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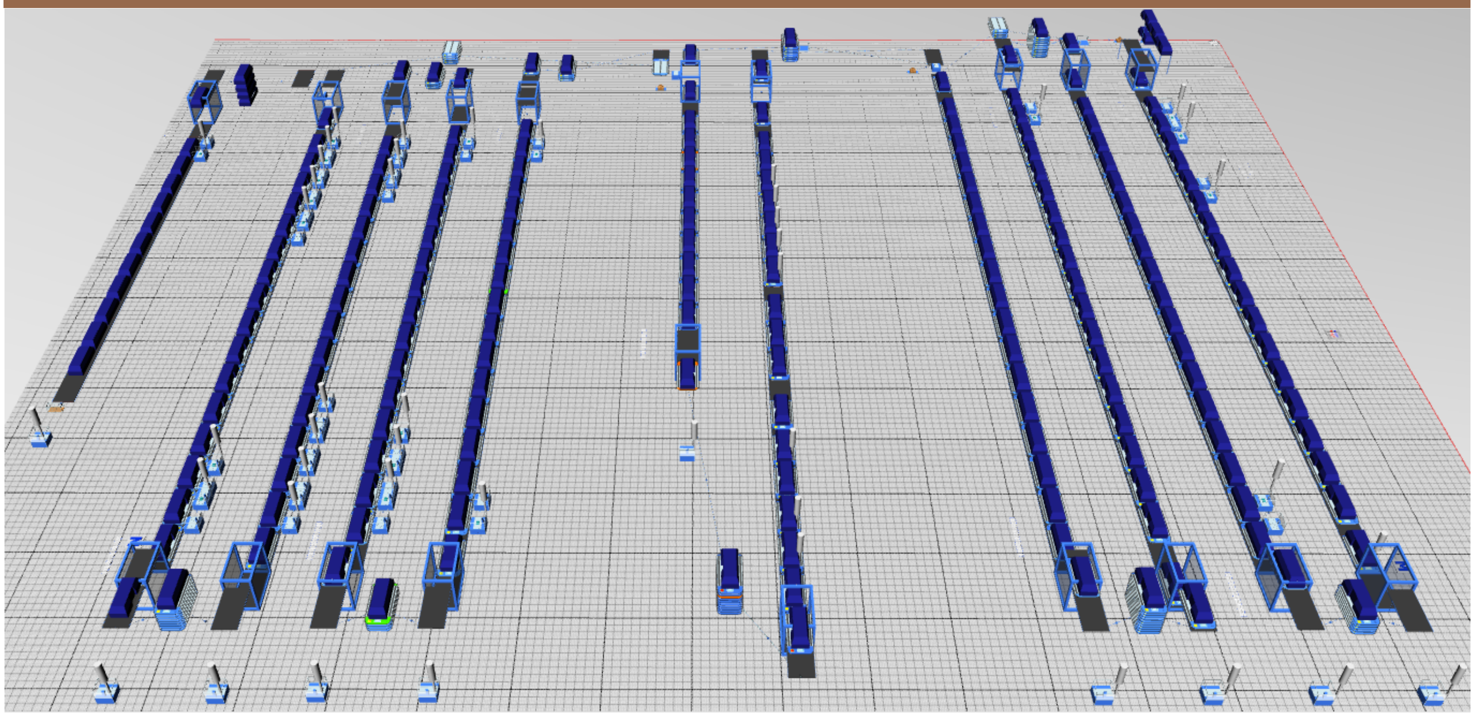

Simulating and validating an ideal factory at Volvo Cars Corporation

An industry case on how to validate a simulation model without a physical counterpart

Master's thesis in Production Engineering

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Cover:
[Overview of the complete simulation model of Volvo Cars Corporations ideal state factory]

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Abstract

A dynamic market with fast paced changes and shifting customer demands requires companies to adjust and find new ways to improve their production facilities in order to stay competitive. A critical industry is the automotive industry where customers order highly customized products with short delivery times as an expectation. This has led to an increased use of concepts such as Industry 4.0 to improve the production and the utilization of resources. Furthermore, digital tools, such as flow simulation models, has become more and more popular to determine how improvements could affect the production facilities without having to implement them in the real system. With that said, this thesis investigates some of the possibilities with the use of digital models, and how to create a credible model of a facility that does not yet have a physical counterpart.

The project started with the creation of a simulation model of an assembly flow in collaboration with an automotive industry. Simultaneously as it was built, the model was verified and validated with some of the already existing techniques to investigate if a credible model could be achieved despite not having any physical counterpart to compare with. The results indicated that it was possible to build a credible model in accordance to the intended purpose, but where this is more thoroughly discussed in the report. Further, experiments were performed when the model had been created to investigate the appropriate buffer sizes and fixtures needed to increase the performance and cost efficiency of the system.

The main conclusions from the project are that the communication with experts and the end-user grows and becomes the most important source of information when verifying and validating a system with no physical counterpart. Also, putting time into the problem formulation phase and formulating the purpose of the model together with the end-user is of greatest importance to achieve a credible model.

Keywords: Discrete Event Simulation, Validation, Verification, Automotive

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Glossary

V&V = Verification and validation

VV&T = Verification and validation testing

IV&V = Independent verification and validation

DES = Discrete Event Simulation

WIP = Work in progress

VCC = Volvo Cars Corporation

MTTR = Mean time to repair

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1 Introduction

This report constitutes master thesis about simulation of an ideal plant and was performed during the spring 2020 and is done at Volvo Car Corporation (VCC). The introduction chapter will provide the reader with the background for the thesis as well as the purpose and aim of it. The chapter ends with stating limitations and some additional prerequisites of the project.

1.1 Background

One major challenge within industries today, is the dynamic market and constant change of customer demands. This has made it more difficult for companies to stay competitive due to e.g. sustainability demands from customers, increasing costs of raw material etc. With that said, VCC are therefore constantly seeking for the best possible way to satisfy their customers and competing with other companies. An initiative that was meant to help companies with this was established by the German government, called Industry 4.0 (Yin, Stecke, & Li, 2018) and have become a global success and widely spread throughout the world. Further, the concept of industry 4.0 is about changing the way things are manufactured and being able to integrate technology in a way that the systems can be controlled with minimum input from human operators.

With that in mind, VCC is a well-known global car manufacturer that is searching for ways to improve production and meet the demands of the customers. For this reason, the department of Global Strategy & Plant Process Development is working on developing an ideal state factory to get one step closer on implementing the concept of industry 4.0. This includes a production layout and ideal processes that every factory is striving towards when making updates on their production. The company is today using digital flow simulation models to make well founded decisions and to be as prepared as possible when “going live” with new implementations in their processes. These models can be used to avoid tying up resources when making tests in production or to avoid investing in machinery that are not aligned with the performance of the present factory. Furthermore, a flow simulation can show how improvements within certain areas could affect and improve the system performance and to estimate performance of factories that does not yet exists. Thus, to know the performance of the ideal state factory, a digital model can be used.

Data handling and decision models are becoming more and more important within the industries, where companies need to come up with new and revolutionizing concepts on how to store data and base decisions on it. However, when creating a simulation model of a factory that does not yet exist, finding methods on how to validate the model will become difficult, and therefore creating uncertainties within such models. Although it is difficult to validate such systems, there is a need to have a correct system according to the purpose of the model in order to conduct experiments on certain parameters and optimizing them. According to Law (2006), simulation models can replace experiments on real systems or systems that has not yet been created. In fact, it can be the only way to make experiments in cases where projects are in an early phase and the physical system does not yet exist. With that said, this project will identify some validation techniques and evaluate how these can be used to validate a simulation model that does not have a physical counterpart, as well as pin-pointing the challenges when doing so.

1.2 Purpose

In order to keep up with the fast paced, changing and demanding market, VCC needs to be in the forefront of production development. In order to be ahead they need to take well founded decisions, based on credible models, in an early stage to develop the production in the right direction. The result of late changes when implementing production improvements can be high cost and less flexibility. Therefore, it is a necessity to use the possibilities and advantages that digital trends, such as Industry 4.0, brings, in order to be flexible and reactive to changes. Thus, the aim of this project is to investigate how to construct a credible simulation model and how to apply already existing validation techniques when validating a simulation model that does not yet have a physical counterpart. With that in mind, the simulation model itself will be built and is also meant to help VCC make well founded decisions in an early stage on how to improve and build new factories in the future.

1.3 Objectives

The intentions with this thesis and the creation of the simulation model, are to investigate the problems and possibilities described in the background. Therefore, the objectives that this project strives to manage are:

- **To investigate how a simulation model without a physical counterpart can be validated with some of the already existing validation methods**
  When having constructed a simulation model, findings from literature research regarding validation of simulation models will be applied to investigate how validation of a system with no physical counterpart will be conducted. Further, it will also be decided how the credibility of the model will be perceived when the validation has been performed.

- **To investigate how experiments on an early stage and high-level model can be used in the organization when taking decisions on how to improve the production**
  When having the model in place, appropriate buffer sizes and number of fixtures in the ideal state factory will be decided to increase the performance of the factory, both in terms of overall throughput and work in progress (WIP). These results will then also be evaluated on how accepted and credible they are, despite that no physical counterpart of the system exists.

1.4 Limitations

The project will be conducted during the spring of 2020 with a planned end date 5th of June. Further, when creating the simulation model of the ideal factory at VCC, the simulation software Plant Simulation will be used, which therefore limits the project to this software.

Currently there are two different ideal state factories, one with a higher capacity and one with a lower, where the higher capacity will be considered during this project. Additionally, this project will be limited to make studies and investigations on the main line of the production and thus not include sub assembly lines. The stations that will be simulated are chosen critical stations, so called hard points, but where the flow and the ideal layout within them will not be cared for. Furthermore, the simulation will be limited to not simulate the internal flow of the station but only the input and output of the station, thus including cycle time, breakdowns and to some extent the variation of the station. Also worth mentioning, the input-data to the model is given from VCC and based on vision KPIs. Therefore, the model will be verified and validated according to this data.

2 Theoretical framework

In this chapter, a background of the most relevant topics needed to understand the thesis will be given. This contains information regarding Discrete Event Simulation (DES) and the process of validating and verifying a simulation model. Moreover, a description of some principles and techniques on how to build a valid and credible model together with some basic definitions for the different processes will be stated. The chapter will end with a brief explanation of the V&V methods used in the thesis.

2.1 Discrete event simulation

In order to deal with complex situations and different kinds of flows within industries, simulation software can be used to create a digital model and thereby getting an overview of these situations. In an even more specific environment, such as situations where the state variable is changing within the system, DES can be used to create the simulation models (Banks, Carsson, Nelson, & Nicol, 1996). Examples of such environments would be e.g. inventory systems within factories, manufacturing plants or distribution systems. In each of those systems, the variables, such as waiting times, throughput and utilization of resources are determining the performance of it in a virtual environment. Further, these factors are changing at specific points in time – for instance when goods are delivered or shipped to/from the factory and can therefore be modelled in a DES (Fishman, 2001).

Another important part described by Banks, Carsson, Nelson, & Nicol (1996) is that this method is merely based on numerical analyses, instead of analytical ones. The analytical methods can be described as methods where a problem is solved rather than creating data that needs further analyses. For instance, a DES of a production flow gives data on e.g. the throughput of the system, but is not generating any direct answers on questions such as determining the minimum cost of inventory models (Banks, Carsson, Nelson, & Nicol, 1996). Instead, the DES gives an indication on where attention is needed in order to solve the problem, rather than giving the exact solution to the problem.

Additionally, there are multiple methodologies on how a simulation project should be cunducted, where maybe the most established method is called Banks methodology from Banks, Carsson, Nelson, & Nicol (1996). This methodology is devided into three main parts – preperation, model building and analysis.

2.2 Validation and verification of DES

In the following section the theoretical framework for validation and verification of DES will be set. The section will start with definitions of validation and verification. Following with good principles when validating simulation models and what approaches there are to validation and who should take decisions and be involved in the process. Lastly the chapter will end by presenting some validation and verification theory from a set of chosen methods. How these methods have been applied to the simulation project and the result from it will be described in the methodology and result.

2.2.1 Definition of Validation and Verification in Discrete Event Simulation

Law (2006) and Banks et al. (2005) defines validation as the process to decide if a simulation model is an accurate representation of the system for the particular objectives of the model. Further, Banks et. al (2005) defines verification as the process of ensuring that the conceptual model is correctly translated to the operational model. Balci (1997) strengthen this definition as he defines model verification as transforming the model from one form to another with adequate accuracy, thus, ensuring that the building of the model is correct.

Worth mentioning as well is what Sergant (2013) mentions about proposed system theories in his article. Proposed system theories are unverified simulation models and should only be seen as a verified simulation model when they are validated and tested against a real system. However, when comparison cannot be done against real system data, Sergant (2013) means that these models cannot be considered validated. This is often the case when simulation is made on new systems which does not exist.

2.2.2 Process of validation and verification in Discrete Event Simulation

Sergant (2013) simplifies the simulation process into three main steps seen in Figure 1. Firstly, a system of the defined problem is translated to a conceptual model using analysis and modelling, which is then validated with conceptual model validation. Sergant (2013) defines conceptual model validation as to determining that the assumptions made when building the conceptual model are adequate for the purpose that the model will be used for.

Secondly, the conceptual model it translated to a computerized model. This is done by coding the logic of the conceptual model into a simulation program, which is then verified by computerized model verification. In similarity to Balci (1997) and Banks et. al (2005), Sergant (2013) defines computerized model verification as assuring that the programming and implementation from conceptual model to operational model are correct.

Thirdly, the computerized model is verified towards the modeled system, which is called operational validation. This is defined by Sergant (2013) as determining that the operational model, within the scoped of the intended usage and application, has an acceptable range of accuracy. This model is then used to make experimentation and translated to an operational model where the problem formulation is solved. In parallel and continuously in all these steps, data validation is done. The definition of data validity from Sergant (2013) is ensuring that data which is required to build, test and conducting experiments on the model have sufficiently good quality to give reasonable output.

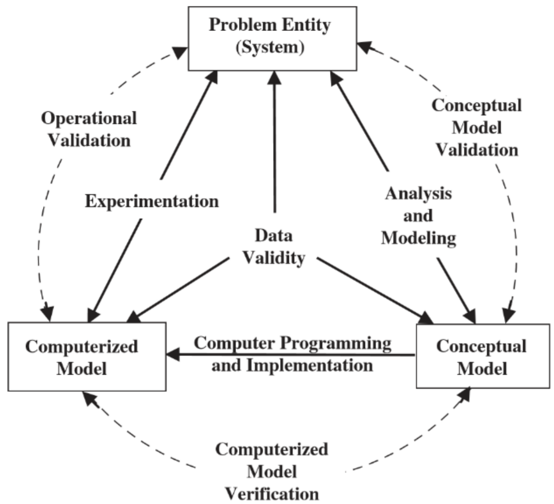

Figure 1 Simplified simulation development process. (Sargent, 2013)

2.2.3 Principles of validating and verifying a simulation model

Balci (2003) states that the process of verifying and validating is nothing that is done once during the project but should be continuously overviewed throughout it. If only considering the verification and validation (V&V) when the model is complete, it will be more difficult to make changes and to learn from mistakes that might have occurred during the study. Also mentioned by Balci (1995), is that it is difficult, or even impossible, to validate the complete model. In order to do so, he explains that all the different possible input data must be tested, which in many cases would be millions of different scenarios. Therefore, the validation should only be aimed towards the predefined objectives that the model is built for, and not be validated against possible scenarios (Balci, 1995).

A simulation model of a complex system can never be completely validated, nor is this in many cases desired. The equilibrium of time (money) and validity is different for models with different objectives. Law (2006) argues that, to increase validity of a model, it might require large amount of data gathering and therefore also time and money. However, this might only increase the validity to a small extent and can thus reduce the cost efficiency of the model. In general, the validity level can be seen as negative exponential to the time/effort/money put into the simulation model. This relationship can be described by Figure 2.

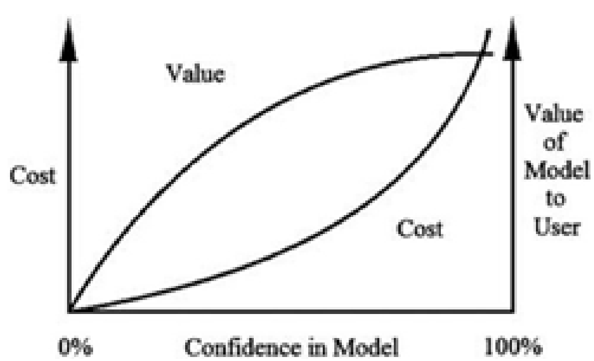

Figure 2: Value vs Cost when validating a model. (Sargent, 2013)

What also should be noted, is that the simulation model cannot be seen as binary – that it is either validated or not, but should instead be seen as more or less validated (Balci, 2003). Even though it might be possible with the technology of today, it would be costly and time consuming to build a model that would mirror the production exactly. Therefore, the model is not correct or incorrect, but will lie on a scale in-between (Balci, 1995). Further, it is important to note that validating sub-systems within the model will not directly imply that all of them combined are validated. All the tolerances that have been approved during the validation of the sub-systems can accumulate and become inadequate to validate the complete model - why it is needed to validate it separately as well (Balci, 1995).

A principle that Balci (1995) talks about is how the model should be built accordingly to the specified objectives that are decided in the beginning of a project. This means that the accuracy needed for a model can differ from case to case depending on how exact the data needs to be when e.g. basing decisions on it. With that said, the credibility can not only be considered based on how exact the model is, but instead in relation to how well it achieves the intended objectives (Balci, 1995) (Sargent, 2013).

Another aspect that could affect the credibility of the simulation study is whom is performing the testing of the model. Balci (1995) mentions that there should be an external party that does the testing, and not the developers themselves or the organization that intends to use the model. This because of the risk that both the developers and organization will overlook the negative testing results because it might affect them in a bad way. However, what also is mentioned by Balci (1995) is that a deep understanding of how the model is constructed and how everything works is needed in order to conduct efficient experiments and tests. Therefore, this is something that makes the validation-phase extra difficult, when having developers with thorough knowledge of the model, but whom cannot be utilized to the full extent in order to become unbiased.

One must be aware that a model can be declared as sufficiently valid for one set of input data, but not valid for another (Balci, 1995). If having a certain type of data, for instance when assuming constant production rate within a factory, the model can be built to manage this setting and become valid with this type of input data. However, if the production rate would become dynamic at a certain point in time, and the orders will not arrive as predicted, the model will no longer be valid if still assuming the input data of a production at a constant rate. With that said, the credibility of the model must always be held against the intended purpose and the input conditions.

A common problem within a simulation study, is that there has not been enough data gathered before starting to build the actual model, and therefore the model implementation is being rushed (Balci, 1995). In this manner, the risk of making errors within the coding will increase which might not be detected in an early phase, and therefore being time consuming and costly to correct. Thus, detecting defects and problems in an as early phase as possible is of greatest importance in order to reduce the cost of the simulation study (Balci, 1995).

It is important to differentiate between having a validated model and acceptable and credibly results, and not assuming that one guarantees the other. A model could be valid according to the defined objectives that are stated in the beginning of the project. However, those objectives could be stated incorrectly according to what the real problem that the model was meant to be used for is, and therefore creating unacceptable results (Balci, 1995). Thus, there is a clear difference between having a credible model and credible simulation results, where the first of the two is based on the definitions of the system and objectives, and the other on the actual problem (Balci, 1995). Balci (1995) further states the importance of formulating the problem in a good manner, and how this will help in increasing the acceptance of the model. In order to create a solution to a problem, it must first and foremost be correctly identified and formulated and thereafter perform the simulation study in accordance to this.

The difficulty to validate a simulation model depends, according to Law (2006), on two main things. Firstly, the complexity of the system being modeled and secondly if a version of the system currently exists. With an existing version of the simulated system, data can be gathered from this system and can be used to compare with the digital model. This possibility is however limited if a current version of the system does not exist (Law, 2006). Also, to get credibility of a simulation model the decision-makers should accept the model and see it as "correct", which also means that they should understand and accept the assumptions made. Credibility can also be achieved by demonstrating how the system has been verified and validated. Furthermore, by involving the decision-makers in the project along the way can give further credibility, as well as presenting the project with animations to give deeper understanding of how the simulation works (Law, 2006).

2.2.4 Approaches for validating decision-making

In the world of simulation, there are some different ways how the model is chosen to be evaluated and validated where some different techniques will be described more thoroughly later. Further, there are also some different ways in how the decisions are taken when constructing the model, and how the coding in general is being evaluated – so called decision-making approaches. Described by Sargent (2013), there are three common ways to take decisions when building a simulation model. These are mentioned as; that the development team themselves takes the decisions and validates the assumptions; the users of the end-product are validating the assumptions; or that an independent verification and validation (IV&V) team outside from the project validates the model.

The first of the above-mentioned approaches assumes that the team itself makes analyses on the results of different experiments, which in turn are based on what the intended purpose of the model is (Sargent, 2013). However, depending on the situation, the other methods might be preferable in order to validate the model in the best way possible. The second approach presented, letting the end-user validate the model, is often used when having smaller groups of people in the development teams, and integrates the user (Sargent, 2013). When doing this, the user will be involved in the decision-making in every phase needed to verify and validate the model and each step within it. Furthermore, according to Sargent (2013), by letting the user being involved in these processes, the credibility of the model will increase and thereby also the acceptance from the organization.

The third and last approach mentioned is to let an IV&V team validate the model and the decisions made. Unlike letting the users determine if the model is validated or not, this approach is more focused on projects with a simulation model that have a wider scope where several different development teams could be involved (Sargent, 2013). When considering such approach, it is important to make sure that the IV&V have a deep understanding of how the model works and the purpose of it. Further, the evaluation could either be done simultaneously with the development team as they progress, or at the end when the complete simulation model has been built (Sargent, 2013). When the V&V are conducted concurrently as the simulation model is built, the model cannot advance to the next step before the previous has been approved, unlike when validating it when the complete model has been developed (Sargent, 2013). In that case, the V&V can be done either by looking at the evaluation the development teams have already performed or creating new experiments and evaluating everything from the beginning - where the last would become very costly and time consuming. Worth mentioning is that V&V from a third party generates credibility and acceptance among other people (Sargent, 2013).

2.2.5 Techniques for developing credible models

Law (2006) states multiple techniques for developing credible and valid simulation models which will be further presented in this section. Both Sergant (2013) and Law (2006) discusses the importance of building the simulation model from a set of well-defined objectives. The problem formulation should contain information about what questions the specific simulation must answer. Law (2006) further mentions that in the beginning of a simulation project the client might not always know the objectives or cannot define them. It is further mentioned that the problem formulation can change or become more well-defined during the project. Having regular interaction with decision-makers ensures that these changes are brought up and the project can stay on the correct course. Additionally, this involvement gives credibility to the model as it allows decision-makers to get an understanding of what assumptions has been made in the simulation model and how the model is constructed (Law 2006). Moreover, to increase the validity further, Law (2006) states that quantitative techniques should be used when it is possible. Sargent (2013) mentions that statistical tests gives the simulation model a subjective validation which can increase the credibility of the simulation model. Further, Law (2006) argues that the output from the overall simulation model can be used as another technique for validation. If the combination of sub-models to a complete model gives reasonably close output to the real system, then this can be used to create validity to the model. This data should then also be compared to system output data to see if there are similarities in the statistical distribution.

When building a simulation model, Banks (1999), Law (2006), Sergant (2013) all mentions the importance of building a conceptual model (sometimes called assumption document). This document contains information of goal of the simulation, description of logics, data, graphical representation, limitations and assumptions of the simulated system. The document should contain enough information to ensure that the simulation can be replicated by another team (Law, 2006). This documentation should further be presented in detail for people involved in the project such as experts and decision-makers so that consensus is reached that the model is adequate (Law, 2006).

2.2.6 Validation and verification methods

According to Leal et al (2009) validation can be made both on a conceptual model as well as on operational systems a.k.a. computer models. Sergent (2013), Abu-Taieh and Sheikh (2007) and Banks (1998) present several techniques to validate systems both operational and conceptional. The techniques presented are used both subjectively (e.g. opinions of experts), and objectively (e.g. use of statistical tools to evaluate credibility) and will in short be presented below. These have been chosen based on this specific case, where a table of all considered validation methods can be seen in *Appendix A*. Further, the method of applying these validation methods can be seen in section 3.4. The result from when applying them on the case will be presented in section 4.1.

Alpha Testing is an early stage acceptance testing where the simulation is executed in a real setting to locate some of the last error in the code before handing it over for further testing from the end-users. In this stage it could be advantageous to not involve stakeholders since the A*lpha Testing* will most likely be of a faulty simulation model and can therefore get stakeholders to interfere on obvious errors (Silberman, 2007).

Boundary value analysis is a technique in which the boundaries of different machines in the simulation model should be evaluated and tested. Also important in such method is that it is not only tested for the specific lowest and highest value, but also somewhat above and below (Abu-Taieh & Sheikh, 2007).

Degenerate test is a test to validate that the model responds accordingly to a set of parameters that will make the model degenerate. For example, if the input to a machine is higher than it is set to handle, a queue is builds up before the machine (Sargent, 2013).

Extreme condition test/Stress Test evaluates different kinds of conditions in the simulation models and how it responds. For example, increase the number of breakdowns and shorten or prolong the cycle time to test the model in different conditions (Banks, 1998).

Face validity is made by asking experts within the area if the behavior of the model is reasonable. Questions that can be asked is if the logic and flow of the simulation are reasonable and if the input and output are correct (Sargent, 2013).

Fault/Failure Analysis is a technique where the output data is analyzed to identify how the model is failing. Faults refers to that a component of the simulation is wrong. Failure refers to the behavior of the model is wrong (Abu-Taieh & Sheikh, 2007). With such technique, the aim is to see how the input-output transformation has changed, and thereby locating the error in the model.

Internal validity is done by simulating multiple runs of a stochastic simulation model and compare the variation between the different runs. If there is large variation between each run the results can be questionable (Sargent, 2013).

Regression testing can be described as the process of redo tests when changes of e.g. data or code of the model has been made in order to ensure that the model behaves in the same way as before (Abu-Taieh & Sheikh, 2007).

Reviews are similar to structured walkthrough, but where this validation technique aims to ensure that the simulation model is built in accordance to what stakeholders wants, rather than the technical and logical specifications (Abu-Taieh & Sheikh, 2007).

Structured walkthrough validates the model by having the developers walking through the code, logic and physical appearances step by step together with people with simulation expertise or knowledge of the system (Abu-Taieh & Sheikh, 2007). This is done in a structured formal event where the developer explains the logic and structure of the conceptual model, code or operational model. The major difference between *face validation* and *structured walkthrough* is that it requires more formal meetings with experts when the system is walked through step by step. A face validation meeting on the other hand could be informal to only show basic animations or specific events.

Symbolic debugging is an iterative process which is carried out in four steps. The first step is to identify that there is a bug in the system. The second step is to identify what causes the bug, which can be done by using the software's debugging tool. In the third step, manipulation to the model is done to solve the bugs. Step four is to test the simulation again. The process is the iterated until the bugs are solved (Abu-Taieh & Sheikh, 2007).

Syntax analysis is the process of checking if there are any syntax errors in the code. In many cases this is partially done automatically in the software as syntax error messages are displayed if the program does not recognize a variable or a string of code. However, this must be checked manually to e.g. confirm if the right resource is called for in the right part of code (Abu-Taieh & Sheikh, 2007).

Trace is validation made by tracing an object trough the simulations to watch if the logic works as intended or if corrections are needed (Sargent, 2013).

Traceability assessment intends to match requirements in one part of the simulation project to another. E.g. the objectives set are checked if they are matched with the designed model (Banks, 1998).

Visualization and Animation is used to observe the simulation models operational behavior in a graphical way. The flow of parts can be observed to get an understanding of the logic in the simulation. Furthermore, states of machines can be seen, which can also be used to verify that the computerized model works without bugs (Sargent, 2013). Animation can additionally be used for demonstrating and presenting the model (Banks, 1998). Additionally, Rohrer (1997) states that in the cases where the modeled system does not yet exist, animation is one of the best methods to use to validate such system. As validation often involves many different experts and people with specific knowledge, animation can be of great help to quickly communicate how the system will work and get peoples understanding to the same level which is important when validating a simulation.

3 Methodology

In this chapter, the procedure of how the project was conducted is described, where the methodology created by Banks, Carson and Nelson (1996) will work as a foundation to how the simulation model was created. This includes several steps, that further can be divided into three different categories, namely, preparation, model building and an analysis of the project. As this thesis is focused on validating a model without a physical counterpart, the V&V phase within banks model will be reviewed in detail. More specifically, the approach for decision-making will be presented in subsection 3.3.1. The basis for how to evaluate the V&V techniques and what factors to pay extra attention to will be described in subsection 3.3.2. The chapter will end with a description of how each of the previously mentioned V&V techniques have been applied on the simulation.

3.1 Simulation model – Banks Model

In this section, a thorough description of how Banks model is constructed and how the different phases have been applied to the project is presented. How each of the steps within the model are divided between the different categories can be overviewed in Figure 3 and will also be described more thoroughly throughout this section.

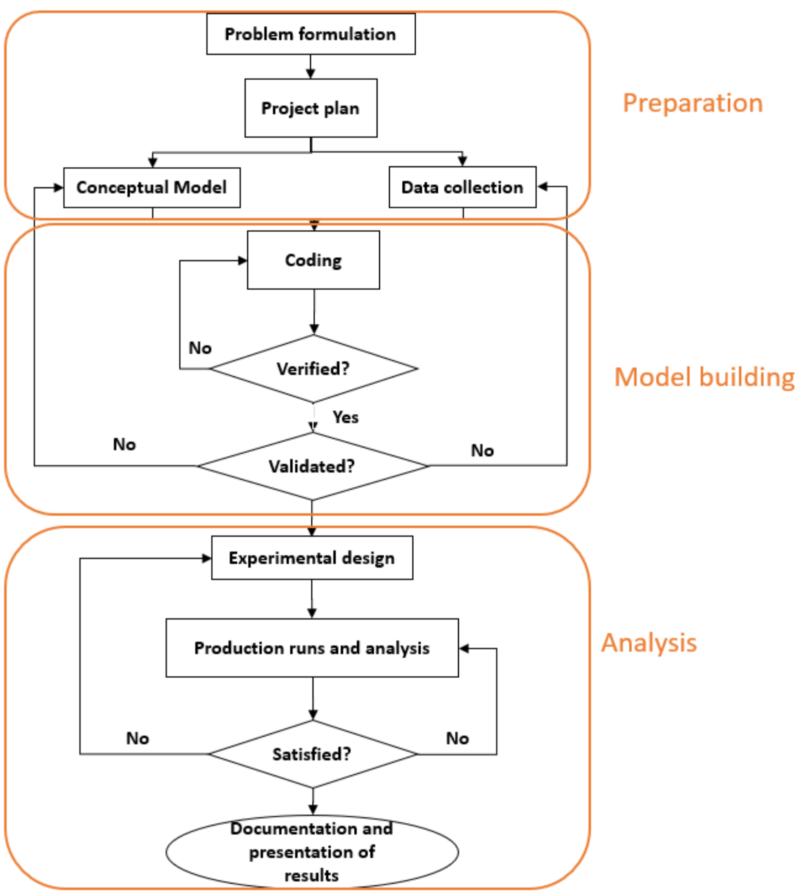

Figure 3. Banks Model

3.1.1 Preparation

The preparation phase within the model mentioned above, consists of four different steps - the problem formulation, a project plan, the conceptual model, as well as the collection of data. For the problem formulation a continues dialogue with both VCC and the supervisor at Chalmers was held to define the problem clearly and provide a clear scope of the project. This was done iterative to confirm that the project was on right path and that the problem formulation was up to date. According to Banks (1999) it is of greatest importance to have a deep understanding of the problem and know exactly what the customer expects from the project. Also mentioned is that the problem might have to be reformulated during the process, even though the problem is clearly understood from the beginning.

Furthermore, the objectives were set together with VCC to ensure that the project would reach the expectations, and the overall plan of what will be achieved with the simulation was further discussed. These objectives that were set were the goals of the project that the stakeholders wanted to achieve, with input from the development team of what could be achieved. This is the second step in Figure 3 and is in line with Banks methodology of working with simulation project.

In the third step a conceptual model was constructed, which aims to represent logical relations in the system and how things interact with each other. The conceptual model helps to create and show basic information on what should be included when building the simulation model, and what would make the model unnecessarily complex. The model was built in an iterative process until the desired complexity was reached. The iterative process consisted of several interviews with experts, at VCC, within each of the different processes and areas in order to make the best assumptions on how the logic would work in the conceptual model. The creation of a conceptual model is an important preparation step before building the computerized model (Banks, 1999).

The fourth and final step in the preparation phase was data collection which was done in accordance with Banks (1999). This step was initiated as soon as the proposal had been approved, and where the input to the model needed to be gathered. As mentioned previously, interviews were held with experts at VCC to gather as much relevant data as possible according to the objectives of the project. This included logic of how specific stations would work, e.g. closed loop with fixtures and behavior of the production line, as well as data regarding availability, mean time to repair (MTTR) and cycle time. For further details of asked question from the data gathering interviews see *Appendix B*. Worth mentioning, the conceptual model building, the coding, and the collection of data was done in an iterative process in order to adjust and construct an accurate model and find the most relevant data for its purpose. This was in line with Banks (1999) final step of the preparation phase. As a result of the iterative process of model building and data gathering the objectives and the problem formulation was also iterated and updated when new information was revealed, and knowledge of the simulation software was gained.

3.1.2 Model building

The aim of the model building phase is to code, verify and validate the simulation model, which was created in the software *Plant Simulation* in this project. The simulation model was based on the conceptual model, previously described in the preparation step, to get the correct logic and a correct model. However, in order to increase the correctness of the model even more, it was constantly verified to make sure that the logic was built as intended. This is in line what is said by Banks (1999), that the verification of the model should not be done when the complete model has been created, but instead simultaneously as the model is being built. Further, this was done by using V&V techniques that was found in the literature study. Also, worth mentioning, is that the final step in the model building is to validate the model, which was done using the techniques found in the literature study and are presented as a result in this project.

3.1.3 Analysis

The analysis consists of five steps; experimental design, production runs and analysis, iteration of runs, documenting and reporting, and implementation. Experimental design consists of designing simulation runs based on what kind of experiments that needs to be done and deciding how many iterations that are needed for the experiment to get good results. Additionally, a warmup analysis was performed to see how much time was needed for the system to operate in normal condition. This was performed by looking at the average throughput per hour to find out when the throughput was stabilized and thereby avoiding unwanted variations and extremes in the result. Further, this is meant to imitate when the assembly lines in the production are running and when there are cars in the entire system.

In this project, experiments to calculate the mean WIP within the system was determined as one of the important experiments. However, experiments on the buffer sizes was also something that was stated to be an important factor to measure with the model. With that said, the buffer sizes will affect the results of the WIP experiments, which therefore makes WIP a factor that will be used in several experiments throughout the project, instead of only measuring it once. Furthermore, to carry out the experiments in a reasonable time, the experiments on the buffer sizes were first overviewed in order to see how much capacity that was needed in the simulation software to perform them. Afterwards, the maximum and minimum value of reasonable buffers sizes were asked for from the experts of the system. Thereafter, a multi-variable analysis was performed where each of the buffers was stepped through from the minimum value to the maximum. However, because of the high demanding simulation model, each value of the buffers could not be evaluated, but instead the capacity of the buffers increased with an interval of two products.

In the second step, production runs and analysis, the simulation was computed and the output from the simulated scenarios was analyzed. Next step was to decide if the experiment was successful or if the previous two steps needs to be iterated once more to provide desirable results (Banks, 1999). The following step is documentation and reporting. To give credibility to the project this step was carried out in parallel with the project to ensure that the project is carefully documented. A careful documentation will give transparency to the model and thus allow for decisions to be made based on the result from the simulation (Banks, 1999). The last step in Banks model is the implementation.

3.2 Literature study

The literature study was conducted through thorough research and data gathering in order to grow good theoretical knowledge of the simulation and the validation processes. Articles that was searched for were mainly articles of DES, validation and verification of DES, and the application of DES in Automotive industries. Furthermore, the literature research was focusing on specific validation and verification techniques to gather enough information of how the techniques should be performed, and in which type of situation they were applicable.

Abu-Taieh and Sheikh (2007) and Sergant (2013) lists Conventional VV&T technique´s used in simulation. These lists were used as a starting point for the screening process of what validation methods that should be evaluated in this project. The screening was based on the applicability of the validation method and included decisions if sufficient knowledge to use the validation method was held, if the validation method would fit within the time frame of the project, and lastly if the method was accessible to use in the project e.g. if the validation method require a physical counterpart. All the techniques that were considered at first are shown in Appendix A.

3.3 How to evaluate the validation techniques

The simulation project consisted of constantly making decisions to align the project with the intended purpose in each of the different phases. Therefore, a thorough description on how the decisions were made in each of these phases will be presented. Furthermore, these decisions will then be verified and validated, which is why the basis for these verifications and validations will be described in the section afterwards.

3.3.1 Approaches for decision-making

To evaluate the validity and verification in the three steps, conceptual validation, computerized validation, and operational validation, the applicability of decision-making was different in each step and thus different approaches were taken. Motivation for the choice of each approach will be presented in following sections.

In the conceptual model validation, the development team did not have enough knowledge about the system to evaluate it internally. Thus, the decision-making approach in this step was to involve the end-user in the validation process. The approach to have an IV&V team to validate the conceptual model was considered to take up too much resources and the availability of such team was limited, which was applicable in each of the validation steps. Therefore, no IV&V team was involved in any of the phases.

In the computerized model verification phase, it was decided to make the validation internally without end-user interaction. The motivation for this was that the end-user has limited knowledge of simulation coding and could therefore not be helpful in this stage. However, in the operational validation phase, it was decided to include the end user when it was possible. On the other hand, due to limited simulation knowledge of the end-users, they were not considered to contribute to many of the validation methods. Thus, they were not included in every method that were used in the validation process.

3.3.2 Evaluation of validation methods

To evaluate if a validation method is acceptable, each method will be evaluated based on two factors, namely, credibility and cost. Credibility in this case refers to the acceptance and trustworthiness that that the model gets after performing a validation method. Further, the credibility factor can be divided into both external - and internal credibility. To measure external credibility, an evaluation of how the experts and end-user interacted and responded during the validation method was made. However, the internal credibility was held when performing validation methods internally within the development team when the validation method ensured that the code was built in a correct manner. Additionally, internal credibility could also be gained when experts or end-users approved that the model worked as intended. Furthermore, to evaluate the cost of the validation methods, the time needed to perform it was estimated, where a high amount of time needed is deemed costly. Also, the involvement needed from experts was considered, with the assumption that more people involved, the more complex validation. In order to get an overview of how well the different V&V methods performed in the criteria, the credibility will be ranked from 1 (low external/internal credibility) to 5 (high external/internal credibility). The cost will also be evaluated from 1 (internally used and low time consumption) to 5 (external parties involved with high time consumption).

3.4 Qualitative study with the case company

In this section, the method will be explained of how the validations techniques, presented in the theoretical framework, has been used. The chapter is divided into the three different phases that has been stated previously – conceptual model validation, computerized model verification and operational model validation. In each of the different phases there will be different techniques used, which have been carefully selected with the intended purpose and the prerequisites of the model in mind and are listed in section 2.2.6. An overview of what validation method has been used in which phase can be seen in Table 1 below.

Table 1. Overview of where the validation methods have been applied

VV&T Technique	Conceptual model validation	Computerized model validation	Operational model validation
Alpha Testing			X
Boundary Value Analysis (BVA)			X
Degenerate test			X
Extreme condition test/ Stress Test			X
Face validity	X		X
Fault/Failure Analysis			X
Internal validity			X
Regression Testing			X
Reviews	X		X
Structured walkthrough	X	X	X
Symbolic debugging		X	
Syntax Analysis		X	
Traceability assessment	X	X	X
Visualization and Animation			X

3.4.1 Conceptual model validation

Face validation

The *face validation* included several meetings in order to make sure that each of the stations and loops of fixtures were positioned correctly in accordance to what was said when collecting data in the beginning of the project. Further, these meetings were both held in private with the persons responsible for each of the stations, as well is in groups where several experts could have their say on how the conceptual model looked. The purpose of the method was to make it possible for the different experts to discuss with each other and come up with ideas and improvements together, as well as they could give separate thoughts when having private meetings.

Reviews

Reviews in the conceptual model building phase was done to ensure that the goals with the simulation was communicated and understood between the simulation team and end-user. The reviews that were held was done partially informal in short meetings but also in connection with the structural walkthrough with the stakeholders. This validation step was done by explaining the possible use of the simulation model and letting the end-user come up with requirements that were needed but not fulfilled. This was done iterative throughout the building of the conceptual model.

Structured walkthrough

When using a *structured walkthrough* in the conceptual model validation, it can be seen as a part of *face validation*, where experts of the system are participating in a meeting where questions on how the conceptual model looks like were asked. Further, each of the different parts of the system were walked through thoroughly by the development team and where the assumptions made are validated for each part within the system. This enables the experts to validate how the conceptual model looks before the actual operation modelling could begin, and where the final adjustments could be made.

Traceability assessment

The *traceability assessment* was used to compare the requirements that were set before the construction of the conceptual model, with how the conceptual model turned out. After the comparison, the model was adjusted in order to match these requirements. Questions were asked to the experts whether the prerequisites that were stated in the beginning should be changed, or if the model should be arranged in accordance to what was stated in the beginning. This in order to enable optimization and improvements to how things should work in the simulation model.

3.4.2 Computerized model verification

Structured walkthrough

To make sure that the coding had been performed correctly and in accordance to what was stated in the conceptual model, a *structured walkthrough* was performed. In this phase of the model building, this was performed internally, where the code was walked through step by step to see if it matched the logic of the conceptual model. This was a continuous process, where the logic of the code was tested and revised throughout the entire model building.

Symbolic debugging

Debugging was performed iterative throughout the entire process when coding the simulation model. This verification step was made within the simulation team and consisted of identifying bugs by observing the behavior of the simulation. Using the simulation software's debugging tool, the code was then executed step by step to see what caused the bug. Manipulation was then done to try to solve the bug, and after that tested again to see the results. This was iterated until the problem was solved.

Syntax Analysis

Syntax analysis was performed to a large extent with the help of the simulation software's built in functions and did not involve external stakeholders or end-users. If the software did not recognize a syntax or if any name of attributes was not identified, the program would show an error message reporting this error. However, as many names of resources were similar and parts of the codes were used multiple times, a resource could be called for in the wrong part of the code, thus, this had to some extent be done manually by spell-checking parts of the code. However, this was mostly solved by using *symbolic debugging* in an iterative manner.

Traceability assessment

When verifying the code in the model, it is important to always make sure that it has been built with the intendent purpose in mind. Therefore, *traceability assessment* was used as one of the techniques to assure this. It was a continuous process where sub-systems and machines were analyzed as soon as the coding for them was constructed, and then revised in accordance to the objectives that was stated in the beginning of the project. Further, it was used internally with the conceptual model in mind, which in turn was constructed with experts from VCC.

3.4.3 Operational model validation

Alpha testing

The final test for the simulation model, before releasing it for usage to the end-customer, an *Alpha test* was performed. This was done within the development team without involving external parties to ensure that all the components within the system works as intended. In order to conduct this validation experiment, the real settings that had been given from experts throughout the entire project and data gathering was implemented and tested. Afterwards, the throughput and utilization of resources were overviewed and analyzed to make sure that the system was built according to how it should perform. The errors that occurred during this test were further evaluated and corrected before releasing the model to the end-user.

Boundary value analysis

To verify that the simulation model would work even if some settings were changed after the simulation model is finished, tests of how the simulation behaved in different settings within reasonable values from the project's perspective was performed. The settings that were tested were increased line speed, shorter and longer cycle times of the machines, and a higher and lower breakdown setting. Furthermore, the test was done internally without help of VCC, but where the variation tested was known factors that had been identified as interesting to vary in the simulation model when in use.

Degenerate test

One way to ensure that the model behaved as intended when something brakes down or a rare setting occur, is to change certain variables and see if the response from the model is "correct", which is called *degenerate testing*. This was used in the model by changing the cycle times of the machines to see if queues were built up as intended, and if the stations before stops when they are supposed to. Further, it was also used to see if the logic in the buffers was working and if the lines are responding accordingly. For instance, the lines before a buffer must stop if the buffer in front is full and where the line afterwards should stop because they are starved. Worth mentioning is that this was investigated by several of the validation techniques, but where this technique was only used internally in the development team.

Extreme condition test/Stress Test

Stress testing was performed on the operational model without other stakeholders due to the limited knowledge from stakeholders of how to analyze the result of this test. The test was conducted by increasing the variation of the cycle time and increasing the number of breakdowns in the simulation. When doing this, extreme events were forced to occur to ensure that the model worked as intended in those situations as well.

Face validity

In the operational phase, face validation was made together with expert at VCC that had an overview of flow on the main lines. The validation was made through formal meetings were experts were asked if the logic of the flow worked in an acceptable way and in accordance with the conceptual model. Further, informal meetings could also be held to get answers on smaller questions or thoughts on the appearance of the model. This validation method was made iterative where several meetings were held to reach the desired level of functionality of the model.

Fault/Failure analysis

A quite general validation approach to a model, but still very important, is to analyze the input-output transformation, and thereafter trying to locate the error – known as *Fault/Failure analysis*. When using this approach, no specific events are highlighted at the beginning, but where the errors are found dependent on if the output corresponds to the input or not. Followed by this is the analysis of the data, and the identification of where the error in the code occur. This was done by using other validation methods where, for instance, the queues to different machines or buffers could be visualized, and thereby highlighting some of the potential errors in the code. With that said, this method is used internally within the development team.

Internal validity

This validation method was done with limited involvement of other stakeholders but where expertise was asked for to set a reasonable variation of the simulation. The internal validity was used several times during the project in order to validate different parts of the model at different points in time throughout the project. More specifically, when each of the sub-systems within the model was constructed, they were tested by conducting multiple simulation runs to measure if the differences of the throughput were too large, or if they could be deemed as valid. Further, when the model was complete, and all the sub-systems were put together, the internal validity test was performed on the complete system as well. This was done to prevent that, even though the different sub-systems performed according what was desired, no bugs appeared when all of them were connected and the throughput stayed within a reasonable variation.

Regression testing

Regression testing was done throughout the building of the operational model, without any external stakeholders since they could not contribute with valuable information in this stage. The validation method was conducted iterative when adding functions to the model and was used by making multiple runs of the simulation to see if the output and the logic of the simulation model worked as intended when a change was implemented. This was identified by observing the logic using the animations as well as how the throughput was affected by the implemented changes.

Review

In the operational validation phase reviews were conducted in similar manner as in conceptual model validation, together with end-users and stakeholders in formal and informal meetings. The review meetings were held to show and present how the operational model worked and what requirements that were fulfilled. In these meeting the end-users and stakeholders could give input of additional necessary features to the simulation model and ask questions of how the model worked in detail.

Structured walkthrough

The *structured walkthrough* is a validation technique which have been applied in both the previous steps and was used in the validation of the operational model as well. As in the conceptual model validation, the *structural walkthrough* was also coordinated together with a face validation meeting, where experts were gathered. At this point, the complete model was walked through step by step to validate that the logic behaved as desired and was correct.

Trace

This validation method is used in combination with *visualization and animation* to follow a single object through the simulation, which in this case will be used to track how the cars or skillets behaves in the system. More specifically, when any new implementation or change had been made to the system, this method was used internally within the development team to ensure that the system was still working properly. This could for instance show how the cars entered and exited the turntables, or if the they were synced on the lines in a correct manner.

Traceability assessment

The *traceability assessment* is a technique which has been used through all the phases when validating the model. In the operational model validation, it was used to compare the final model and its performance against the requirements to see if the model behaved as intended. The comparison was first and foremost with the code to ensure that the animation behaved according to what was written in the code, but also once again with the objectives set in the beginning of the project. Further, this method was used in combination with other techniques, such as face validation meetings and structural walkthroughs, and thereby also involving the end user and experts.

Visualization and Animation

During the construction of the operational model, animations of the system was incorporated. This was done by building the model in plant simulations 3D environment and using the standard 3D models incorporated in the software. Furthermore, drawings of the plant layout were used to get the correct size and location of the resources as accurate as possible to replicate the system.

Additionally, graphics were added to show specific attributes of different cars, e.g. simulate different kinds of failure rates by giving the cars different colors. Furthermore, this method was used both internally when debugging certain parts in the system, but also when having face validation meeting to explain how the logic worked.

4 Results

In this chapter the results will be presented, where it will start by presenting the findings from using the V&V techniques on the simulation model with cost and credibility in focus. Secondly, how the simulation model was created, and its parts will shortly be described to give the reader a deeper understanding of how the model is constructed. Finally, the results from the experiments on the model will be stated more thoroughly, but where no exact data from them are presented due to confidentiality.

4.1 Qualitative study with the case company

In accordance to what was presented in chapter 3.4, the methods that are used for each of the steps are evaluated with credibility and cost in mind. In order to give the reader a quick overview of how much external/internal credibility the different methods generated to the project, and how time-consuming and costly they were, a table will be presented below each method with the ranking from 1-5 that was described in section 3.3.2.

4.1.1 Conceptual model validation

Face validity

When using *face validity* according to what was stated in the method, the conceptual model was accepted from several parts within the organization, which in turn gave trustworthiness and credibility to it. However, to organize meetings and interviews with several different experts, and coordinating appointments where several of them were included at the same time, was rather time consuming. Therefore, this validation method, in this certain phase, could be useful to create credibility, but can in some cases also lead to high expenses due to the time consumption.

Table 2. Credibility and cost of Face validity in conceptual model

	1	2	3	4	5
External credibility			X		
Internal credibility			X		
Cost				X	

Reviews

As this validation involved communication with end-users and stakeholders it gave better understanding to what was important in the simulation and what the simulation would be used for in detail. Thus, this validation step gave the model acceptance from end-users and stakeholders as they could communicate and argue for why it was important. The involvement of external parties in this validation step made the validation somewhat time consuming if considering that different experts together with the end-user needed to be present at the same time, but still easy to perform.

Table 3. Credibility and cost of Reviews in conceptual model

	1	2	3	4	5
External credibility				X	
Internal credibility		X			
Cost				X	

Structured walkthrough

The validation method *structured walkthrough* in the conceptual model validation phase was perceived to result in both credibility and acceptance of the model to a large extent. This because the meeting gave good interaction with the stakeholders to ensure that the conceptual model and the results from the data gathering interviews were translated correct to the conceptual model. As this method was depending on including experts and stakeholders together in structured meetings, the method was considered time consuming and therefore also costly.

Table 4. Credibility and cost of Structured walkthrough in conceptual model

	1	2	3	4	5
External credibility					X
Internal credibility				X	
Cost					X

Traceability assessment

When using the *traceability assessment* to compare the conceptual model to the requirements that was stated in the beginning of the project, it made it possible to assure that the conceptual model was built according to what was said from the experts and end-users. Hence, the credibility of the model increased, as well as it is crucial to perform this kind of validation in order to make sure that all the future steps will align with the objectives. If considering that this method both is performed together with experts and internally within the development team, the technique is somewhat time consuming.

Table 5. Credibility and cost of Traceability assessment in conceptual model

	1	2	3	4	5
External credibility			X		
Internal credibility			X		
Cost			X		

4.1.2 Computerized model verification

Structured walkthrough

By making continuous walkthroughs step by step when building the model and creating the code, the credibility of the model increases internally. However, because that this validation technique was only used internally and no involvement of external stakeholders, the acceptance was not affected externally. On the other hand, as many of the other techniques, it was important to continuously adapting the code and the logic of the simulation to what had been decided in earlier phases from the experts and end-users. With that in mind, it was still a quite time-consuming activity to walk through every bit of code, not only once, but several times to ensure that everything was constructed as intended.

Table 6. Credibility and cost of Structured walkthrough in Computerized model

	1	2	3	4	5
External credibility	X				
Internal credibility			X		
Cost			X		

Symbolic debugging

The result of the debugging process was a more correct code that worked as intended. Thus, it gave more credibility to the development team that the code worked. However, since there was limited involvement of other stakeholders in this verification step it did not contribute to greater acceptance or credibility to the end-user. On the other hand, symbolic debugging was still necessary to get a functional operational model.

Table 7. Credibility and cost of Symbolic debugging in Computerized model

	1	2	3	4	5
External credibility	X				
Internal credibility					X
Cost			X		

Syntax analysis

As a result of this verification method, the correct resource was called for in the correct part of the simulation code. The process of checking errors of syntax manually was experienced as vastly time consuming. Therefore, the help of having the simulation software to display syntax errors was to great help. This verification method did not directly add credibility or acceptance of the simulation model to the stake-holders and end-users as they were not involved. However, the method was crucial to ensure that the code worked in the correct way and can thus be seen as it gave internal credibility to the simulation model.

Table 8. Credibility and cost of Syntax analysis in Computerized model

	1	2	3	4	5
External credibility	X				
Internal credibility			X		
Cost			X		

Traceability assessment

This kind of validation technique was important in order to assure that the coding was done with the correct logic in mind. Further, this gave internal credibility to the model in terms of that the coding always was made according to what was stated in the conceptual model and therefore also what was said from the experts at VCC. However, the validation technique in this certain phase was nothing that was notable from an external perspective, which therefore did not increase the external credibility to the model. Instead, it was used continuously when building the model, and increasing the validity of the model continuously. Furthermore, the cost of such validation technique is difficult to evaluate due to that it was used continuously, and that it is inevitable to use when building a model according to certain objectives.

Table 9. Credibility and cost of Traceability assessment in Computerized model

	1	2	3	4	5
External credibility	X				
Internal credibility			X		
Cost		X			

4.1.3 Operational model validation

Alpha Testing

Alpha Testing was one of the last validation techniques used in the V&V phase. When the alpha testing was performed the testing gave credibility and acceptance internally from the development team as overall functions was tested together as a whole. This did not give any external acceptance since external stakeholders were not involved. However, the test was necessary to perform to ensure the function and the user experience was acceptable. Functions that could be added to enhance the user experience was added in this stage. After the alpha testing the simulation model could be handed over to the end-user for further testing.

Table 10. Credibility and cost of Alpha testing in Operational model

	1	2	3	4	5
External credibility	X				
Internal credibility					X
Cost		X			

Boundary value analysis

The result from the boundary value analysis was some identification of problems with changing the line speed. This caused trouble with clashing MUs on the line which could be corrected. As a result of this, the model could be considered more functional and possible to use with confidence in the set boundary value tested. The test was easy to perform and did not require extensive time or involvement of stakeholder.

Table 11. Credibility and cost of Boundary value analysis in Operational model

	1	2	3	4	5
External credibility	X				
Internal credibility				X	
Cost		X			

Degenerate test

By conducting this testing, the logic of the machines and buffers was ensured to work properly. However, one of the main purposes with this testing was to evaluate how the waiting time within the buffers was calculated. More specifically, the buffers were said to have a dynamic waiting time, depending on the capacity and thereby the length of the transportation on the conveyors. Because this was done internally and continuously throughout the project, it was not a validation technique that gave trustworthiness or acceptance to the external parties. Instead, it made it possible to build the rest of the model in a correct manner with the logic that was intended, and therefore giving trustworthiness to the complete model. With that said, this is a technique that was deemed necessary to perform continuously and not only when the complete model was built, and therefore also somewhat time-consuming.

Table 12. Credibility and cost of Degenerate test in Operational model

	1	2	3	4	5
External credibility	X				
Internal credibility				X	
Cost			X		

Extreme condition test/ Stress Test

The result of the stress testing gave confidence that the simulation would work in starved and congested conditions, thus correctness of the model was ensured. The test was relatively easy to conduct and did not require extensive preparation and analysis time. Therefore, this test was considered inexpensive to perform. The test could not be considered to give external credibility to the model since it did not involve other stakeholders. However, the test was required to ensure the correctness of the model and therefore establishing an internal credible model.

Table 13. Credibility and cost of Extreme condition/stress test in Operational model

	1	2	3	4	5
External credibility	X				
Internal credibility				X	
Cost	X				

Face validation

The result of this validation method in the operational phase gave the simulation credibility since expert and stakeholders could give their input to the operational model and the correct function of the simulation model could be achieved. However, as in the conceptual model phase this validation method occupied a lot of resources and required the involvement of experts and stakeholders to make this validation. Therefore, this method was quite time-consuming due to the coordination to involve as many people as possible. Worth noting is that many of the meetings that were held could be perceived as informal meetings, and therefore not as time-consuming as the formal meetings.

Table 14. Credibility and cost of Face validation in Operational model

	1	2	3	4	5
External credibility				X	
Internal credibility				X	
Cost				X	

Fault/Failure analysis

As stated in the method, this approach of validating the model was used as a quite general validation method where the input-output transformation in the model was analyzed. This resulted in that the model could be partially tested, where each of the sub-systems had a specific setting of input parameters and therefore also an expected output. This in turn made it possible to see if the model behaved as intended or if there were any major errors in the coding. Worth mentioning with this method, is that before it was used in this case, each of the different stations within the sub-system had already been tested and validated somewhat with other methods. Thus, this method gave an indication if the combination of sub-systems gave a reasonable output.

Further, this was something that did not generate credibility and acceptance to the model externally, due to that it was used internally with no other party other than the development team. However, it facilitated the creation of a model that performs according to the set objectives, and therefore internally generated credibility and acceptance to the model. Regarding the cost of using such method, the time spent on doing the simulation runs was quite extensive due to the high demanding model. However, when locating the errors that could be found from doing the simulation runs, other validation techniques were mainly used, and therefore not burden the time consumption of the *fault/failure analysis* specifically.

Table 15. Credibility and cost of Fault/failure analysis in Operational model

	1	2	3	4	5
External credibility	X				
Internal credibility			X		
Cost			X		

Internal validity

This validation method was easy to perform due to the limited involvement of stakeholders and the effortlessness and speediness in which it could be checked. The result of this validation method gave the simulation model additional credibility and knowledge that there were no rare occurrences that would freeze the simulation model. Furthermore, the validation method gave confirmation that the desired throughput was reached. Additionally, it generated acceptance to the simulation model from the stakeholders as they could see the variation of throughput and that the throughput reached the set target.

Table 16. Credibility and cost of Internal validity in Operational model

	1	2	3	4	5
External credibility			X		
Internal credibility					X
Cost	X				

Regression testing

The result of regression testing was that faults in new functions of the model could quickly be identified and reworked to function as intended. Thus, the method was important to use to identify problems with the model when changes were made. Additionally, this validation method gave the model credibility to the development team, that the recently added functions worked as intended without interfering with the rest of the simulation model. However, due to the lack of interaction with external stakeholders, the validation method did not add additional acceptance or credibility for the end user but was necessary to conduct in order to build a correct simulation model.

Table 17. Credibility and cost of Regression testing in Operational model

	1	2	3	4	5
External credibility	X				
Internal credibility				X	
Cost		X			

Reviews

From these validation sessions, the stakeholders were involved and could see what requirements were fulfilled and to what extent it was fulfilled and resulted in increased acceptance of the model. However, to some extent these meetings resulted in some level of rejection when requirements of stakeholders were not interpreted in the right way. On the other hand, this contributed to a dynamic path forward in the project where parts that was not satisfactory could be corrected to ensure that the correct simulation model was built. The involvement of stakeholders resulted in a bit time-consuming validation method but still a crucial part for correct development of the simulation model.

Table 18. Credibility and cost of Reviews in Operational model

	1	2	3	4	5
External credibility				X	
Internal credibility		X			
Cost					X

Structured walkthrough

When walking through the simulation model with experts at VCC, each of the experts on different fields could easily have their say on how things looked and if they thought any changes were needed to be made. When giving the experts a chance to come up with final adjustments, and explaining every step of the operational model, the credibility increased. However, explaining every step thoroughly was quite time consuming at some points, but also a necessity to ensure that the model was built correctly. Therefore, it is to some extent deemed as a costly method to use, but also inevitable if wanting to involve the end-users and experts in the validation process.

Table 19. Credibility and cost of Structured walkthrough in Operational model

	1	2	3	4	5
External credibility					X
Internal credibility					X
Cost					X

Trace

When applying trace as validation method this validated if the model behaved as intended. As this was done internally it did not gain any external credibility. However, it was seen as necessary for the simulation team to do to ensure the correct function of the code. Moreover, this method was relatively easy and efficient to perform as it did not require any setup and did not involve external stakeholders.

Table 20. Credibility and cost of Trace in Operational model

	1	2	3	4	5
External credibility	X				
Internal credibility				X	
Cost	X				

Traceability assessment

It has not been used as a separate tool, but instead combined with other validation techniques such as *visualization and animation* and thereby increasing the credibility and acceptance of the model internally. In terms of cost and time spent using this technique, it is a combination of other methods such as looking at the animation and having structured walkthroughs with experts of the system. Therefore, it is deemed as difficult to say if this certain validation technique is costly or not, or if this must be based on several other techniques as well. However, both external and internal credibility are perceived to be achieved when validating the model with the code and the objectives, both internally as well as involving external parties.

Table 21. Credibility and cost of traceability assessment in Operational model

	1	2	3	4	5
External credibility			X		
Internal credibility			X		
Cost			X		

Visualization and Animation

There were multiple advantages when using animation in the operational model. The first advantage that could be identified was the pedagogical use of the simulation model. Technical experts that did not have previous simulation experience could quickly understand the logic of the flow in the simulation. This made it easy for them to confirm or reject if the model was working in accordance with their described logic. A second important result was the acceptance that was gained from showing animation. This gave the end users a good understanding of how the model worked and was therefore easy to accept. To build the simulation model with animation required additional resources which thus could be considered costly. However, as the animation contributed to let people involved rapidly understand the flow and the logic of the model, the value of the validation method could be considered to increase.

Table 22. Credibility and cost of Visualization and animation in Operational model

	1	2	3	4	5
External credibility					X
Internal credibility			X		
Cost					X

4.2 Simulation model

In this section, the results of the verified and validated simulation model will be presented. First, the results from the preparation phase, such as problem formulation and the objectives will be stated. Secondly, the final appearance of the model will be shown together with a description of the resources used. Finally, a description of how the model was used to conduct experiments on buffer sizes, throughput and WIP will be given, which is connected to the second of the two project objectives.

4.2.1 Preparation

The first step in the preparation phase was to identify to what extent a simulation model could be used in an early phase and construct the problem formulation for the project. As stated previously, this was done together with the end-user and iterated throughout the entire project. Moreover, a set of objectives were stated which the simulation project should aim to achieve in order to meet the demands and expectations from the end-user. These objectives are as follows:

- Get an estimation of how an ideal system would perform
- Get an estimation of WIP of the system
- Get an estimation of throughput of the system
- Get an estimation of how variation of buffer sizes affects the throughput and WIP
- Get an estimation of necessary fixtures needed in the systems closed loops
- Get a visual overview of the systems main line and layout to use in communicative purpose.

In order to construct a model that would be able to achieve these objectives, a conceptual model of the simulated system was built. This can be seen in *Appendix C*, and is first and foremost used in this project as a visual aid to get an overview of how the layout should be built, and where the different resources should be located in relation to each other. It also explains how some of the basics in the logic should work to achieve the objectives previously stated, such as where the loops of fixtures should be located.

4.2.2 Model Building

As previously stated, the model was created with close collaboration with the people at VCC to verify and validate that everything is build according to the objectives. Further, the model created can be shown in Figure 4, where the model was constructed based on four different sub-systems. Each of them was evaluated and tested independently and together when every sub-system was put together.

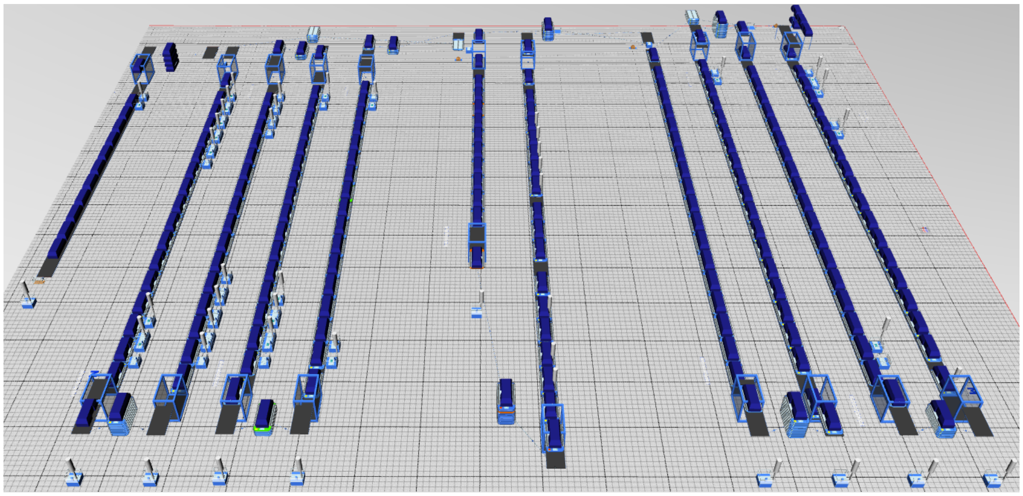

Figure 4. Overview of the Simulation model

To model the system in the most efficient way, the already existing resources in the program have been used, but where the logic in them have been changed to match the requirements. Table 23 presents the resources in the program that have been used to simulate the entire system with a short description on how they have been used.

Table 23. Resources used in the simulation model

Resource	Description
Lines	A continues moving line with manual stations with no breakdowns
Continuous stations	Stations located next to the line that simulates a continuous moving station with a technical availability
Stop and go stations	Stations where each car moves into completely before being processed, and then moves on after processing is done
Acceleration	An acceleration out of each of the elevators to sync the cars with the line speed
Deceleration	A deceleration out of each of the elevators to sync the cars with the line speed
Turn tables	Turn tables after each elevator to simulate the movements in the buffers between the lines
Elevators	Moves the cars on/off the lines and travels between the lines and the turntables
Closed loop skillets	A loop that reuses the skillets that the cars are traveling on instead of creating new
Andon Stations	A station that stops the line and simulates all the manual stops that are present during the assembly

4.2.3 Analysis

After consulting with experts at VCC a simulation time of 40 days per simulation run was used to get statistical accurate data. Further, a warmup of five days indicated a stable WIP and throughput of the system, which therefore will be used before gathering statistical data from each of the experiments.

The first experiment that was performed on the model was to construct a code to sample and calculate the mean WIP in the system. This was carried out by implementing a solution which took data each time a car entered and exited the system, and then calculated the cars in the system at that specific time. This data was then saved into a data table in which the total value was calculated and divided by the number of samples taken. By doing this, it is possible to both look at the WIP at certain points in time, but also to make multiple simulation runs and make comparisons between each of them and calculate the mean WIP. As mentioned in the methodology, the WIP was evaluated each time when performing experiments on the buffer sizes, but where an example of how the WIP varies during 40 simulation days can be seen in Figure 5. This graph can be visualized for each of the runs, and where each of the data points in the graph are used to calculate the average WIP. The x-axis represents the simulated time in *days:hours:minutes:seconds*, and the y-axis is the number of cars in the system. Due to confidentiality, no numbers can be presented, but where the valleys in the graph occur because of breakdowns of some resources where the lines in the end can continue running and empties their buffers. This leads to fewer cars in the buffers, and therefore also a decrease in WIP.

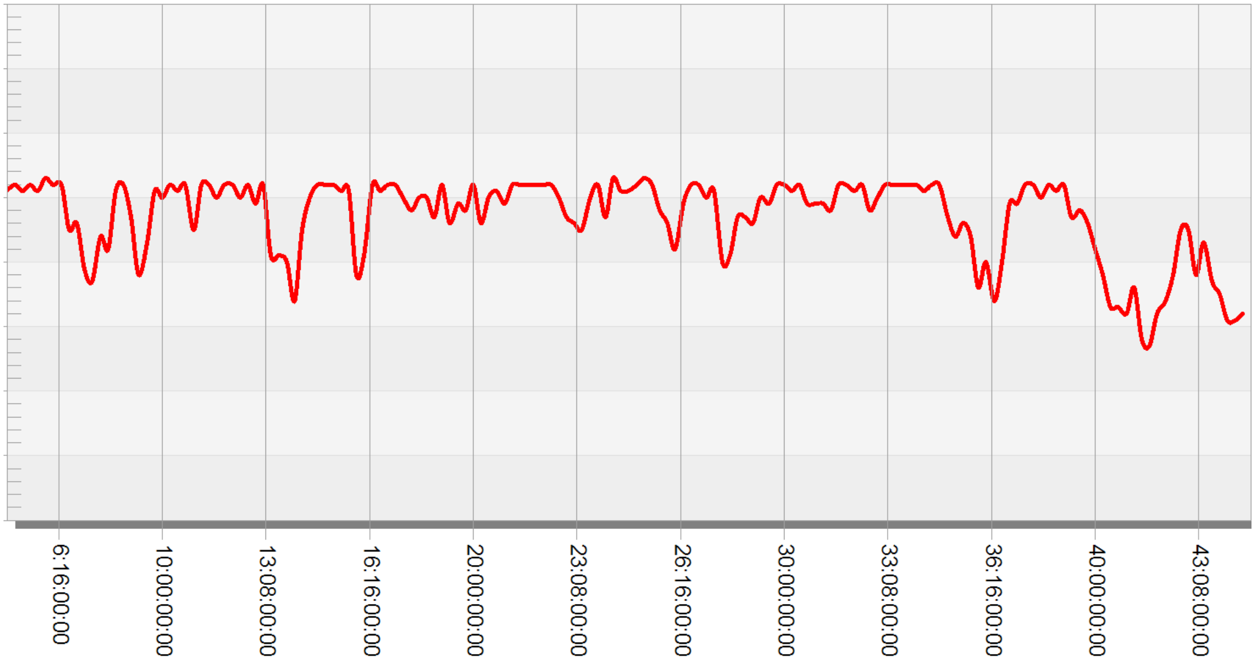

Figure 5. Variation of WIP when simulating 40 days of production.

After the implementation of a WIP counter in the system, experiments on the buffer sizes were performed. Within each of these runs, statistics could be found on how occupied the buffers have been. This can be seen in Figure 6, where the x-axis shows the number of manufacturing units (MU), which in this case is cars, and the y-axis is the time portion of how many products that are in the buffers. The output from these graphs indicates where the bottleneck is in the system and could help determine where changes in the layout must be made, or if the line speed or cycle times must become faster.

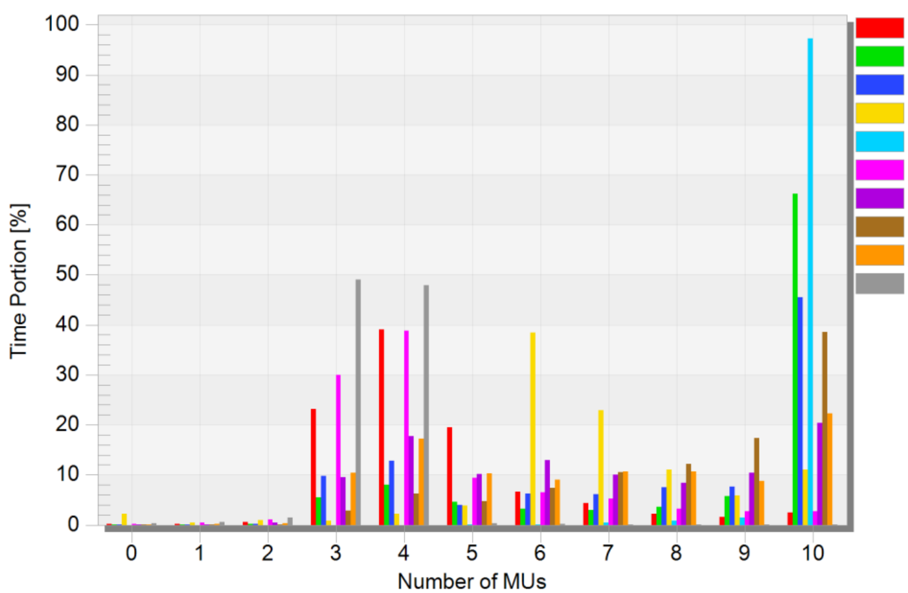

Figure 6. Time portion distribution of number of cars in buffers.

5 Discussion and Analysis

In this chapter, a discussion of how the model was built and how the model has been affected from certain situations that have appeared throughout the project will be held. Further, an analysis of the challenges in the validation process of the simulation model will also thoroughly be made to give a deeper understanding to how these affected the end-result of the project.

5.1 Verification and Validation of model

As mentioned in chapter 2.2.3, there are different approaches to choose from when taking decisions and validating a model, which all have different pros and cons. In this project, the main approach that have been used is to verify the model internally within the development team. This due to several reasons, but mainly because the lack of knowledge of the simulation software within the department that the project was performed at. In turn, this might have affected how biased the verifcation of the simulation model was, and if some decisions were taken to ease for the building of the model or if they helped in creating the best solution possible. The other two methods that was mentioned was either involving the end user of the product, or to have a separate VV&T team – which both generates acceptance from the organization and credibility to the model. However, there were no possibilities of involving a third party who had enough knowledge about our simulation model whom could verify and validate the model. Therefore, the end users and experts of the system were instead tried to be involved as much as possible in order to create acceptance within the organization. However, there is a risk that the experts and end-users at VCC are biased and will therefore accept a model that shows what they want to see. Thus, they might more easily accept a model showing good result and reject a simulation model which shows unwanted results.

As the end-users were involved as much as possible when validating the model, this could also be a more costly approach than trying to verify and validate everything within the development team. However, the involvement of experts and end-users throughout the entire project also made it possible for them to interact with our decisions and hinder wrong assumptions. This in turn might have spared the development team time from making larger errors that would have been even more time-consuming and costly to correct in the end.

As the project started, stating a clear scope and problem formulation were identified as important through literature research. Therefore, a lot of time was invested in this phase to avoid problems in later stages. However, due to that this thesis was carried out in such an early stage, simultaneously as the ideal state project was developed at VCC, the scope changed to some extent in the meantime. Therefore, this made it difficult to work directly towards the objectives in a straight path, where iterations on how the project at VCC changed were needed. Furthermore, this also showed the importance to continuously communicate with stakeholders to enable that the model is built in accordance to the updated system. Although there was a need to iterate and update the information and objectives of the project, the time spent on stating clear objectives in the beginning made it possible to create a foundation on what to work towards and was therefore identified to be of greatest importance.

When performing validation and verification methods on the simulation model three interesting categories of validation and verification method could be identified. How each of the V&V

techniques has categorized is summarized in *Appendix D*. The first one was the validation method that was crucial for the development team to perform to ensure the functionality of the simulation model, which is called “Model Building Tools”. Examples of these method are, internal validity, boundary value analysis, extreme condition testing. These methods did not involve stakeholders but were important to conduct to see that the model did not have bugs or would freeze when simulating. The methods could be seen as useful tools for building a simulation model, however since stakeholders were not involved in these methods it could not be considered to increase the acceptance and credibility of the model externally. These methods were often perceived as easy and non-time consuming to perform as it was seen as a way to build the simulation model.

The second type of validation methods involved the stakeholders to a much greater extent has been called “Requirement Validation”. These validation methods were Review, Structured Walkthrough and Face Validation, and were very important for the validation process as these methods were essential to know that the model was functioning correct and as intended. Since the simulation model does not have a physical counterpart the validation methods including experts and stakeholders became much more important since this was the only source of fact that was known of the system. Validation methods that involved stakeholders and experts of the simulated system forced the project to have continuous dialogue. The communication revealed information that had been missed during the data gathering phase and could with the help of these meetings be brought to surface and corrected in time. This in turn lead to a better simulation model with greater accuracy of the simulated system. Additionally, by involving the stakeholders, they could better get an understand of how the simulation worked during the project and see what its limitations were and thus getting acceptance and credibility to the model. The methods performed in this category perceived as more time consuming since it involved scheduling meetings and extensive preparation was needed to conduct these validation meetings.

The third type of validation method noted in this project were methods that included comparison of data which has been called “Data Comparison Validation”. However, due to the lack of physical counterparts of the model, these types of validation method were highly limited in the project. In many cases the input to the simulation model was the target KPIs and could therefore not be compared against any confirmed data. On the other hand, the combination of these input data gave a result to the total throughput which worked as a crucial verification method to see how the combined performance of subsystems worked together. The validation methods in this category was perceived as the most trustworthy verification methods. The reason for this was that comparison of numbers are highly objective and was much more unbiased compared to many of the other validation and verification method.

The division of credibility into external and internal credibility made it possible to evaluate the validation methods even though no external party was involved. However, it was difficult to tell which of the two that generated most acceptance and trustworthiness to the model. At first, the external credibility was assumed to be of most value when validating the model due to that the end-user and experts could be integrated in the decision making. However, as the model was built, the importance of internal V&V was discovered to be of more value than it was assumed to have in the beginning. Without the internal credibility that the development team gained when verifying and validating the model, it would have been built with no assurance that it was made according to the objectives, as well as the confidence in the model would have decreased drastically. With this in mind, both internal and external credibility were identified to fulfill different purposes in the model building, but where each of them created credibility to the model in different manners.

The evaluation method, to use a scale from 1-5, was used in order to create a more visual picture of how the methods performed. Further, they were also used as a tool when verifying and validating the model to give insights in how much credibility they generated, and therefore how well they were interpreted from both VCC as well as the development team. Another way of measuring this could have been to apply a hierarchical ranking system to each of the methods and give each of them a number from 1-14. By doing this, a clear scale on which of methods that performed best in relation to each other could have been created. However, this would only allow for a relative scale with no consideration to their actual cost or how much credibility they gave to the model. For instance, if all the methods would have been very costly, they would still have to be ranked from 1-14 and therefore generating misleading information. With that said, the way of how the evaluation was created allowed for both relative interpretations, but also enabled an evaluation that highlighted if they generated much or little credibility and how costly they were.

The use of multiple validation method has contributed to a simulation model which has gained acceptance and credibility among the stakeholders. However, this does not mean that the simulation model is validated. Sergant (2013) argued that simulation models cannot be considered validated unless data is compared against a physical counterpart. Thus, according to Sergant this simulation project cannot be considered validated since the physical counterpart does not exist. In this manner the development team agrees to this statement as it cannot be compared and monitored if the simulation replicate a real production facility. On another note, the simulation model built in this project was validated using several validation methods that were still applicable for models that does not have physical counterparts and can thus be seen as validated simulation model, but not confirmed against a real system. Additionally, as mentioned by Law (2006) and Banks et al. (2005), the simulation model can only be validated against the set objectives. The model developed in this project will not be useful to predict detailed information of how the system behaves, but rather give an estimation of how to dimension buffer sizes and fulfill the other objectives set for the project.

Another matter to discuss is the fact that the project was to a large extent performed on site with the customer. This made it possible to set up quick formal and informal meetings with experts. The validation method including experts and stakeholders would be much more time consuming if the project would have been done off-site as it was seen necessary to have face-to-face meetings when reviewing the conceptual model. However, during the project, the covid-19 virus stopped the project from being on-site for a period. When this occurred the validation of the simulation model became much more difficult as people knowledgeable of the system were less available and could only be used to a limited extent to validate the model. As a result, many of the validation method could only be used briefly and thus make the validation somewhat more questionable. This also raise some questions for the future; how the restrictions with physical meetings will become a part of the future work places and how this will affect future validation processes.

The change of how meetings are conducted due to the travel restrictions did affect the result of this thesis. To some extent, it became more difficult to perform certain types of V&V methods e.g. that it was hard to give a visual presentation of the simulation model, and that the interpretations of how the stakeholders reacted to the model was limited. However, to perform meetings in this manner might become much more common in the future. This due to both the covid-19 virus and future pandemics, but also the sustainability demands from the end-users and customers. By decreasing the traveling and introducing online meetings on a more regular basis, it would enable a more sustainable behavior. However, these types of meetings need to be developed to minimize the negative effects on the end-products and to ensure that the product requirements still are met even though the physical meetings decreases. As in this case, the online meetings were not optimized to enable visualization and animation in the V&V, which could be a potential source of error in the later stages of the project.

5.2 Model building

One important aspect to discuss is how the prior knowledge of the development team within the simulation software affected the end result of the simulation model. With only knowledge from another simulation software, called Automod, the commands and simulation language were different between the different programs, and therefore acting as a barrier in the start of the project. In addition to this, no expertise that could provide examples on how a model should be built was easy to access on site. With this in mind, there was a need to start doing the simulation model at a certain point in time, independent of if the team was ready or not, to be able to perform different validation techniques on the simulated system. Therefore, qualified guesses on how it was supposed to be built in the best possible manner had to be made in order for the project to continue. When gradually learning throughout the project, some commands could have been used with more care in the beginning of the project, but which were too time demanding to change towards the end. Moreover, the prior knowledge of Automod might also have led to building the model in a way that was more suitable for that simulation software, rather than adjusting the building to Plant simulation.

When discussing the experimentation on the simulated system, one of the largest issues was the time consumption of performing them. Because of the large amount of WIP and animations within the modelling, the simulation required high capacity computers to run the simulations in a reasonable time interval. However, once again, due to the lack of knowledge within the simulation software, there might have been ways to build the model in a more efficient manner and thereby reducing the capacity required to perform the simulations.

Another decision that also affected how the modelling was constructed was if it was supposed to be used as a tool to perform experiments on, or if it was aimed to act as a visualization tool to show the management. In this case, more focus was aimed towards creating a visually pleasant model, and thereby taking decisions that makes specific events in the model behave as in reality, and not focusing on only providing the correct output from the model. This resulted in some logic that demands more capacity when simulating and thereby also reducing the possibilities to perform extensive experiments. Furthermore, this also questions to what extent this model can be used and how well the objective to be able to perform experiments on the buffer sizes have been met.

As this project was to simulate a factory in a very early stage in which a lot was not defined, this became a challenge as well. In this stage, the so called hardpoint were decided, but not the exact location and to what line the different station should belong. This put requirements on the simulation model to be flexible and possible to continuously be developed when the project was finalized. This demand was translated in the computerized model to be modular and easy to change. Furthermore, this was also the case when it came to the input of data. More or less all stations lacked information of the cycle times and if there would be variation between the variants. Thus, the model was built with temporary input data that could be updated when more information about the system was known. Thus, the experiments on the buffer sizes could be questionable due to the accuracy of the input data to the machines and lines. The buffer sizes are dependent on how large the output from each of the lines are, and therefore corresponds to the cycle times and the availability of the machines, as well as the speed of the main lines, sync stations and elevators. When having inaccurate input data, it also leads to inaccurate results in the experiments on the system, which in turn might be too uncertain to base decisions on. Furthermore, dependent on where each of the hardpoints are located in the system, the output will be different. Therefore, the uncertainty of where the machines should be in the system leads to uncertainties in the results as well. In order to use the simulation model as a decision-making tool, the input data needs to be updated as it becomes available.

6 Conclusion

One of the more central conclusions from this project is the great importance of a continuous and stable communication with the stakeholders. This in order to, simultaneously as the simulation model is being built, verify and validate each of the steps that are taken and to continuously assuring that the project is aligned with the objectives that are stated in the beginning from the stakeholders. In addition, it is even more important to involve them when not having a physical system to compare and retrieve data from. This due to that this is the only source of information on how the system should behave and what the input-output transformation should be.

In connection to communication with stakeholders, during the project the closeness of working with the project on site was identified as a great advantage, as contact with stakeholders, experts and end-users could easily be maintained. Less effort was thus needed to conduct several validation meetings, compared to making the project off site.

To achieve a credible model, the possibilities with the simulation model had to be identified to determine how the model could be used and what the purpose of it should be. Therefore, putting time into the problem formulation phase and completing the objectives for the model was deemed as highly important to create a basis for what the project is meant to fulfill.

When connecting to the first of the two objectives of the report, it was deemed as possible to validate the model in accordance to the intended purpose of the model. Regarding the second objective, it could be seen that a simulation model on this stage and level could be used to give an overview of the production and retrieving approximation of throughput, buffer sizes, WIP and number of fixtures.

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Appendix A

VV&T Technique	Accepted	Discarded
Face Validity	X	
Degenerate test	X	
Internal validity	X	
Structured Walkthrough	X	
Desk Checking	X	
Syntax Analysis	X	
Reviews	X	
Turing Tests		X
Correctness Proofs		X
Data Analysis		X
Basis- Path Testing		X
Graph- Based Testing Methods		X
Execution Testing		X
Regression Testing	X	
Equivalence Partitioning		X
Boundary Value Analysis (BVA)	X	
l Checking	X	
Bottom- Up Testing		X
Top- Down Testing		X
Visualization and Animation	X	
Field Testing		X
Functional (Black- Box) Testing		X
Stress Testing	X	
Sensitivity Analysis		X
Structural (White- Box) Testing		X
Submodel Testing	X	
Symbolic Debugging	X	
Cause- Effect Graphing		X
Interface Analysis Techniques		X
Fault/Failure Analysis	X	
Traceability Assessment	X	
Trace	X	
Graphical Comparison		X
The Lambda Calculus		X
Acceptance Test	X	
Alpha Testing	X	

Appendix B
Questions for station experts

The following list with questions was asked to station experts to document how the flow of the ISF is intended to look. The question was asked during individual interviews with each expert.

Layout

What line is the station positioned:

Stations position / constraint: Before station / after station

Station length:

How many stations (within the station):

Buffer sizes:

Technical information

Cycle time:

Availability:

MTTR:

MTBF:

Characteristics of failure mode? E.g. constant or exponential.

Failure rate on car:

Is this repaired on the main line in a station?

Additional questions

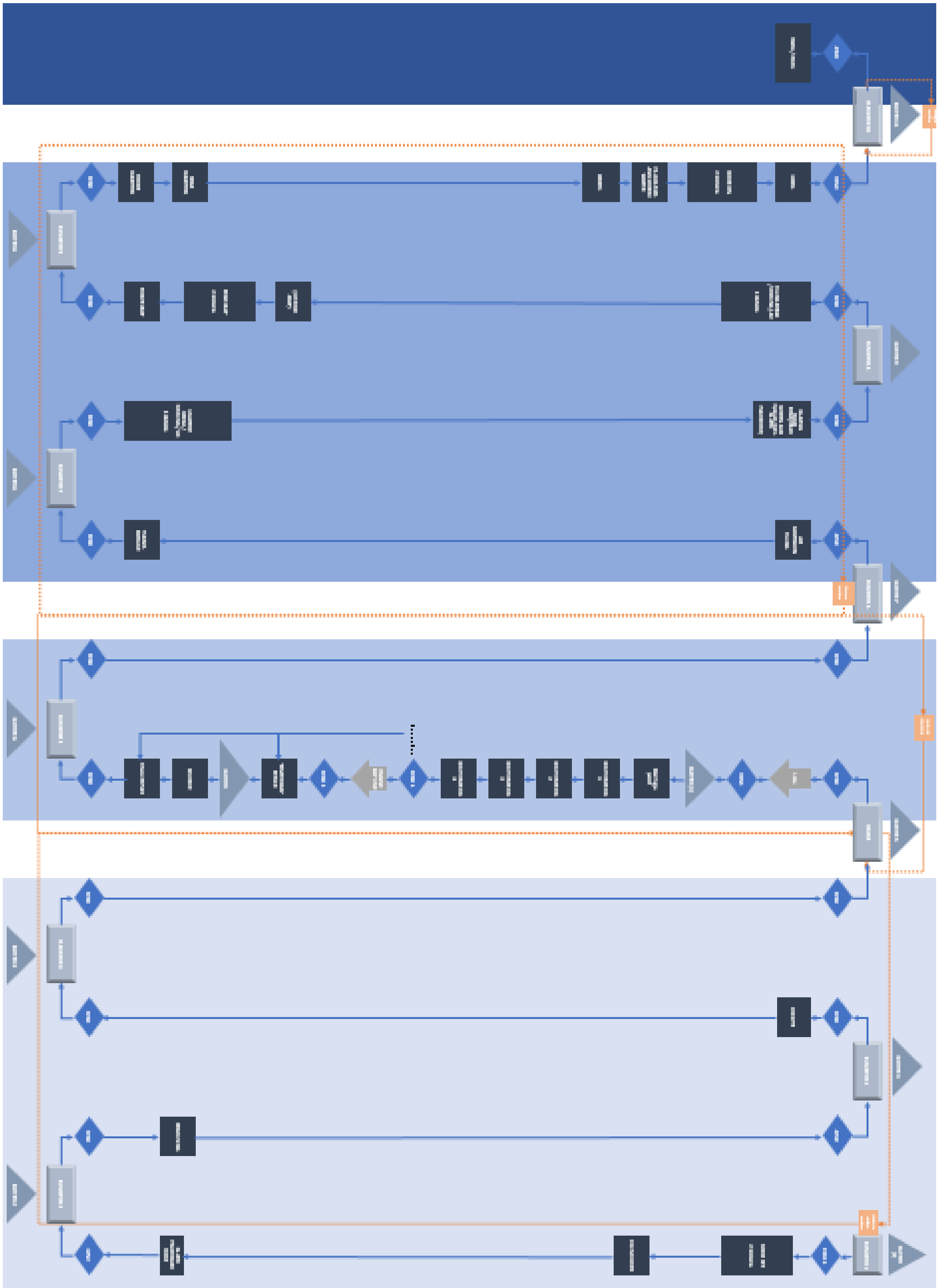
Are there any fixtures or additional parts that travel with the product in a closed loop?

Is the station continuous or stop and go?

Buffers connected to the station or line?

Name conventions of the station:

Appendix C



Appendix D

	Internally	Externally	Model-building tools	Requirement validation	Data comparison validation
Alpha Testing	X		X	X	
Boundary Value Analysis (BVA) (Operational)	X			X	
Degenerate test	X		X		
Extreme condition test/ Stress Test	X		X		
Face validity (Conceptual)		X		X	
Face validity (Operational)		X		X	
Fault/Failure Analysis (Operational)	X		X		X
Internal validity	X			X	X
Regression Testing	X		X		
Reviews (Conceptual)		X		X	
Reviews (Operational)		X		X	
Structured walkthrough (Conceptual)		X		X	
Structured walkthrough (Computerized)	X			X	
Structured walkthrough (Operational)		X		X	
Symbolic Debugging (Computerized)	X		X		
Syntax Analysis	X		X		
Trace	X		X	X	
Traceability Assessment (Conceptual)		X		X	
Traceability Assessment (Computerized)	X			X	
Traceability assessment (Operational)	X	X		X	
Visualization and Animation (Operational)	X	X	X	X	

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