2 Conceptual design

Necessary information, namely names of processes, location of buffers, location and usage of personnel, were mapped in the conceptual models to ease the later model translation. Operations were categorized according to subsection 4.1.1 to be easily identifiable. As seen in figure 6.1, cycle and setup times, and batch sizes of each operation were also mapped. Rework loops were added where inspection takes place, since components travel back to a previous operation if they do no pass the inspection.

6.2 Step B - Model building

Applying the methods presented in section 5.3, the results obtained for Step B of the framework, namely model structure, model translation and verification, are presented below.

6.2.1 Model structure

Closer analysis of the conceptual models showed that there were many repeating operations within the component flows, where only process/setup time and batch size would differ. It also became clear that different components that belonged to the same production flow used similar operations. For example, an assembly operator and an assembly workbench were the only required resources for numerous processes, such as assembly, disassembly, mounting, tinning and soldering. Based on this, the different flows were modelled separately, and general modules, with dynamic process/setup time and batch size, were used within these flows. Other functions within the production, such as kitting and the creation of orders, that were not considered part of any flow or unit and performed very specific operations, were also modeled separately.

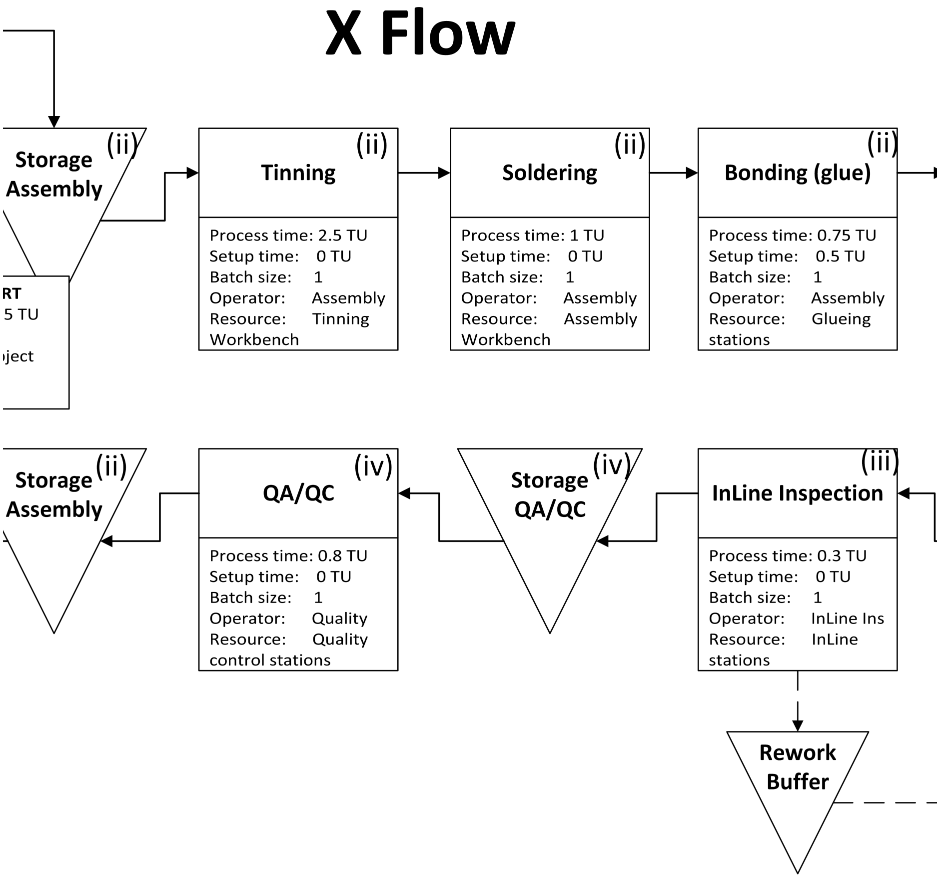
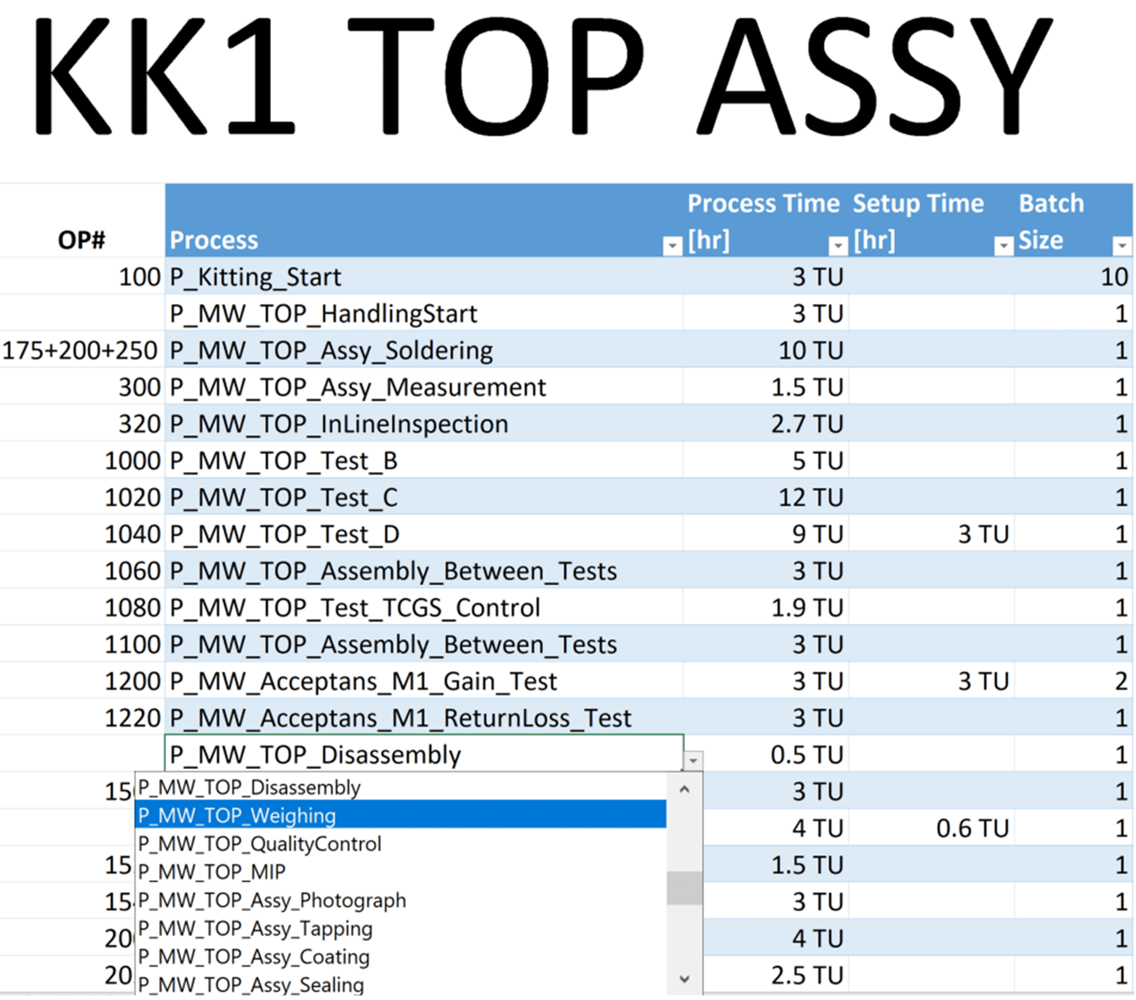


Figure 6.1: An example of a conceptual model that was developed for the project.

From the semi-structured interviews during the production walkthroughs it became known that the number of operators/machines that were working within a production unit could fluctuate over time. To simplify future updates of the model, and at the same time support future experimentation, functions were created for assigning operators/machines to the components moving throughout the production. This meant that if a new operator is hired or transferred from another unit, there is only one line of code in the model that needs to be updated.

Since only a limited number of products were modeled initially, the handling of data, such as routings, times and batch sizes, was done outside of the simulation software, in order to allow persons without programming skills to add additional products to the simulation model or update it with more accurate data. Excel workbooks were created for each component flow, containing separate spreadsheets depending on the product type and product variant. The spreadsheets were designed so all mapped processes of that particular component flow are included and can be used by selecting them from a drop-down list when arranging the component's routing. Figure 6.2 shows an excerpt of an Excel file, displaying the aforementioned properties.



KK1 TOP ASSY

OP#	Process	Process Time [hr]	Setup Time [hr]	Batch Size
100	P_Kitting_Start	3 TU		10
	P_MW_TOP_HandlingStart	3 TU		1
175+200+250	P_MW_TOP_Assy_Soldering	10 TU		1
300	P_MW_TOP_Assy_Measurement	1.5 TU		1
320	P_MW_TOP_InLineInspection	2.7 TU		1
1000	P_MW_TOP_Test_B	5 TU		1
1020	P_MW_TOP_Test_C	12 TU		1
1040	P_MW_TOP_Test_D	9 TU	3 TU	1
1060	P_MW_TOP_Assembly_Between_Tests	3 TU		1
1080	P_MW_TOP_Test_TCGS_Control	1.9 TU		1
1100	P_MW_TOP_Assembly_Between_Tests	3 TU		1
1200	P_MW_Acceptans_M1_Gain_Test	3 TU	3 TU	2
1220	P_MW_Acceptans_M1_ReturnLoss_Test	3 TU		1
	P_MW_TOP_Disassembly	0.5 TU		1
15		3 TU		1
		4 TU	0.6 TU	1
15		1.5 TU		1
15		3 TU		1
20		4 TU		1
20		2.5 TU		1

Figure 6.2: An example of how input data for the simulation model is handled in an Excel spreadsheet.

6.2.2 Model translation

The first parts of the model to be translated were the order creation and the data reading functions. The process that reads data was designed to read data from Excel workbooks, specified in the order creation, at the start of the model run, and store the data (routings, cycle and setup times, batch sizes) in arrays. Reading all the data at the start of the simulation takes time, but the other choice, to only read the data as an entity needs it, was shown to slow down the simulation significantly.

In the order creation, one entity of each component/sub-assembly type is created. Each entity is given the path of the Excel file and worksheet where the data for its component/sub-assembly type is located, and is then sent to read that data. After it has read the data, the entity returns and waits for an order in which it is included. When an order is to be created, all components/sub-assemblies that are part of the order are told to send a clone of themselves to the routing function.

Example code for how the reading of Excel files and order creation are performed can be found in appendix A.1 and A.2 respectively.

The next parts of the model to be translated were the routing function, kitting and the lower level components in the product structures. The routing process is presented in listing 6.1.

```
begin P_ROUTING arriving procedure
  //Set the values of the next elements in the array
  set A_ProcessPtr = A_ProcessPtrArray(A_i)
  set A_CycleTime = A_CycleTimeArray(A_i)
  set A_SetupTime = A_SetupTimeArray(A_i)
  set A_BatchSize = A_BatchSizeArray(A_i)
  inc A_i by 1

  send to A_ProcessPtr
end
```

Listing 6.1: The process in the model handling the routing, times and batch sizes used in the different processes.

The translation of the lower level components required the design of modular processes that could make use of the data assigned by the routing process. As seen in listing 6.2, the modular processes use subroutines to claim and free resources. This example shows how a testing procedure requires a machine and two operators at different time intervals in the same operation. It also shows how data read from the Excel files is utilized in the processes.

```
begin P_Vibration_Test arriving procedure
  move into Q_Test_Storage
  call S_Vibration_Machine_Get
  call S_Vibration_Operator_Get
  move into Q_Vibration(A_Index_Vibration)
  wait for A_SetupTime
  call S_Test_Operator_Get
  wait for A_CycleTime * A_BatchSize
  call S_Test_Operator_Free
  call S_Vibration_Operator_Free
  call S_Vibration_Machine_Free

  send to P_ROUTING
end
```

Listing 6.2: Example of a modular process

Depending on the operation and the processes included, entities may call both for an equipment and an operator, or just claim an operator and, by using an attribute, get their assigned equipment as well. For example, as mentioned in 4, assembly operators have their own workbench. This translates into a subroutine where the entity claims only an assembly operator, and if the process includes assembly operations, the entity uses the operator's workbench. How the operators are chosen and the index of the workbench is obtained can be seen in listing 6.3.

```
begin S_Assembly_Operator_Get
    /* Comment out or add more operators as the number decreases or
   increases in the real system over time */
  choose a resource from among R_Assembly_Operator(1),
                               R_Assembly_Operator(2),
```

```
                                R_Assembly_Operator(3),
                                R_Assembly_Operator(4)
    whose current loads is minimum
  save choice as A_OperatorPtr
  set A_Index_Assembly = A_OperatorPtr index
  if A_OperatorPtr current loads > 0 then begin
    wait to be ordered on OL_Assembly_Waiting
    call S_Assembly_Operator_Get
    return
  end
  get A_OperatorPtr
end

begin S_Assembly_Operator_Free
  free A_OperatorPtr
  if OL_Assembly_Waiting load list size > 0 then
    order 1 load from OL_Assembly_Waiting to continue
end
```

Listing 6.3: Examples of subroutines for getting/freeing resources

As the flows were translated, they were connected together so that components from the lowest level in the product structure could be assembled to sub-assemblies in other flows. It should be noted that the listings that have been presented here are only a generalized excerpt from the simulation model.

6.2.3 Verification

When performing the verification a significant amount of logical errors were found, that were the cause of faulty translation of the conceptual models. As described in subsection 5.3.3, the resources and buffers were placed at their respective locations, which helped with the identification of errors. The major errors were connected to the interactions between the flows, where one component from a sub-flow was consumed by its parent flow. A graphical representation of a small part of the simulation model can be seen in figure 6.3. The floor-plan has been removed due to confidentiality.

6.3 Step C - Validation

Applying the validation strategy and execution methods presented in section 5.4, the results obtained for Step C of the framework are presented below.

Approach I

Approach I of validation revealed multiple previously unknown flaws of the model which were subsequently corrected. The most significant flaws of the simulation model identified at this stage were:

- Batching problems if the batch size was above a certain number.
- Deadlocks caused by restricting buffer capacity.

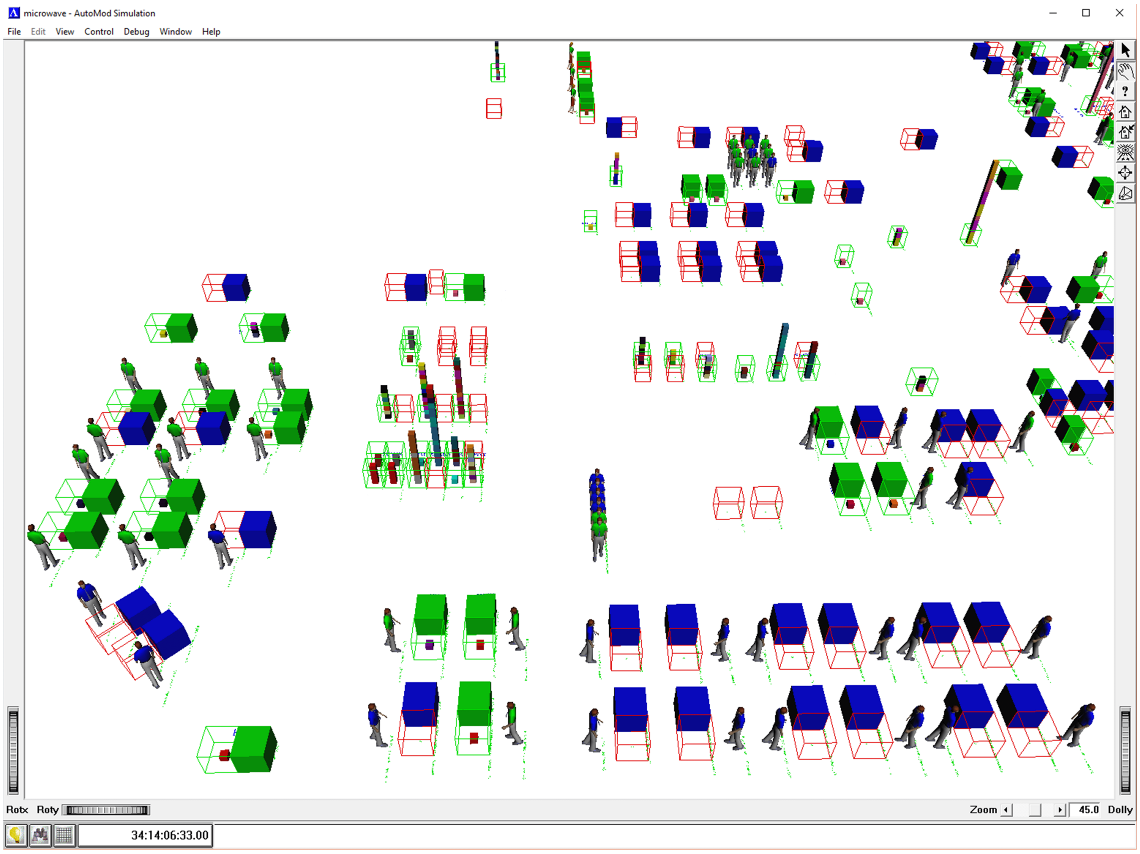


Figure 6.3: A small part of the simulation model during a simulation run in AutoMod. The floor-plan has been removed.

- Entities not utilizing the correct resources.
- Input number of orders had a high deviation with the output number.

When this approach stopped showing errors and the simulation model could no longer be "broken", this part of the validation was considered completed.

Approach II - Part 1

Approach II, part 1 was performed with knowledgeable persons from the company, as described in subsection 5.4.1. The participants managed to find all flaws that the project members had planted, together with further flaws. Most of the non-intentional flaws that were found were of the same nature as the intentional flaws presented in subsection 5.4.2, and were mainly the result of the unreliable data that was used. For example, the participants could present better estimates of cycle times or point out errors in the extracted routings about the order of processes. Another significant outcome of this validation session was to correct the imported layout of the shop-floor by moving the misplaced resources to the correct place according to the current arrangement of the production floor. The flaws found by the participants were minor, few in numbers and highlighted on the flow-maps. This allowed the project members to easily fix the errors after the validation meetings, and eliminated the need for re-validation.

Approach II - Part 2

Approach II, part 2 tested input/output relations of the simulation model, comparing them with the real system as explained in subsection 5.4.2. The comparison between simulation and estimates is presented in figure 6.4. Due to confidentiality restrictions, bottlenecks of the system are not presented.

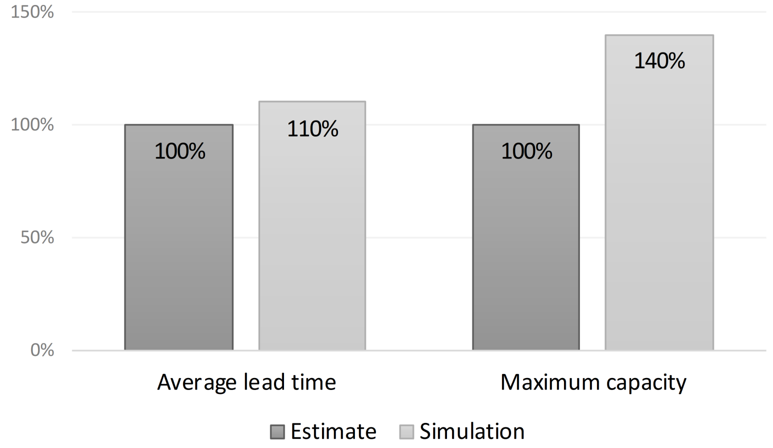


Figure 6.4: Comparison of performance measures between the simulation runs and the estimation of the actual system. Values have been normalized.

The results from the model were, by the participants, deemed accurate considering that the model does not take into account the problem of missing material that the real world system is affected by. However, when comparing the perceived bottlenecks with the bottlenecks identified in the simulation model a mismatch was identified. It was exposed that a mistake from the validation of one of the component flows, a process using the wrong resource, had passed unnoticed. After the validation meeting with the managers, the simulation model was updated to correct the mistake. The model was then analyzed yet again by the project members using AutoStat. A comparison between the new results from the analysis and the previous estimates can be found in figure 6.5.

As seen in figures 6.4 and 6.5, the lead time is significantly reduced after the problem had been corrected, while the maximum capacity is nearly unchanged. This is due to the fact that the results are from different analysis, as described in 5.4.2. When analyzing the maximum capacity, the average lead time is increased, since there are more products in the system.

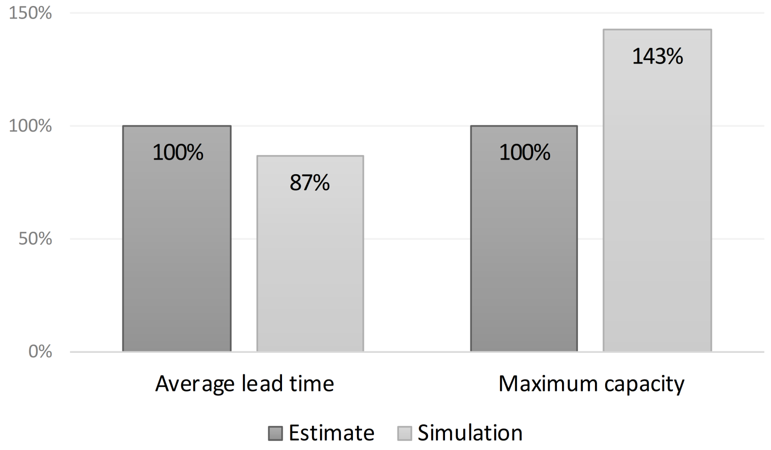


Figure 6.5: Comparison of performance measures between the simulation runs and the estimation of the actual system, after correction. Values have been normalized.

7

Discussion

The chapter presents a discussion about the development, application and integrity of the suggested framework, through a deep reflection on the framework's practice and usefulness. Towards the end are sustainability aspects with regards to the simulation field touched. The chapter concludes with the authors' insights of future work regarding the topic of simulation of FJS with re-entrant flows.

Motivation behind framework development

Not being familiar with the production system of RUAG, the members began this project with optimism of a substantial but smooth simulation project. However, when visiting the production facilities it became apparent that the operations were far more complex than anticipated. Three separately controlled but interacting production units in the same factory, each organized in an FJS fashion with re-entrant flows and mainly consisting of manual labour, presented a challenge when it came to mapping of products, collection of data, translation of conceptual models and validation of the simulation model. RUAG operates in an ETO environment which leads to a high product variance, which also complicated the project. A literature study was performed to find guidelines of how such a production system could be simulated, but efforts proved to be fruitless on this particular subject area. Due to the lack of literature on the subject, the project members had to develop a framework for how a simulation model of this complexity should be developed and validated, and how it could be applied to the company's context, but also serve as a baseline for potential application in other production systems with similar characteristics.

Quality of data

Performing production walkthroughs and semi-structured interviews with key personnel at the same time, enabled a wide extent of primary data collection. This allowed for an early indication of what data was currently available, and therefore an indication of the level of accuracy that the simulation model could obtained.

However, one issue during the application, that was not a result of the framework, was the poor quality of the quantitative data obtained. It is possible that the lack of quality data is a common problem within manual FJS production systems, and that may be a reason why literature on the subject is scarce. The data is lacking quality in all eleven dimensions explained by Balci et al. (2000), except consistency and relevance. Expanding on this, the encountered problems and their perceived effects of the poor data quality on the simulation model are presented in table 7.1.

Table 7.1: The data dimensions that were found to lack in quality, and their effect on the simulation model.

Dimension	Effect on simulation model
Accessibility	The data was not easily accessible without detailed knowledge about product naming schemes, which limited the number of products the project members were able to extract data for, reducing the accuracy of the model.
Accuracy	Data did not possess sufficient accuracy and correctness. Data was hard estimates made from experience or from the ERP-system. This reduced the ability of making the correct decisions based on simulation analysis and results.
Clarity	It was not always clear what the data represented. For example, in the case of batching, it was not clear if the given time represented process time for the whole batch or cycle time per item. The risk was thus increased that the data was misunderstood and wrongly applied.
Completeness	All parts of the data were not available. For example, scrap and rework rates were not measured. Historical data was not tracked or stored. This reduced the accuracy of the model in terms of representation of the physical system.
Currency	The data, such as cycle times, was sporadically updated to better reflect the real world. However, there was no indication of when the data was last updated, which limited the ability of the model to represent the current system.
Precision	The quantitative data was based on estimates, and hence lacked in precision. Connected to accuracy, it reduces the quality of decisions made based on the simulation, which will be problematic when performing experimentation.
Resolution	The data did not contain any statistics such as standard deviations or similar, which limited the randomness that could be incorporated in the simulation model, resulting in a less dynamically representative model.
Reputation	Data had the reputation of being unreliable and outdated. This decreased the chances that the simulation model would be accepted.

Table 7.1: (continued)

Dimension	Effect on simulation model
Traceability	The source of data was not always clear, since data could stem from people's experience and estimates or ERP-system estimates. However, there was no clear distinction between them, and therefore problems in accuracy and clarity were created.

Modular design

In an FJS production system there is a certain number of resources, but also a wide variety of processes that may or may not use the same resource in different parts of a product/component flow. To deal with this inconvenience, the structure of the simulation model followed a modular design, in a similar way to what was explained by Valentin and Verbraeck (2002). Looking on the benefits that this approach brings to the simulation project, it reduces the workload of the simulation developer since identical processes are only translated once and translational code can be reused to model similar processes. Following a modular design also reduces the risk of bugs during the translation, but also is easier to debug the model since most of the processes use the same code structure. Combining a modular design of the simulation model with a robust and flexible input data management solution, e.g. Excel integration for feeding data in the system, the simulation developer can more easily manage a large number of product variants and production flows. Additionally, it enables simplified future updates of input data, even by someone who has limited simulation experience. These benefits characterize the presented solution, but are likely to be obtained if the framework is applied in other, similar projects.

Validation aspects

It was necessary to design a validation strategy where the most appropriate validation methods, explained by Banks (1998), Sargent (2013) and Robinson (2004), would be chosen and fitted to the needs of this simulation project, ensuring a structured execution of the validation step. The poor quality of data limited the choices of validation methods, since no quantitative methods could be applied. *Trace* and *extreme condition testing*, in Approach I, assisted with the identification of major inconsistencies in the simulation model and enabled a smoother execution of Approach II. When performing the validation of the logic in Approach II - Part 1, as explained in section 5.4, the strength of the framework was quickly shown, as the modular operations facilitated a frictionless validation of the flows. Moreover, the inclusion of a shop-floor layout in the simulation model was proven to be valuable towards model validation, as it created a visual friendly environment that represented reality. The validation of the overall behaviour or the simulation model, Approach

II - Part 2, considering the limitations and assumptions involved showed that the model served as an accurate digital representation of the real system. However, due to lack of participation of the Digital and Antenna production units only the part of the simulation model representing the Microwave production unit can be considered valid. The outcome of the project may have been different if the other production units would have been included in the project in an earlier stage.

Furthermore, model integrity was evaluated during the validation step. The aspects considered were logical integrity, visual integrity and input data integrity. Logical and visual integrity were ensured, with the help of the production employees, during the validation of the conceptual models and the validation of the model's logic while the simulation was running. The integrity of the input data was partially ensured. Data regarding number of resources (operators and equipment), buffer and storage sizes, batch sizes, and working times were deemed to be accurate. On the other hand, data regarding cycle times, setup times, transportation times, rework and scrap rates were inaccurate and were approximated with the assistance of people knowledgeable of the production.

Finally, an aspect that could be improved upon would be to perform validation of the conceptual models prior to the model translation step. This would ensure that the logic of the conceptual models is correct in regards to the real system and possible flaws are caught early, so that they can be corrected before the translation begins, enabling higher accuracy of the translated model and possibly less effort during the validation step.

Capturing operation variability

One aspect of the framework that was reflected on during the application was the choice of which products to map. The framework suggests selecting a limited number of products, but does not give any recommendation of how to select these products. In the application of the framework it was decided to use the products with the highest production volume, previously identified by Olsson and Henriksen (2017), but it was discovered that it would have been better to select products with high operation variability instead. Operation variability refers to products whose components pass through a great variety of processes until their completion, enabling a wide capture of information that will be used in model conceptualization, and later in model translation. The selection of products would then require more finesse, and discussion with knowledgeable persons at the company, but it would mean that a greater number of operations could be mapped while investigating fewer products. This would also reduce the risk of missing uncommon operations, which will result in extra work when adding products requiring these operations at a later stage.

Framework integrity

The framework builds upon the simulation project methodologies suggested by Robinson and Bhatia (1995) and Banks (1998), and addresses an application area of simulation with lacking literature. Because it is grounded in established methodologies, it can be argued that the foundation for the framework is solid. Further more, the framework applies established theory regarding verification and validation. The weakest part of the framework is the model translation step, which partly builds upon the experience of the project members. This part is also the weakest in terms of reliability, as the implementation of the model translation will vary greatly depending on the skill, preference and experience of the user. It would have been possible to present more concrete guidelines in the framework, but that would reduce the flexibility, and limit the number of compatible software solutions.

Finally, the framework maintains the possibility for the user to obtain the advantages that can be achieved with simulation, as explained by Robinson (2004) and Law (2007). However, since the FJS environment with re-entrant flows is so complex, it can easily suffer from some of the disadvantages, mainly problems with collecting and analyzing large amounts of data, which can be costly and time-consuming.

Sustainability aspects

Companies constantly need to adapt to their market situation, which means that the production of said companies needs to adapt. When the production system of companies becomes so large and complex that it is no longer obvious where in the system change is needed, simulation can be a powerful tool. As explained by Robinson (2004) and Law (2007), the application of simulation can provide valuable advantages, but also disadvantages. Several of the advantages can help the company stay economically sustainable by offering decision support when adapting the production system. It can also be argued that simulation can help with social sustainability, as it can be used to redistribute employees' workload in the production. However, the advantages of simulation can turn into disadvantages if, e.g. the simulation model is flawed, or there is overconfidence in the precision of the results. Regarding environmental sustainability, performing experiments in the virtual world reduces the use of resources in the real world even though electronic equipment is needed.

Future work

An area that needs to be further explored is the data collection process in an FJS with re-entrant flows that is characterized mostly by manual work. Since quality data is hard to find and collect, a framework or guidelines should be developed that would guide the simulation expert through the collection phase.

Furthermore, it is important to evaluate the usefulness of the developed framework by applying it to other similar environments. This would confirm if the results and conclusions drawn in this thesis are accurate and can be used to produce similar studies, proving the framework's reliability. If that would not be the case, flaws and irregularities of the framework would be pointed out and adjustments would be made to make it suitable for different environments that operate on a similar production setup. As mentioned earlier in the discussion, the authors suggest to map products with high operation variability that will help not to miss any process that is required in the simulation. This would also constitute a future work task that will test the strength of the framework and its suitability for ETO environments.

Finally, a study on different validation methods applied on similar context would be of interest to evaluate the strengths and weaknesses of the validation methods used in this thesis, but also to point out differences between the different techniques, in order to assist the simulation expert while on the validation step.

8

Conclusion

The chapter answers the research questions that were stated in the beginning of the thesis report, section 1.5.

RQ1: How can a flexible job-shop production system with re-entrant flows be simulated?

Based on well-known simulation project methodologies, but twisted to fit to an FJS of an ETO business, the developed framework provides a structured path in the simulation model development of such complex production systems. Aspired by the lack of literature and the challenging environment, the authors believe that the framework guides the simulation expert in this difficult venture, and supports decision making in uncharted situations.

RQ2: How can a simulation model of a flexible job-shop production system with re-entrant flows be validated?

The framework achieves satisfactory results during the validation step, through a well-defined validation strategy, which were comparable with the real system giving reasonable figures. Choosing the correct validation methods might prove to be a difficult task, mainly due to the complexity of the system and data quality implications. Applying the validation techniques in a bottoms-up approach shows flaws of the simulation model that must be corrected before proceeding to the next level of the validation. In a situation where better quality data is obtained it may be possible to apply a wider range of validation techniques that will strengthen the model's validity.

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A

Example code from the simulation model

In this appendix longer segments of code examples are presented. For anyone attempting to perform a similar project, these might prove to be a useful stepping stone to get started.

Listing A.1 presents a way of extracting data from Excel-files, while listing A.2 presents how order creation with large product structures can be handled.

```
begin P_READ arriving procedure
  /* This is only run once, by each load in the OrderCreation. This reduces the number of excel-reads during the simulation. */
  //Set the row  and column of the first heading
  set A_Row = 2
  set A_Column = 1
  set A_TempString = null
  set A_Process_Column = 0
  set A_ProcessTime_Column = 0
  set A_SetupTime_Column = 0
  set A_BatchSize_Column = 0

  //Find columns of Process, Cycle Time, Setup Time and Batch Size
  while (A_Process_Column = 0) or (A_ProcessTime_Column = 0) or
        (A_SetupTime_Column = 0) or (A_BatchSize_Column = 0) do begin
    set A_TempString = XLGetR1C1(A_File,A_Row,A_Column)
    if A_TempString = "Process" then
      set A_Process_Column = A_Column
    if A_TempString = "Process Time [hr]" then
      set A_ProcessTime_Column = A_Column
    if A_TempString = "Setup Time [hr]" then
      set A_SetupTime_Column = A_Column
    if A_TempString = "Batch Size" then
      set A_BatchSize_Column = A_Column

    inc A_Column by 1
    end
  end

  //Get all process pointers
  set A_Row = 3
  set A_i = 1
  set A_i_max = 100
  while A_i <= A_i_max do begin
```

```
    set A_ProcessPtrArray(A_i) = XLGetR1C1(A_File,A_Row,A_Process_Column)
    //If there is no process on the row read, the last process was on the row above.
    //Carry this information over to the reading of process time,
    //setup time and batch size by breaking their while loops after A_i_max - 1
    if A_ProcessPtrArray(A_i) = null then begin
      set A_i_max = A_i - 1
      break
    end
    inc A_Row by 1
    inc A_i by 1
  end

  //Get all process times
  set A_Row = 3
  set A_i = 1
  while A_i <= A_i_max do begin
    set A_ProcessTimeArray(A_i) = XLGetR1C1(A_File,A_Row,A_ProcessTime_Column)
    inc A_Row by 1
    inc A_i by 1
  end

  //Get all setup times
  set A_Row = 3
  set A_i = 1
  while A_i <= A_i_max do begin
    set A_SetupTimeArray(A_i) = XLGetR1C1(A_File,A_Row,A_SetupTime_Column)
    inc A_Row by 1
    inc A_i by 1
  end

  //Get all batch sizes
  set A_Row = 3
  set A_i = 1
  while A_i <= A_i_max do begin
    set A_BatchSizeArray(A_i) = XLGetR1C1(A_File,A_Row,A_BatchSize_Column)
    inc A_Row by 1
    inc A_i by 1
  end

  //Set the initial pointer + values for the load (first process)
  set A_i = 1

  //Return to the process in OrderCreation
  send to previous process
end
```

Listing A.1: Example of how the reading of data from Excel was solved.

```
/* Example code, not the actual code used in the simulation model! */
begin P_OrderCreation arriving procedure
```

```
    /* Create all the different loads, and send them to their specific processes */
    create 1 load of load type L_ProductA_Component1 to P_ProductA_Component1
    ...
    create 1 load of load type L_ProductA_Component4 to P_ProductA_Component4
    ...

    while 1 = 1 do begin
        // Decide what the next order is
        set variable to oneof(0.7:ProductA,0.3:ProductB)
        // Order the proper loads
        if variable = ProductA then begin
            order 1 load from OL_ProductA_Component1 to continue
            ...
            order 1 load from OL_ProductA_Component4 to continue
            ...
        end
        else if variable = ProductB then begin
            ...
        end
        // Wait for some delay before continuing the while-loop
        wait for some_time
    end
end

begin P_ProductA_Component1 arriving procedure
  /* First time entering the process, set the name of the file with the routing data, and send to "master" process to read the data */
  if current queue <> Q_Supervisor then begin
    move into Q_Supervisor
    set A_File = "[ProductionFlow.xlsx]ProductNumberA_Component1"
    send to P_READ
  end
  /* When called upon by the order creation, clone 1 load to the master process. Then return to this */
  wait to be ordered on OL_ProductA_Component1
  clone 1 load to P_ROUTING
  send to P_ProductA_Component1
end
// Do the same for all other components
...
```

Listing A.2: Example of how the order creation can be performed.

B

Data collection execution

The appendix includes questions asked to company's representatives during production walkthroughs and are in the form of semi-structured interview.

Production walkthrough questions

While on a production walkthrough, a set of predefined questions was asked to each representative, that was complemented with follow-up questions if the subject was interesting or difficult to comprehend. The questions were asked, mainly, to operators from each flow of the company's production. If the same person was responsible for more than one production flow, the introduction part of the questionnaire was skipped since this data was already gathered. Moreover, some questions during the walkthroughs were repeated to increase the accuracy of the findings. Below, the structure of the interview and the asked questions are presented in the form of a list:

Questionnaire - Production walkthrough

A. **Introduction, right before walkthrough**

    I. We are Georgios and Markus and we are master students from Production Engineering at Chalmers University of Technology. Currently, we are conducting our master thesis here at RUAG Space. What we are currently working on, is the development of a simulation model of RUAG's production that would be used in the future to evaluate scenarios and help in decision making regarding the shop-floor. Also, an important aspect of our thesis is to deal with complexity and product variation.

    We want to do this production walkthrough in order to get a better understanding of how the production system works, what the steps of production are and how different components interact in the system. The information you provide will be the base of an accurate simulation model, so feel free to make additional comments about any topic you think might be important to know.

    II. Can we record this session?

        i. The recording will be used internally to support us in developing the simulation model and later writing the report of our thesis.

III. All participants in the study will be kept anonymous, but we may use your job title or department in the report. Is that ok?
    i. What is your name?
    ii. What is your job title?
    iii. How long have you been working in this role?
IV. What we want from you is a tour in the production, where you show us the production flow of components and explain the processes.

B. **During walkthrough**
  I. What is your everyday interaction with production?
  II. How does communication take place?
  III. How long do you usually work per day, excluding lunch time and breaks?
  IV. How many operators of your process category work in this production unit?
    i. Do all operators have the same competence?
    ii. What types of operations do you perform?
    iii. Where do these operations take place?
    iv. What other operations exist?
    v. Can operators work with different production flows and/or different production units?
  V. Can you explain, step by step, the different operations? We would like to see the physical place of where operations take place as well.
  VI. How do you handle the different production flows and their components that a product consists of?
  VII. Is there a production schedule to follow and know when each components should be manufactured, or do you start making all components simultaneously when you receive an order?
  VIII. What resources do you share with the other production units?
    i. How many of these resources exist?
  IX. Where do you store you work-in-process?
    i. Do you use different cabinets for each component depending of the flow or do you store everything in the same cabinets?
    ii. Where do you store completed units?
    iii. What is the capacity of the cabinets you use for components and what is for completed units?

C. **Job specific questions**

I. Assembly
   i. How many different operations can you perform at your workbench?
   ii. Where does the other assembly operations take place?
   iii. What kind of machine or equipment do you use and do they have any setup/changeover time?

II. Inspection
   i. Where does the inspection take place?
   ii. Apart from inspection, do you perform other tasks?
   iii. What happens if you find a defective components/unit?
   iv. How is rework performed?
   v. Is there any data on reworked products or failure rates that we can use in our model?

III. Quality control
   i. Where does the quality control take place?
   ii. What other tasks do you perform?
   iii. What happens if a component/unit is not according to quality standards?

IV. Test
   i. What types of test do you perform?
   ii. What other types of tests exist?
   iii. Where does testing take place and what tests can you perform on your test workbench?
   iv. Do you use any machinery, equipment that require setup/changeover time and what might these be?
   v. What happens if a component/unit does not pass a test?

V. Kitting
   i. What is your interaction with every day production?
   ii. How do you handle the orders that arrive?
   iii. Where do you store the kits?

VI. SMT
   i. What does the work procedure look like?
   ii. Is there setup/changeover/calibration time needed before you use the machines?
   iii. Do you produce SMT boards for all production units?
   iv. How many operators can use the machines and how many do the

manual work?

D. **Completion of walkthrough**

  I. Do you have any more comments to add?
  II. Do you think we missed something during the walkthrough?
  III. Would you like to ask us anything?
  IV. Can we reach out to you if we require any more information or to clarify parts that we may have misunderstood?
  V. We would like to remind you once more that the data we gathered will be used in the development of the simulation model and our thesis report. We will likely use some data on our presentation as well, which you are welcome to attend and participate.
  VI. Thank you very much for your time and valuable input.

C

Introduction to validation sessions

Appendix C presents two introduction texts that were presented to the company's representatives prior the validation sessions. Section C.1 refers to the first part of validation with operators knowledgeable of the system and production flows, whereas section C.2 refers to the second part of validation which performed with the help of upper management (see 6.3 for detailed description on how validation was designed and executed).

C.1 Validation, part I

Hello,

We have asked you to come to this meeting to help us validate the simulation model that we have been building for the last 3 months. Validation of a simulation model is the process where the model is compared with the real world system and the level of accuracy is determined by testing, observing and comparing certain facts.

To make the validation easier, we have created flow-maps, representing the logic and data we are using in the model.

What we will ask from you at the meeting, is that we go through the flow-maps, step by step so you can verify the data we use or point out objections and other issues. At the same time we will see the steps in the simulation model to confirm that the product/component flows correctly in the system. The whole process will not take more than 1 hour and your input will be much useful for our work and the company.

C.2 Validation, part II

Hello,

We have asked you to come to this meeting to help us validate the simulation model that we have been building for the last 3 months. Validation of a simulation model is the process where the model is compared with the real world system and the level of accuracy is determined by testing, observing and comparing certain facts.

The validation is divided in two parts. The first part is already completed with the help of people knowledgeable about the production flows, mainly operators. They helped us to understand mistakes in the model and to better approximate production data of different components and units.

Now, for the second part of validation, we would need your help since this part will test the overall model and its input - output relations compared to the real system.

But first of all, we would like to introduce some of the limitations and assumptions of the model:

A. The simulation takes into consideration net production time. For example, 24 hours in the simulation means 24 working/manufacturing hours.

B. The product types that are modeled are only 8 for microwave. They are the products that Daniel and David identified during their analysis last year.

C. Material for Kitting is always available at any given time.

D. The data used in the model (cycle times, setup times) are extracted from the ERP system and adjusted with the help of the operators at the previous validation step.

E. There is a stock of completed MCM hybrids at the beginning of the simulation run that the model uses to build products.

F. In the simulation, a component/unit claims any resource (operator, workbench, machine, equipment) that is free at any given time. Waiting times are calculated during the simulation if components build up.

G. Right now, at Microwave production we have assumed that there is a limited number of operators (for assembly, inspection, test, etc.). This number can change for testing purposes during simulation runs.

H. We have made an assumption on arrival frequency of customer order that we want to discuss with you during the validation meeting.

Then, the main areas we would look into during the validation session are:

A. Output - Is it reasonable for certain amounts of time?

B. Bottlenecks - You will be asked to point known bottlenecks of the real system and then we will compare (utilization) with results from the simulation model.

C. Lead time averages between different product types.

D. Finally, is there a scenario that you would like to test? For example, we can test the interaction between output of the system and storage space.

Performing the simulation to extract the data takes some minutes, so we want to have performed most simulations runs before the validation meeting with you.