Roadmap of Virtual Commissioning Inertia

An Investigation of Technical and Non-Technical Fields of Action

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Roadmap of Virtual Commissioning Inertia

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Abstract

Virtual Commissioning (VC) enables simulation of the combined work of mechanical, electrical, robot and automation engineers prior to commissioning of the real production equipment. Hence, testing of areas like collisions, PLC and robot code can be performed in risk free virtual environments and thus, errors can be detected and corrected early in the development phase of the production equipment. Effectively, both the time and the cost of commissioning will decrease significantly. In addition, advantages like operator training, increased knowledge about the equipment, a more mature and optimized system prior to installation is enabled. Nowadays, the commissioning phase of a production system accounts for 25% of the total project time and research has shown that VC can decrease the commissioning time with up to 75%.

However, despite all advantages and existing solutions that enables VC, it is not a standard among manufacturing companies nor production equipment providers to use VC today. Therefore, we wanted to investigate why VC is not a standard today.

There are many barriers and challenges that must be solved prior to successful implementation of VC. A global survey concerning simulation concluded that eight fields of action must be addressed in order to facilitate the use of simulation. These eight fields address barriers and challenges and they are assumed to apply for VC too. The fields are categorized into four technical and four non-technical fields of action. The technical concerns: model re-use, modeling efficiency, integration and usability. The non-technical concerns: work-flow, education, acceptance and collaboration.

The purpose of this project is to investigate barriers that prevent VC from becoming widely used in the industry. Thus, each field of action was researched to better understand why VC is not commonly used. In addition, the objective of the project is to provide an investigation regarding the technical and non-technical fields of actions and how each of the parties along the value chain relate to each field. Therefore, the following research question was formed. What barriers are preventing VC from gaining momentum and becoming widely used by the industry?

Through our interviews we did not find any company that currently use VC. We conclude that it generally is the non-technical fields of action that contain barriers that prevent VC from becoming a standard in the industry. Especially, it is the organizational related barriers that are the most severe. Nowadays, there exist technical solutions that enables VC and the technical fields of action mainly treat modeling efficiency improvements. However, interoperability is considered to be the most severe technical barrier towards VC and is therefore an important area to improve. Nonetheless, we conclude that the technical barriers are considered less severe compared to the non-technical in terms of enabling VC to becoming widely used.

Keywords: Virtual Commissioning, Fields of Action, Simulation, Logic Enabler, Industry 4.0
Sammanfattning

Virtuell Idriftsättning (VC) Virtual Commissioning är ett aktuellt tillvägagångssätt som underlättar installationen av nya maskiner för producerande företag och därmed hjälper att möta ett tuffare produktionsclimat. VC minskar risken, tiden och kostnaden för idriftsättningsprojekt, eftersom att man knyter ihop olika ingenjörsdiscipliner till en gemensam simuleringssplattform där deras arbete kan valideras. Dessa discipliner gäller primärt, mekanik, el-installation, automation och robotik. Vidare så kan fördelar som operatörsträning, ökad kunskap om utrustning och högre mognadsgrad av optimerade system valideras innan installationen av maskinen påbörjas. I dagsläget tar idriftsättningen 25% av den totala projekttniden och forskning visar på att VC kan minska detta med upp till 75%.

Trots att VC innebär många fördelar och att det finns programvaror som möjliggör VC är det idag inte ett etablerat tillvägagångssätt inom industrin. Därför ville vi i vårt examensarbete undersöka de underliggande anledningarna till detta.


Nyckelord: Virtuell Idriftsättning, Simulering, Åtgärdssperspektiv, Logikvalidering
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Glossary

Behaviour Model The behaviour model is the embedded information of how a mechanic component are allowed to behave. A behaviour simulation consists of several behavioural models. (Süß, Strahilov, and Diedrich, 2015) It captures design and process intelligence and the range of engineering specifications required to define e.g. the component. The behavioural model goes beyond the traditional core geometric features to increased adaptive process features divided into two distinct categories. Firstly, application features that describe process information e.g. NC part programming intelligence including the tools and tool paths necessary to manufacture itself. Secondly, behavioural features contain engineering and functional specifications that encapsulate product and process information. For example behavioural features include information about design specifications regarding desired weights, kinematics, angles of reflection, mass properties, or other measurements (PTC, 2000).

Black-Box Describes the geometry of a 3D CAD model. No details besides the geometry is included in the file. Used to reduce computational power and modeling effort.

co-simulation Co-simulation enables joint simulation of already established tools.

Component Manufacturer The first part of the value chain, the most upstream within our scope, is the component manufacturer (CM). These companies offer software, mainly CAE-tools and components to production equipment e.g. sensors.

Digital Twin A digital twin is as the name suggests, an identical virtual/digital replica of a component (electrical or mechanical), machine, cell or factory/plant. Thus, all levels of abstraction are covered.

Discrete Event Simulation (DES) models the operations of a system as a discrete sequence of events. It means that the simulation can directly jump in time from one event to the next, since DES is designed on the assumption that, between sequential events, the system will stay as it was in the previous event. When the event occurs, the system snapshots the current system and present it to the user. Thus, DES handles small amount of data, making the simulation to run smooth, in comparison with continuous simulation. According to Carlsson et al. (2012) discrete event system simulation is the same as production flow simulation, which means that it should be used to analyze product flow in a cell, factory or enterprise.

Efficiency Measuring Problem The problem of balancing input activities with output activities.

Emulation Emulation is defined to explain a virtual version of an exact representation of the real system. (Berger et al., 2015; Oppelt and Urbas, 2014).

Ethernet Ethernet describes a whole set of computer networking technologies evolving since the 80s. The development of the Ethernet has made it possible to support higher bit rates and longer link distances.

Factory Acceptance Test The hardware and software test includes three parts. Firstly, the factory acceptance test (FAT) that analyzes if the process control system and its software is according to its specification. Thus, the production equipment is mounted on site at the PEP and then dismantled and shipped to the customer (OEM).

Functional Mock-Up Interface Is a tool independent standard that supports exchange of dynamic models and co-simulation.

Functional Mock-Up Unit A FMU is a instance of an FMI component.

High Maturity level within Virtual Mfg implies that the company has experience, developed methods and processes, and use virtual manufacturing a lot in their daily business.

HiL Hardware-in-the-loop, see (2) in table 2 for further explanation.
Intellectual Property  IP concerns intangible creations of the human intellect and protection of these is partly the foundation of willingness to invent and develop. Artistic works like discoveries, inventions, and designs, can all be protected as IP. 34, 36, 39, 43, 56, 58–60

Key Performance Indicators  By setting KPIs the company enables the team to make smart business decisions about the direction of all current projects. 60, 61

Manufacturer Behaviour Model  MBM represents all aspects of a components behaviour, built and maintained by the manufacturer. It could be deliver as a black-box. vi, 49, 50, 72

Non-Disclosure Agreement  An agreement that constitutes agreed rules between two parties that, when signed, most be obliged. 6, 34, 44, 58, 59

OPC DA  Roughly explained, OPC is used to allow communication from operation systems (OS) to industrial hardware devices (e.g. PLC). OPC was founded in the mid 90s, aiming to ease the exchange of process data. The exchange of data is done through different OPC specifications. The data from the hardware (the PLC) is converted by a OPC server into a OPC protocol that allows the application (e.g. graphical console, simulation tool) to read and interpret the data and vice versa. OPC DA is part of the traditional OPC family, “OPC Classic”. OPC Classic is only operable with Windows OS. (Foundation, 2018). 10

OPC UA  OPC Unified Architecture (OPC UA) is the most recent (OPC) solution to communicate data between software and industrial hardware devices. OPC UA made it possible to communicate with several OS (i.e. Apple OSX, Android, or any distribution of Linux). (ibid.) OPC UA uses two different transport protocols: SOAP over HTTP and TCP. In addition, OPC UA support binary encoding. Siemens (2018) summaries the benefits with OPC UA as: it is platform neutral, it provides security mechanisms, powerful performances, seamless communication with third-party applications and can flexible be scaled to the need for the industry. Therefore, Siemens (ibid.) call it the communication standard for Industry 4.0. 10

Original Equipment Manufacturer  The last part, the most downstream within our scope, is the Original Equipment Manufacturer (OEM) and other producing companies. These companies use production equipment to manufacture goods. v, vi, 4, 7, 18, 30, 31, 33–35, 37–69, 71, 72

Production Equipment Producer  The middle part of the value chain are production equipment producer, machine builders, line builders, system integrator and service providers (PEP). These companies aid OEMs with design, construction and commissioning of production equipment. vi, 4, 7, 30, 31, 33–35, 37–45, 47–53, 55–72

Programmable Logic Controller  A PLC can simply be explained as a small industrial computer that controls one or more hardware devices and is based on event-controlled programming. v, 9

SiL  Software-in-the-loop, its one of the ways to carry out Virtual Commissioning. It mainly consider the tools the automation engineer work in. It considers a virtual PLC and a virtual fieldbus. See (4) in table 2 and figure 5 for further explanation. 10

Site Acceptance Test  Secondly, the site acceptance test (SAT) which is a test to test the final production site after delivery generates the same results as with the FAT. Effectively, the production equipment is mounted again on site at the customer and the same tests as in the FAT are conducted. 29, 31, 53, 54

Site Integration Test  Thirdly, site integration test (SIT) where testing of multiple systems and whether they are integrated and interact with each other is conducted. The commissioning ends with plant start up, proof of performance and continuous and stable production is conducted. 29, 31

TCP  Transmission Control Protocol are communication protocols to interconnect devices on either the internet or private networks. The protocols specifies how data should be distributed into packets, addressed, transmitted, routed and received at the destination. v
The Human Machine Interface  The Human Machine Interface (HMI) is the interface between the process and the operators – in essence an operator’s dashboard. This is the primary tool by which operators and line supervisors coordinate and control the industrial and manufacturing processes in the plant. 30, 62

user  the general actor that utilizes software developed by vendors. In this report it is either PEP, OEM or both. vi, 49, 52, 58–60, 64, 70

User Behaviour Models  Consists of several MBMs together with additional customer specific functionalities, the added functions dose not affect the MBM. 14, 49, 50, 72

vendor  the general actor that produces software and sell it to the user. vi, 48, 49, 51, 56–58, 63, 66

Virtual Manufacturing  Virtual manufacturing refers to activities that involves manufacturing activities performed with computers and the aid of software. Thus, it concerns virtual/digital activities within companies that supports real manufacturing or other real manufacturing related activities. Thus, VC, CAD, robot simulation, flow simulation, process simulation and other similar are included in the term ”virtual manufacturing”. 47, 67, 69
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Appendix ................................................ a
1 Introduction

In this section, the background of this field of research and why it is important is provided. In addition, the problem and clarification of what will be studied is presented followed by the purpose, objective and research questions of the study. Ultimately, delimitation and limitation of the study is provided.

1.1 Background

Virtual Commissioning (VC) is a promising technology for the industry as it is likely to lower risk, time and costs in commissioning projects. However, despite all advantages there are barriers hindering a successful implementation in the industry. Nonetheless, these barriers are subjects of research and are likely to be lowered as development in VC progresses and this progress is expected to be rapid due to an overall increased pressure to decrease time frames in the industry. In this project, the current status, barriers and development of VC is investigated.

Development and improvement in the manufacturing industry has historically been a driving force in overall economic growth, where major advancements often implies increased level of automation. Currently, attempts to increase the productivity and lower costs in the prevailing automation paradigm have been made by implementing e.g. lean philosophy, reallocation of the factories abroad to have cheap labor and make factories larger to achieve economy of scale. However, none of these attempts have been the crucial overhaul and factories look the same today as they did 50 years ago (Kong et al., 2011). It has just been a change of the location, size, how they operate, and now the limit of great productivity improvements is reached. Globalization and a connected world leads to higher customer requirements and increased competition. For companies to survive in this business climate they have to comply with several critical factors, mainly the ability of customization and overall decreased time frame to meet demand. A general paradigm shift can be found, moving from cost to time management. (Reinhart and Wünsch, 2007)

Nowadays, technological advancements in the Internet and Communication Technology (ICT) are being implemented in the manufacturing industry. As technical innovation has been the disruptive force for all previous industrial revolutions, ICT is believed to be a driving force behind the current and future industrial revolution. (Drath and Horch, 2014; Henning, 2013) This industrial revolution has many names, and to the vast majority it is known as Industry 4.0 (Drath and Horch, 2014; Gilchrist, 2016; Henning, 2013).

A common goal when adapting to new technologies, processes or ideas is usually to become more productive and effective since such improvements reduce production cost and thus increase the profit (Lee and Park, 2014). In the digitalization era, the goal is achieved by fusing ICT to ones business, since such fusion facilitate information to flow seamlessly between, e.g. production planning and the shop-floor (Schwab, 2017). Recent trends that enable above mentioned and influencing automation technology are the Internet of Things, Cyber-Physical-System, and the emerging tactile internet (Wollschlaeger, Sauter, and Jasperneite, 2017), which enable reliable and automated information exchange. Therefore, in short, Industry 4.0 can be seen as a second wave of automation assuring reliable and automated exchange of information (ibid.). As stated earlier, this concept is known by many names and Industry 4.0 is just one of them. However, in this thesis Industry 4.0 refers to the above mentioned idea of increased automation of information.

Another key feature of Industry 4.0 is simulation (Drath and Horch, 2014; Kuehn, 2006; Posada et al., 2015; Süss, Strahilov, and Diedrich, 2015) and it enables virtual experiments prior to real tests of systems or processes. Effectively, time consuming and costly mistakes can be avoided, and thus simulation leads to both time and cost savings (Oppelt, Barth, and Urbas, 2015). Simulation within the scope of Industry 4.0 concerns simulation both before and during operation (Posada et al., 2015), e.g. testing the feasibility of production plans and the real time simulation of processes. However, simulation can also be used during the standard plant engineering process (Oppelt and Urbas, 2014), i.e. during the design of a production system. In the plant engineering phase, the use of simulation is mainly applied towards the end when the mechatronic development process, i.e. automation (control software etc.) commences and before the commissioning phase starts.

During commissioning of new systems, machines or processes, production downtime is inevitable. The time the production is reduced is directly proportional to profit loss, and thereby undesirable. Since
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the absolute cost of an idle production is astronomical, the commissioning time should be as short as possible. For instance, in the automotive industry downtime can be as costly as $22 000/minute (Advanced Technology Services, 2006). Furthermore, Hoffmann et al. (2010) present a study stating that commissioning consumes 25% of all the time available for plant engineering and construction, and 15% of the commissioning time is used to correct errors within the control software alone. Errors that could be detected in a simulation. Therefore, it is promising to use simulation during the commissioning phase, i.e. VC in order to virtually test e.g. control software. In this line of reasoning, Hoffmann et al. (ibid.) propose that VC would solve such time consuming problems and argue that up to 75% of the time during commissioning can be saved by implementing VC before actually executing the real commissioning.

The basic idea behind VC is to create a simulation model of the production equipment and simulate prior to the real commissioning. The goal is to understand, detect and correct errors generated during planning, designing and programming of the production equipment in a safe environment (Hoffmann et al., 2010; Lee and Park, 2014) and nowadays software that enables VC exists (Drath, Weber, and Mauser, 2008). However, it is not widely used by the industry (Oppelt and Urbas, 2014).

There are many barriers hindering the use of VC. In a survey conducted by Oppelt, Barth, and Urbas (2015) eight fields of action needed to be dealt with in order to facilitate the use of simulation were derived. Each field contains challenges and the fields can be divided into technical and non-technical. Among the technical fields, challenges regarding reducing modeling efforts are mainly discussed, whereas the non-technical treats organizational challenges towards simulation. In this thesis we investigate each field of action.

1.2 Problematization

Despite existing technical solutions on the market that enables VC, and that VC offers great benefits, it is not an industry standard today. Technical and non-technical barriers contained in different fields of action hinders a successful implementation of VC. Therefore, we investigated these fields of action in our thesis to provide a better understanding about them.

In more detail, there are four technical fields of action and four non-technical fields of action that are investigated. The technical consists of: model re-use, modeling efficiency, integration and usability. The non-technical consists of: work flow, education, acceptance and collaboration. These will all be presented elaborated in the Literature Review (page 8). In short, the technical fields of action concern reducing modeling efforts as modeling is considered to be a major hurdle towards pursuing VC. Therefore, modular concepts, automatic model generation, libraries, level of detail and interoperability issues are investigated. The non-technical fields concern organizational challenges as the increasing use of simulation, and more precisely VC, is exposing organizations to new requirements that challenge the current work methods. Therefore, current work-flows, attitudes, knowledge requirements and collaboration between stakeholders are investigated.

1.3 Purpose

The purpose of this project is to investigate why the implementation of VC is inert and to investigate barriers that prevent VC from becoming widely used in the industry. In more detail, we want to investigate the technical and non-technical fields of action and the barriers within these that hinders VC from becoming an industry standard.
1.4 Research Question

In order to fulfill the purpose of this project, the following research question (RQ), with the corresponding sub-research question (SRQ) are answered. The barriers and our proposed recommendations to attend to them can be found in Barriers to Virtual Commissioning, section 7.1.

RQ What barriers within the eight fields of action are preventing VC from gaining momentum and becoming widely used by the industry?

SRQ Which actions and factors must be addressed in order to reduce the barriers?

1.5 Delimitation

This project will only consider technical and non-technical barriers towards VC on a theoretical and conceptual level. Thus, general technical difficulties and organizational challenges will be covered. However, specific case studies of e.g. technical set ups to conduct VC with existing applications will not be covered. In order to write a thesis with findings applicable to VC generally we chose not to favor a specific software provider.

1.6 Disposition

The thesis is outlined in the following way:

- **Introduction**
- **Research Methodology, section 2** this chapter presents the research design and the methods for data collection and analysis that are applied in this study.
- **Literature Review, sections 3 - 4** this chapter is divided in two sections, Introduction to Virtual Commissioning and Fields of action. The latter is the base of the report that origin from a thorough quantitative study from 2015, highlighting the key factors to enable simulation technologies within organizations.
- **Results, section 5** this chapter presents the results from our interview study. Participants of the interview study can be seen in table 1.
- **Discussion & Analysis, section 6** this chapter presents the summarized view of the results. This chapter works as the reader’s companion towards our conclusions.
- **Conclusion, section 7** this chapter presents the conclusions discussed in section 6 and will additionally give recommendations to the industry and on future work.
2 Research Methodology

This section explains our research design that we used in order fulfill the purpose of the project. In short, we performed a pre-study, literature review and a interview study to better understand our area of research and to obtain theory and empirical results which helped us to answer the research questions.

2.1 Scope

In order to obtain a holistic view of each fields of action (see Fields of action section 4), a set of companies along the value chain were interviewed. The first part of the value chain, the most upstream within our scope, is the component manufacturers and software developers (CM). Further downstream are the production equipment providers, i.e. machine builders, line builders, system integrators and service providers (PEPs). The last part, the most downstream within our scope, are the Original Equipment Manufacturers and other producing companies (OEMs). The value chain is illustrated in figure 1. Each part of the value chain will be explained and defined in the their corresponding order in section 5.

![Figure 1: Visualization of the Value Chain](image)

2.2 Pre-Study

A pre-study was conducted to gain a broad understanding of digitalization, VC and Industry 4.0. During our pre-study we aimed to reach a non-trivial scope linked to these above mentioned topics.

The pre-study was performed through our literature review, unstructured interviews and a VC workshop at Siemens AB. Our literature review can be found in section 2.8. The unstructured interviews were carried out to understand the academical and industrial perspective, therefore, interviews were conducted with researchers at the Royal Institute of Technology and staff at Siemens AB. The workshop conducted by Siemens AB invited companies from the industry to introduce them to VC. During the VC workshop we interviewed people interested to implement VC. These short interviews helped us understand challenges that users of VC had.
2.3 Research Design

Based on the findings from the pre-study and literature review we formulated our problematization and conducted the interview study based on this. Siemens AB assisted us in finding an interesting topic that would benefit them. Thus, making our research approach deductive (Blomkvist and Hallin, 2015). In addition, since the aim of the report was to solve a specific, non-trivial, existing problem and the project was less than six months, our research classification is linked to applied research (Collis and Hussey, 2013a). During our interview study we conducted interviews with employees responsible for modeling, design and operation of this technology. In addition, we interviewed both simulation and emulation experts and production and development project leaders to obtain the required data and their experiences with virtual and traditional commissioning. All interviews were recorded and notes were taken during the interview.

The study has been carried out through Blomkvist and Hallin (2015) 4-phase method. Which means that the report progress iteratively through 4 specific prototypes. (ibid.)

2.4 Data Collection

As part of gaining understanding of the technology (VC), unstructured interviews with employees at Siemens AB were conducted. Once sufficient knowledge was assessed (from our client and the literature review) we created material, i.e. questions that was used in the interview study in order to gather empirical data to contribute with important primary sources to the study. Multiple sources of empirical data were used in order to reach empirical saturation (Yin, 2009). The planning of the interview study was conducted with the help of our client’s network and many of the interviewees were customers to Siemens AB. The process to find people to contribute the interview study consisted of five steps which originated from our supervisor at Siemens AB. Firstly, she recommended which sellers within Siemens AB who had customers that were interested or part of ongoing VC projects. Secondly, based on the suggestion from our supervisor, we contacted the recommended seller and presented our master thesis project, with the aim that the sellers should give us contact information to their customers. Thirdly, we contacted the recommended customers and scheduled an appointment (either an online meeting or a physical meeting). Fourthly, we sent the questions so that the interviewee got the chance to understand and prepare for our interview. Fifthly, we conducted on the interview where one of us asked the questions and the other documented the answers. All the interviews were recorded. See table 1, on page 7.

To gain a comprehensive understanding of the view of the technology from a market perspective, we decided that we wanted to interview all parts within the value chain. Since they all are affected to some extent by the same challenges that VC implies.

2.5 Data Analysis

Immediately after the interviews the documented interview notes were analyzed and compared to the recordings. Thus, the notes were complimented to increase the quality of the note and to make sure that sufficient information from the interviews was documented properly. After the interviews were done, each question within each part of the value chain was examined. The answers were thematically clustered into the same categories as the interview material. Effectively, general findings were grouped the same way as the framework (Fields of Action) is presented in the literature review.

2.6 Literature review

A literature review was continuously performed throughout the thesis project. It was performed through a critical and systematic search of scientific publications and books within the scope, as recommended by Yin (ibid.). In order to achieve this objective, we used the databases KTH Primo, Google scholar, Web of Science, IEEEEXplore and Science Direct with the following pre-determined key words (Collis and Hussey, 2013b):

'Industry 4.0', 'Simulation Model', 'Industry 4.0 Virtual Commissioning', 'Simulation', 'Virtual Commissioning', 'Digital Factory', 'Cyber-Physical-System', 'Logic Enabler', 'Cyber Physical System',
2.7 Quality of the Report

When evaluating the quality of scientific work based on case studies it is important to consider; realabilty, validity and generalizability. (Blomkvist and Hallin, 2015) According to Blomkvist and Hallin (ibid.) reliability is to study in the right way, while validity is to study the right phenomenon. As the work with the thesis evolves, one must reflect upon if validity and reliability is achieved and sufficient. A way of ensuring validity (within the scope of RQ) is to let empirical data and literature guide the study towards relevant topics and assure that the same conclusion is drawn by several sources, i.e. triangulation (Collis and Hussey, 2013b). Reliability is best achieved by reflecting if the method chosen to answer the research question is the most accurate and suitable way of obtaining an answer.

2.8 Ethics

The project was performed in cooperation between the Royal Institute of Technology (KTH) and Siemens AB, we being the link between the two stakeholders. We were assigned one supervisor at Siemens AB and one at KTH, both assisting with support and knowledge in the form of guidance and connections to relevant interview candidates. Siemens AB also gave us a monetary reward for helping them obtaining a deeper understanding of the research topic. Before the research was initiated a Non-Disclosure Agreement (NDA) was created by Siemens AB and signed by us. The NDA states how we should relate to information obtained during our work with Siemens AB and their customers. In addition, all interviewees are anonymous in this thesis. Moreover, audio recordings and notes are only seen and accessed by the authors (Per Bondeson and Stefan Liss) and audio recordings are deleted upon approval from KTH of this thesis.
<table>
<thead>
<tr>
<th>Part of the Value Chain</th>
<th>Data Source</th>
<th>Respondents</th>
<th>Date and Duration</th>
<th>Documentation</th>
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<td>Regional VC Promoter for a global CM</td>
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<td>Company C5</td>
<td>Method Developer Virtual Tools &amp;* Technical Consultant at global car manufacturer</td>
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<td>2018-03-29 (45 min)</td>
<td>Notes &amp; Audio recording</td>
</tr>
</tbody>
</table>

* '&’ indicates several number of respondents

Table 1: Data source for the interview study
Literature Review

In the sections 3 – 4, our literature review will follow. The literature review will cover basic concepts and technology behind VC. In addition, challenges towards VC will be divided into eight fields of actions and research conducted within each field will be presented. However, we will cover the concepts and technology briefly since we do not want to confuse the reader with too many unjustified dives into advanced technology. For further reading we refer to cited authors. Our objective is to present relevant technology on the appropriate level to ease understanding of the coming chapters.

3 Introduction to Virtual Commissioning

Time management and flexibility has become increasingly important in the manufacturing industry due to shorter product life cycles (Reinhart and Wünsch, 2007). Therefore, both the product development process and the development process of automated production must become more efficient. This implies that all stages in the plant engineering life cycle, from development to continuous operation must work with time-decreasing initiatives. In addition, due to trends towards individual products, the ability to handle a wide product portfolio in the same factory has led to increased requirements on flexibility. Therefore, mechatronic components combined with control software is continuously rising to ensure a high flexibility of the plant (see figure 2). Effectively, prior to production of new products, mainly software must be adjusted and the control software developer focus on developing, optimizing and testing the control programs (Süß, Hauf, et al., 2016).

![Figure 2: Contribution of engineering disciplines to product functionality graph (Reinhart and Wünsch, 2007)](image)

The standard plant engineering process can be divided into three main stages (Oppelt and Urbas, 2014). Firstly, product life cycle consisting of product planning and design. Secondly, plant design consisting of conceptual design, basic engineering, detailed engineering, installation/construction and commissioning. Thirdly, plant operation, maintenance and modernization (see figure 3). Stage one and two can be grouped into design and engineering and stage three operation (Oppelt, Barth, and Urbas, 2015). These stages occur in the order they are presented and parallel work in the respective stages is not common (Drath, Luder, et al., 2008; Neugebauer and Schob, 2011; Westkämper et al., 2012).
In the end of the development phase, and before the continuous operation phase, a ramp-up phase takes place. Prior to obtaining a stable and reliable production system, this ramp-up phase is required. It consists of two parts, 1) commissioning phase and 2) ramp-up phase. The commissioning phase consists of activities aiming at achieving a production system (completely assembled and mechanically reviewed) operational with the objective is to obtain a plant capable of production. The commissioning phase ends when the first workpiece that is approved can be produced (Kong et al., 2011). The ramp-up phase aims at making the production system stable and compliant with demanded production costs, quality and output. (Reinhart and Wünsch, 2007) Nowadays, the commissioning phase alone consumes up to 25% of the plant development phase. Hence, due to stricter time management requirements, the time needed for the ramp-up of the production system is important for a product’s economic success (Hoffmann et al., 2010; Kong et al., 2011; Reinhart and Wünsch, 2007).

Commissioning is a crucial part of the plant engineering phase, but despite its important role, it occurs late within the mechatronic development process (Reinhart and Wünsch, 2007). As previously stated, the commissioning phase accounts for approximately 25% of the total plant development (i.e. all phases in the plant design, see figure 3). The major part of this time (90%) is due to delays caused by electric and control related activities and in 70% of the cases the delays are a consequence of errors in the control software. Effectively, defective control code is the most common reason to delays and consumes up to 60% of the commissioning time which implies a total of 15% of the total plant development, see figure 4. (Hoffmann et al., 2010; Reinhart and Wünsch, 2007) Therefore, it would be beneficial to bring forward the commissioning phase and make it in parallel with other plant engineering phases since it would enable earlier error detection and thus decrease the total project time.

VC makes it possible to bring forward the commissioning phase and to manage the commissioning phase in parallel with other plant engineering phases by using virtual prototypes to test control software (Reinhart and Wünsch, 2007). In other words, VC is used to virtually test control code deployed on PLCs (Programmable Logical Controllers) before the real systems are commissioned (Hoffmann et al., 2010; Puntel-Schmidt and Fay, 2015; Westkämper et al., 2012). The objective with using VC is early validation of specific automation projects within a specific plant operation, and thus reduce the risk of deploying an automation program containing errors (Hoffmann et al., 2010; Oppelt and Urbas, 2014). Nowadays, the major part of the commissioning and ramp-up phases consist of software implementation or software redesign. Hence, using VC is promising since it would enable higher software quality, and thus
shorten the commissioning phase when implementing the software. However, despite that VC offers great possibilities, VC is not an industry standard today (Oppelt and Urbas, 2014).

3.1 Virtual vs Real Commissioning

The difference between real commissioning and VC is that a real commissioning involves testing directly on a real manufacturing system (i.e. machine), a real controller (i.e. PLC) and the needed field devices (i.e. sensors, actuators, cylinder, I/Os or frequency changer/ converter). VC on the other hand, involves commissioning with virtual replicas of the system’s components and can be configured in three different ways, see (2), (3) and (4) in table 2. Our scope only consider (2) and (4).

<table>
<thead>
<tr>
<th>Combination</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Conventional way to commission:</td>
<td>When the commissioning is done, no extra work is necessary</td>
<td>Testing is potential hazardous, considerable implementation costs, modification costs are even more expensive</td>
</tr>
<tr>
<td>Real controller &amp; real manufacturing system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2) Hardware-in-the-Loop Commissioning:</td>
<td>Low cost to control and to validate &quot;off-line&quot;</td>
<td>Development effort of realistic manufacturing system, a switch between VC and traditional commissioning is needed as an additional effort.</td>
</tr>
<tr>
<td>Real controller &amp; virtual manufacturing system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3) Reality-in-the-loop Commissioning:</td>
<td>Debug control systems, quickly reach strategies on how to control system</td>
<td>Development effort to transform virtual control to real controllers. Trial and error might result in hazardous development efforts</td>
</tr>
<tr>
<td>Virtual controller &amp; Real manufacturing system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4) Constructive Commissioning or Software-in-the-loop:</td>
<td>Low cost</td>
<td>Switching from simulation to reality requires considerable effort</td>
</tr>
<tr>
<td>Virtual controller &amp; virtual manufacturing system</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Commissioning configurations of how to conduct VC, as highlighted by (Berger et al., 2015; Lee and Park, 2014)

3.2 Simulation

VC can be seen as a simulation, i.e. a virtual experiment. The goal is to better understand the system’s behaviour over time based on dynamic and mathematical models imitating the reality. When the replication has been modelled, observations from the model can be assessed to verify and validate if the model is correct.

VC can be conducted through hardware-in-the-loop (HiL) or through software-in-the-loop (SiL) (see figure 5). HiL implies that the simulation is connected to real controllers and real devices, enabling the fieldbus emulation. In contrast, SiL is when the simulation is connected to a virtual control system and virtual fieldbus emulator, see figure 5 (Oppelt and Urbas, 2014). One important detail that can be seen in figure 6 is how one physical device can be disguised and replicated as a user-defined field device, the orange line represent such replication. Therefore, during a HiL the creation of a field bus emulation is used instead of having to connect extra hardware into the simulation model (or creating extra PLC logic). Note, this explanation follows the automation process (see figure 5) of virtual commissioning, it is still necessary to construct the model according to all the VC building blocks (see 3.3). The description made here only explain the first and second building block in figure 7. In either case, the communication between the computer and HiL or SiL is achieved through some kind of signal distribution terminal. According to Dahl et al. (2017), OPC DA or OPC UA are well established techniques that utilize a standardized protocol to transmit signal between different clients over Ethernet. However, there are many CMs who aim to share and establish standardized protocols to enhance the interoperability between the building
blocks. Some of the most widely used standardized protocols in industrial applications are PROFIBUS, PROFINET, MODBUS, Fieldbus Foundation, HART, ASi, LonWorks, DeviceNet, ControlNet, CAN Bus, and Industrial Ethernet (Gonzalez et al., 2016).

3.3 Building Blocks of Virtual Commissioning

In order to conduct VC, a virtual model of the reality must be built and the PLC-code is tested against it. The model consists of four blocks, connected to each other, see figure 7. Firstly, the control program that is supposed to steer hardware that constitute the process or system, done through programming the PLC. Secondly, the emulation of field device included and their signals that are being forwarded to the behaviour model, which is the behaviour of all the emulated components, i.e. kinematic and electrical, this third step represent Electrical & automation behaviour simulation and Process & Mechanical simulation in figure 5 (Westkämper et al., 2012). Fourthly, the visualization of the process or system, i.e. the
animated 3D model where all previous parts are put together to simulate the behavior, which is the
center of the triangle of figure 5 where all different discipline’s work are put together (Süß, Strahilov, and
Diedrich, 2015). Each part contain time consuming activities. Therefore, as one of the objectives and
reasons of conducting VC is to shorten the overall commissioning, time and effort decreasing initiatives
in each phase/part of VC are crucial (ibid.).

Figure 7: Basic Virtual Commissioning setup (Süß, Strahilov, and Diedrich, 2015)
4 Fields of action

Oppelt, Barth, and Urbas (2015) conducted a global survey where the authors derived fields of action to enable simulation along the life-cycle of a process plant. As virtual commissioning is commissioning accomplished through simulation (see Simulation 3.2), it is assumed that the fields of action applies for VC too. The fields of action can be clustered into technical and non-technical actions. The technical actions consists of the following subcategories: model re-use, modeling efficiency, integration and usability. The non-technical actions consists of: work-flow, acceptance, education and collaboration. An elaborated explanation of each field of action is presented below and in addition, research conducted in each field is reviewed, see figure 8.

Figure 8: Fields Of Action, freely interpreted from (Oppelt and Urbas, 2014)

Technical Fields of Action

The technical fields of action are model re-use, modeling efficiency, integration and usability. They mainly concern technological research regarding modeling, models, libraries, modularity, automatic model generation, integration of applications, information and model exchange.

4.1 Model Re-Use

Model re-use concerns the ability to recycle simulation models and to re-use models developed early in the plant engineering process in later stages and to various projects. Model re-use can be achieved by modular concepts i.e. plug-and-play (see Modular Concepts 4.1.1). However, this modular approach will demand development of a commonly accepted modelling standard for simulation. In addition, a co-simulation standard accepted by both vendors and users combined with a standard for model exchange between different simulation tools must be developed.(ibid.)

Model re-use is an important field of action as modeling is considered one of the major hurdles towards using simulation in the engineering work-flow (Oppelt and Urbas, 2014). Hence, the subject is discussed among many authors. Drath, Weber, and Mauser (2008) argues that the models created during the VC phase enables re-usability of those models through the complete engineering life cycle and Oppelt and Urbas (2014) stress that the industry ought to re-use already built simulation models to larger extent and for multiple purposes. Furthermore, Drath and Horch (2014) argues that when VC is embedded into the standard engineering workflow, the creation of sub models that make up the VC model starts already in the early phases of engineering and are passed on to later stages. Effectively, models can be re-used through the complete engineering life cycle. This will be further discussed in Work-flow 4.6. However, prior to achieving seamless information exchange between engineering discipline’s software along the engineering phases, development in data exchange must be improved, which will be discussed in Integration 4.4.
4.1.1 Modular Concepts

In order to conduct VC, behaviour modeling and 3D geometry modeling of the plant are the two extensive, but necessary tasks to perform. To ease behavior modeling, modular approaches with customization possibilities are being researched, see Behavioural Models as Modules 4.1.2. In addition, exchange of models is a major issue too. Therefore, standardized model exchange methods are researched as well, see Model Exchange Methods 4.1.3.

4.1.2 Behavioural Models as Modules

Normally, the behaviour simulation consists of several behaviour models and in turn, these represent individual components of the plant, e.g. electric drives and pneumatic drives. Currently, each component’s behaviour model is created by the user of VC or a subcontracted service provider (e.g. machine builder), since manufacturers of such standard components do not deliver any kind of behaviour model today. The service provider considers the specifications of its customer and builds "User created Behaviour Models" (UcBMs). UcBMs usually only contain certain aspects of the real behaviour of the components and are individually built for each user respective customer which complicates the use for other customers. Effectively, UcBMs must be maintained by each user separately. Additionally, service providers of these UcBMs often assumes the responsibility to prepare the entire behaviour simulation of a plant, named Plant Behaviour Model (PBM). (Süß, Strahilov, and Diedrich, 2015) figure. 9 demonstrates the relationship between UBM/UcBM and PBM.

To distribute the efforts of creating behavior model, CMs ought to deliver behaviour models of their models in an open and standardized format since it enables them to use their preferred tool. The conversion to an open and standardized format enables their customers in their turn to use their specific simulation tool, given that import functions are available.(ibid.) Appropriate modeling languages for behavioural models will be discussed in Integration 4.4 and Model Exchange Methods 4.1.3.

Another challenge for the manufacturer is to provide its component behaviour models and at the same time enable the user to modify these for own use. The customization possibility is important since the user on the one hand does not always use all functions of a mechatronic component and on the other hand the effort for the CM to provide a customized component with specific functions for each user is immense.(ibid.)

To overcome this customization issue and to distribute the burden, Süß, Strahilov, and Diedrich (ibid.) suggests a Manufacturer Behaviour Model (MBM) that represents a component behaviour model. It is built and maintained by the manufacturer of the component and contains all aspects of its behaviour, and can be delivered as a black-box. The MBM can be used as a base when customer specific functionalities are added. MBMs make up User Behaviour Models (UBM) and additional functionalities that match the requirements that VC have internally, without changing the MBM, see figure 10. In short, the MBMs are used as a modular base to create UMBs and the PBM combines different UMBs (and sometimes UcBMs) together to represent the behaviour of a whole plant, see figure 9. However, nowadays UBM (and UcBMs) are only created by the user of VC without the aid of MBMs as these do not exist (Süß, Hauf, et al., 2016).

Figure 9: Structure and correlation of PBM, UBM and MBM (Süß, Strahilov, and Diedrich, 2015)
Research regarding standardized classification and interfaces of complex behaviour models in VC is currently being conducted. If the in and outputs of MBMs could be provided in a standardized format, MBMs could be offered independently to customers respectively users. In addition, transformation from MBM to UMB could be accomplished semi-automatically through standardized interface definition and thus, the modelling time could be reduced. The research also includes investigation of a division of the interfaces and its in and output signals to the four sections: Parameters, PLC interface, 3D interface and Physics interface, see figure 11. (Süß, Hauf, et al., 2016)

4.1.3 Model Exchange Methods

Research regarding model exchange has led to the development of Functional Mock-up Interface (FMI). FMI is a tool independent standard that supports exchange of dynamic models as well as its co-simulation and is based on a combination of xmlfiles and compiled C-code. The main purpose with FMI is to re-use and share simulation artifacts in the wide landscape of tools and environments. This is accomplished by putting the model specifications into a simple compressed file called Functional Mockup Unit (FMU). (Bertsch, Mukbil, and Junghanns, 2017) Furthermore, according to Süß, Strahilov, and Diedrich (2015), FMU is an appropriate format for behaviour models of mechatronic components.

A FMU is an instance of an FMI component and as an example, a zip archive with multiple files describing a model constitutes such a FMU. The archive contains files with information about parameters, variables, model equations and other information concerning the model. The concept of FMI is illustrated in figure 12. In addition, FMI enables simulation of different FMUs in an approach called ”FMI for co-simulation”, see figure 13. (ibid.)
FMI is meant to solve problems that current VC-tools implies, namely that current tools use proprietary data formats and are mainly adapted for one task, which leads to several drawbacks. Firstly, import and export of single component models or complete plant simulations is not possible. Secondly, archiving becomes an issue due to tool change or older versions of the same tool may imply obsolete simulation files. In addition, multiple formats require multiple VC models and the simulation engineer using such tools need long training since these are expert tools. FMI offers sustainable behaviour simulation within VC by using open source and standardized formats solutions. (Süß, Strahilov, and Diedrich, 2015)

4.1.4 Co-Simulation

The concept of co-simulation could be explained as the joint simulation of the already established tools and semantics and that they are simulated with their suitable solvers, see figure 14. In other words, “co-simulation is defined as the coordinated execution of two or more models that differ in their representation as well as in their run-time environment” (Steinbrink et al., 2017, p. 4).

Therefore, the models used in the co-simulation have been developed and implemented independently. It implies that modeling and simulation is separated which is considered the major benefit. Furthermore, analysis of the dynamics of larger “systems of systems” becomes possible as co-simulation users can employ models created by researchers or institutes. Thus, co-simulation supports reuse of simulation models. (Oppelt and Urbas, 2014; Steinbrink et al., 2017)

4.2 Modeling Efficiency

Modeling Efficiency concerns the initiatives towards decreasing the effort of using simulation and currently, two approaches are researched: The approach of automatic generation of simulation models and ready-to-use libraries for devices as well as for processes. Furthermore, two challenges to ease the use of simulation must be addressed: the management of simulation models throughout the life-cycle and the management of change in simulation models. (Oppelt, Barth, and Urbas, 2015)

Modeling Efficiency is an important field of action as the efforts of building the VC model nowadays can exceed the benefits achieved with VC (Oppelt and Urbas, 2014). As the required effort for building these
Literature Review Technical Fields of Action

models is high and considered one of the major hurdles towards VC, the need of more effortless set up of virtual plants is required (Oppelt and Urbas, 2014; Süß, Strahilov, and Diedrich, 2015).

Currently, modeling effort is saved by omitting models of electrical components, e.g. contactors, motor protection, switches or door locking devices since it would require the model to be very detailed. Thus, all signals from the PLC-program are not used in the model. In an analysis of a typical model used for VC, it was found that approximately 50% of all signals affect the simulation of mechanic events. Remaining signals concern communication signals with the electrical components, for instance switching a contactor, controlling clearances or obtaining status information. Therefore, two scenarios can occur (1) the PLC code must be adapted to VC, i.e not the real PLC-code, or (2) the model must be detailed in order to use the real PLC code. The first scenario is not aligned with the goal of VC: to test the real PLC-code. Thus the need of effortless setup of detailed models is needed. (Westkämper et al., 2012)

In addition, since there are only two paths to choose, conduct VC or not, the possibility to know the benefits beforehand is difficult. Therefore, evaluation of the benefit ratio between VC and conventional commissioning is difficult in hindsight. This problem is known as the efficiency measuring problem (EMP) of VC (Reinhart and Wünsch, 2007). As a comment on EMP, Drath, Weber, and Mauser (2008) stresses that during the introduction of VC some efficiency losses should be expected, but these losses ought to decrease as new concepts become known and simulation libraries are built. Therefore, the authors suggest a smooth introduction of VC by testing on an existing project.

In summary, to ease modeling efforts two approaches are being researched: Automatic model generation and ready-to-use libraries.

4.2.1 Automatic Model Generation & Component Library

Automatic model generation is achieved by using existing data from the latest engineering or operating phase information, e.g. data from automation system configuration files or plant engineering data. (Oppelt and Urbas, 2014) It can be accomplished by the integration of various heterogeneous information models, the use of transformation mechanisms and a manual enrichment of simulation-specific information. Drath, Weber, and Mauser (2008) stress that the virtual model should be created (semi-) automatically out of proven library elements.

In addition, as explained in Introduction to Virtual Commissioning 3, VC consists of four blocks (see figure 7) and each part contain time consuming activities. Hence, time decreasing measures have been developed in each discipline, which will be provided in the following sections.
4.2.2 Programmable Logic Controller Code

In the control system part (of PLC research), research regarding generating PLC-code more effortlessly and efficiently has been conducted by Hossain and Semere (2013) and they developed hardware independent programmable logic code using capabilities of MATLAB. Additionally, Andemeskel (2013) presented a method (also developed in MATLAB) that virtually captures and represents all relevant modes of a system in block forms, which enables the generation of thousands of lines of PLC-code only with few hours of modeling efforts. Nonetheless, these contributions do not provide new tools for VC nor new methods for behaviour simulation, but they combine different models to enable time saving impact in a control system development process (Süß, Strahilov, and Diedrich, 2015).

4.2.3 Emulation of Components & Behavioural Model-Challenges

Emulation is defined to explain a virtual version of an exact representation of the real system. (Berger et al., 2015; Oppelt and Urbas, 2014) Currently, VC utilize emulation as the mimicking of specific hardware device (i.e. field devices) e.g. actuators and sensors, see figure 6 (Berger et al., 2015; Oppelt and Urbas, 2014). Nowadays, it is argued that manufacturers of mechatronic components should provide virtual components with corresponding behaviour models in libraries. More precisely, the 3D-models, kinematics, collision-objects and logical behavior (Westkämper et al., 2012). However, as discussed in Model Re-Use 4.1, manufacturers of standard components do not deliver behaviour models and the user of VC must create them themselves (Süß, Strahilov, and Diedrich, 2015). Nonetheless, to realize shareable libraries, open data formats to enable exchange of the behavior models is needed and will be discussed in Integration 4.4.

There are two challenges towards building behaviour models for users of VC. Firstly, the component modeling issues regarding how to verify the consistence between the physical component’s behaviour and its behaviour model. Complex components, like e.g. frequency converters and electrical drives, require considerable engineering for the appropriate behaviour model and the behaviour modeller must make assumptions to approximate the behaviour which reduces the model’s similarity to reality. Secondly, is the problem of duplication, i.e VC user must model component on their own, starting with nothing but the real component and the documents delivered by the manufacturer of this component. Obviously, this duplication is more severe for standard components that are used by a huge variety of users. According to Süß, Strahilov, and Diedrich (ibid.), it is likely that CMs already have behavior models, but they do not deliver these. Instead, CAD-data in many different formats are delivered. These include 3D, 2D, wiring diagram data. In addition, documentation like general specifications, operating conditions or data sheets is also provided to customers and the amount of documents provided can easily reach 50 and more.

The solution to both mentioned problems (the correctness of the behaviour models as well as the overhead through user modelling) could be to enable CMs and make them willing to provide customers with additional information. The next step could be to additionally provide behaviour models and supplementary material e.g. a ready to use PLC-model (ibid.). This might not be a unrealistic since Oppelt, Barth, and Urbas (2015) claim that OEMs will provide simulation models for their equipment in the future. However, sharing this kind of detailed information about components with customers without revealing confidential data is a proprietary data problem that must be dealt with. Otherwise, competitors might be able to analyze these models closely, resulting in the loss of a potential competitive advantage of a specific firm. Currently, there is research about using neutral data formats in order to overcome this issue, which is discussed in Integration 4.4. (Süß, Strahilov, and Diedrich, 2015)

4.2.4 Emulation of Components and Behavioural Model- Automation through Libraries

In a paper by Westkämper et al. (2012), the authors describe how a library solution can be used to automate the modeling and still provide the flexibility of the mechanical side. As each machine is unique, geometrical parts and the kinematics between them is unique too. However, actuators, sensors and other electrical components, e.g. contactors, are usually just standard parts when delivered from suppliers and can be used in various engineering projects. Therefore, standard components are suitable to keep in libraries.

Furthermore, these components are contained within the wiring diagrams and are connected to each other and to all necessary signals within the PLC program. Effectively, the generation of behaviour models
for VC based on the wiring diagrams and on behavior models for the components becomes possible and also to store them within a library. The logical behavior model (containing all electric and fluidic ports) of each component within the wiring diagram must be defined in the library of the VC tool. The mapping between the material created from Electronic and Electrical Computer-aided design, i.e. the ECAD-component and the logical behavior model must only be done once in order to enable immediate generation of the appropriate detailed logical behavior. This is accomplished by replacing the components in the wiring diagram with the simulation components and the connection between components extracted from the wiring diagram, see figure 15. In addition, from the 3D-CAD model that is designed during the mechanical engineering, geometry and kinematics can be re-used and the interface between the behavior model and the mechanics is exactly defined. The PLC is only connected to the behavioural model since the current position of actuators in run-time is written to the mechanical model by this interface and sensor-signals are calculated from collisions within the mechanical model are written to the Behavioural model. The suggested modeling approach enables high flexibility concerning geometry and kinematics and still minimizing additional effort for modeling the mechanics of the VC model. Additionally, the automatic generation of the electrical behavior models is accomplished. (Westkämper et al., 2012)

Figure 15: On the left, wiring diagram and on the right, equivalent objects for components and connections within virtual commissioning model (Westkämper et al., 2012)

4.2.5 Simulation Model-Model Driven Architecture

Research conducted by Neugebauer and Schob (2011) investigated an automated approach to generate machine simulation models through a method called Model Driven Architecture (MDA). It is an approach to enable the consequent use of models by defining key aspects of software applications where activities performed by a simulation expert are formalized and put into rule-based algorithms. The transformation of information from digital files into a simulation model is based on the rules that represent the knowledge and ability of the simulation engineer to find patterns. Patterns are translated into objects within the simulation tool and many patterns make up the simulation model, the process is demonstrated in figure 16. The digital files contain information like the mechanical construction with geometric bodies and their relations, the electrical plans with components like sensors, switches and actuators and their wirings or the fluid plans with hydraulic or pneumatic components and their connections. (ibid.)

The documents used as source were standard documents developed during a standard engineering process, e.g. CAD drawings, electric plans, fluid plans and manual parts. Nowadays, the simulation engineer creates the model based on above mentioned documents and decides which important aspects to include in the behaviour model, see figure 17. However, nearly all information created during the development process is available as digital files, which enables easy access. (ibid.)
Figure 16: Model-to-model transformation on meta model level. A model of one domain is transformed into another domain through rules defined on the level of meta-models (Neugebauer and Schob, 2011)

Figure 17: A simulation expert performs a manual interpretation of different product documents to create a simulation model (Neugebauer and Schob, 2011)

The transformation and retrieval of information is enabled by application programming interfaces (APIs), the objects attributes and relations are acquired through APIs and stores them internally. Thereafter, the predefined rules will be matched with the internal data and in the event of a match, a new object designated for the simulation model is created. In the final step, all formal connections in source documents are applied to the respective simulation elements and thereby a usable simulation model is created. (Neugebauer and Schob, 2011)

The research concluded that it is possible to re-use development documents to derive simulation models by just following pattern based rules. Effectively, the majority of the machine’s functionality could be transformed automatically without having to convert properties or attributes, since real documents were used. However, manual import is required in case information is missing in formal documents. Furthermore, the automation feature enables execution of transformation at different stages of the development process which facilitates an iterative working process due to detection of design flaws and software errors. The developed rules that enabled automated transformation are re-usable and can be extended for other machines. Thus, the effort in creating virtual machine models is significantly reduced. Nonetheless, interoperability challenges remain as the transformation implies acquisition of various data formats and interdisciplinary formats like AutomationML must be further developed, as discussed in Integration 4.4. (ibid.)

4.3 Level of Abstraction

Another important aspect of the modeling efficiency is the level of detail the model must have since it affects the modeling effort that must be invested. Therefore, the understanding of what needs to be modelled to execute a VC is important. Normally, the level of detail that the model must have depends
on the test cases the user is interested to analyze. A rule of thumb could be that “a simulation model for VC is sufficient if the automation system cannot notice the difference in the connection with the simulation model than with the real production system” (Oppelt and Urbas, 2014, p. 2567). Or, that the level of detail should be “as abstract (and less complex) as possible, but as complex and detailed as needed” (Puntel-Schmidt and Fay, 2015, p. 923). Effectively, modeling every aspect and detail of the simulation model is not necessarily the case in order to reach the goal.

As manufacturing plants can be simulated at any level of detail, a wide range of models can be considered (see figure 18). In addition, the more complex and detailed level the model must have, the more detailed databases are needed and the more CPU-intensive the simulation becomes. Nowadays, it is often unclear what granularity these simulation models must have and how different levels and model types should be defined (ibid.). Researchers have done several attempts to agree on modeling levels, but there is currently no systematic definition of simulated components or modules and which level of detail that ought to be used. Some of the ongoing research and attempts to address this issue is presented below.

![Figure 18: Visualization of how the different abstraction levels relate to each other. (Jhel, 2017)](image)

### 4.3.1 Level of Abstraction—Current Research

One suggestion, proposed by Lasa et al. presented in Oppelt and Urbas (2014), is to divide it in four different levels. Firstly the state level, where state machines and binary signals are used to model the system. Secondly, the system level where individual components of a system are modelled without interconnection between the individual components, and how components affect each other is neglected. The resulting mathematical descriptions tend to be ordinary differential equations. Thirdly, network level, characterized by the connections and the influence different components have on each other. In this case, mathematical system is described in differential algebraic form, building a model with bidirectional mass, energy and material flow between the components. Lastly is the finite level, where modelling results in partial differential equations usually solved using finite element methods and the level of detail is high. Individual aspects of components like e.g. deformation, heat transfer or chemical reactions are modelled. In addition, geometrical information (3D) becomes important on this level for manufacturing industries (ibid.).

Another suggestion proposed by Manske and Lotz, also presented in Oppelt and Urbas (ibid.), is also divided into four levels, consisting of: (1) Input-Output model where a feedback model of actuators and sensors are connected to the automation systems. (2) Model without dynamics consisting of just basic time functions. However, the connections between components of the system are modelled, but not the dynamic interaction between the components. (3) Model with dynamics, i.e. the dynamical interaction between the components is modelled. (4) Physical model that contain physical representation (ibid.). The work of Lasa et al. and Manske and Lotz is summarized in figure 19

As the model must be sufficient to cope with the investigated test cases the user ought to choose the
appropriate modelling depth that suits the task at hand. Oppelt and Urbas (2014) concludes from above mentioned levels a three level classification: signal-, device-, and process level. The signal level concerns the connection between the automation system and the simulation model, that ensures that the automation system can be connected to a simulation without any changes. The device level enables the test of individual devices. On the process level, different modelling levels ought to be considered: model without dynamics or system level, model with dynamics or network level and physical model or finite level.

Reinhart and Wünsch (2007) presents Milberg’s five level plant model. The levels are hierarchical and consists of: planning, plant, cell, machine & process level. Each level within the model has varying demand on information technology. Generally, the higher up in the hierarchy, larger amount of data must be handled and as descending in the hierarchy, the data becomes more detailed. For example, the planning level handles large amount of data and the cycle times of interest are between hours and weeks. On the machine and process level, the data normally consists of bits and bytes and the cycle times are often in the span of milliseconds or less. When researchers investigate different approaches regarding VC and testing of control systems, they only focus on one of the above mentioned levels, see figure 20. (ibid.)
Plant level focuses on discrete event simulation and application of material flow simulation with 3D visualization for the VC of a manufacturing execution system (Reinhart and Wünsch, 2007). Cell Level focuses on 3D simulation environment with embedded programmable logic control (PLC) for the development and test of a cell control. On the machine level, a real time simulation environment to test various machine PLCs is key whereas the process level focuses more on a real time simulation environment with an integration of a simplified finite element method model solved in real time. Reinhart and Wünsch (ibid.) reaches the conclusion that discrete event simulation is sufficient for plant and cell level where standard material flow simulation packages can be used. Furthermore, process level requires real time simulation and for machine simulation standard-PC based simulation is adequate.

The virtual model could be built to support scalability, i.e. being able to raise the level of detail locally while maintaining global coherence. The principle of the magnifying glass used here, means that the ability to zoom in on different levels of abstraction should be possible, see figure 21. This would enable horizontal and vertical integration of control systems within VC approaches. In this way, control systems would be tested locally and the networking functionalities as a whole. Hence, the aim to perform total commissioning of the control systems in the production system would be possible. (ibid., p. 374)
However, above mentioned approaches are suitable within their respective use case, but a systematic definition of levels of detail and fitting model types is lacking (Puntel-Schmidt and Fay, 2015).

In the article "Levels of Detail and Appropriate Model Types for VC in Manufacturing Engineering" by Puntel-Schmidt and Fay (ibid.), the authors present an overview of levels of detail and the comprised model types and several important aspects in modelling of automated plants. The authors divide all model types into three different levels: macroscopic, microscopic, and mesoscopic modelling depths. Macroscopic models track the time behaviour of considered systems and modelling efforts are considered moderate whereas Microscopic models are used to examine individual behaviour and interaction of unique entities. Thus, the simulation is carried out at high level of detail and modelling efforts are high. Mesoscopic models are a mixture of macroscopic and microscopic models. These levels are described in more detail in figure 26.

Furthermore, the authors concludes another important distinction between modeling depths and model types. Firstly, to simulate with aid of a module as an integrated mechatronic model of the mechatronic domains (mechanic and electronic). Secondly, to use a single or a combination of models of components which are granular and fine decomposed when modelling individual components of the mechatronic system. This difference is explained in figure 22.

From this differentiation, four different kinds of models can be derived: Dead Time Models and device and kinetic-models (Simple, Ordinary and Complex). The Dead Time Models and device and kinetic-models are classified as either macroscopic, microscopic and and mesoscopic. The mesoscopic level of detail can be separated into two levels: non-dynamic and dynamic.

The Dead Time Model can be seen as black-boxes and corresponds to a coarse-granular modelling approach, see figure 23. This level describes a mechatronic system, but ignores its inner structure. Control input is simply delayed by a dead time and transformed to an output and no physical characteristics are considered. Errors like runtime monitoring (e.g. a transporter in a process does not finish on time) or
discrepancy errors (e.g. errors that describe discrepancies on sensor signals) ought to be modelled in a suitable manner to fit deterministic and stochastic investigations.

The device and kinetic-models can be seen as white-boxes, describing the inner structure of a mechatronic system. These can be divided into three different types: Simple, Ordinary and Complex device and kinematic models.

Simple device and kinematic models show behaviour and function of a device but offer no extra functions or physical behaviour, see figure 24.

Ordinary device and kinematic models provides physical behaviour to describe the characteristics of the mechatronic system/module, see figure 25. Thus, models of components must provide functions containing equilibrium of power and moments. However, movements are limited to stated paths, covering both translational or rotational movements and combinations of those, but free movement within space is excluded here.

Complex device and kinematic models are used to describe free movement in space and emulates reality so that cases like possible collisions between objects and other structural elements are simulated. Models of the basic system therefore depend necessarily on geometric design data and movement of goods and items is subject to physical rules. In addition, complex device-models must provide behaviour like switching hysteresis of sensors or s-curves of variable-frequency drives.

\[ f(x, y^{(0)}) = 0 \]
The above mentioned levels of detail are summarized in figure 26 and which type of aspect they cover.

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Macrosc. Modelling</th>
<th>Mesoscopic Modelling</th>
<th>Microsc. Modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dead Time Models</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consideration of entire process mapping</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Time-based behaviour</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Detailed device behaviour</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Dynamical/physical behaviour</td>
<td>no</td>
<td>no</td>
<td>yes**</td>
</tr>
<tr>
<td>System knowledge needed</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Failure States</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Consideration of processed good*</td>
<td>no</td>
<td>-</td>
<td>yes**</td>
</tr>
<tr>
<td>Properties of goods (mass, measurements, ...)</td>
<td>no</td>
<td>-</td>
<td>yes**</td>
</tr>
<tr>
<td>Movement of goods on stated paths (= degrees of freedom)</td>
<td>no</td>
<td>-</td>
<td>yes**</td>
</tr>
<tr>
<td>Free movement of goods in space</td>
<td>no</td>
<td>-</td>
<td>yes**</td>
</tr>
<tr>
<td>Collision of goods possible</td>
<td>no</td>
<td>no</td>
<td>yes***</td>
</tr>
</tbody>
</table>

* Good is synonym to bulk goods or piece goods  
** Acceleration free movement  
*** Only possible in simulated degree of freedom

Figure 26: Defined levels of detail and their comprised model types (Puntel-Schmidt and Fay, 2015)

4.4 Integration

Integration in this thesis refers to the ability to share models and data seamlessly between different IT-tools both internally and externally. It is a very important field of action as data exchange is a significant bottleneck within the engineering value chain today.

Strong separation of phases is normally the case in the plant engineering process and each phase uses variety of specialized engineering tools. In addition, the number of tools and sub-suppliers in a typical engineering value chain is increasing. Effectively, a broad heterogeneous IT-tool landscape is developed and becomes an issue regarding interoperability as each tool often handles individual and proprietary data formats. Therefore, development of data exchange that supports seamless data exchange is needed (Drath, Luder, et al., 2008; Kong et al., 2011) and the overall challenge regarding Integration is interoperability.

4.4.1 Interoperability and Information Management

The integrated approach in organizations today implies that systems, applications, databases and tools are connected to each other, which results in complicated, complex and comprehensive systems. The connections ought to be made so that information can flow as seamlessly as possible and be used without any difficulties (Kuehn, 2006). Therefore, two areas that must be dealt with are interoperability and information management.

Interoperability defines as the characteristics of a product or a system, whose interfaces are completely understood, to work with other products or systems, at present or future, in either implementation or access, without any restrictions (August Hugnell, 2016). There are many solutions to this challenge, and neutral data formats and interfaces are frequently presented as solutions. However, as sharing of simulation models across organizational boundaries offers high-quality models, it also leads to possible data propriety issues and the domain experts demand a way to protect their critical knowledge. Therefore, in order to accomplish subsequent use of simulation within operations, it is crucial to provide
a secure interface between the simulation system and the real plant operation. (Süß, Strahilov, and Diedrich, 2015)

Information management concerns three aspects. Firstly, the acquisition of information from one or more sources. Secondly, the custodianship and the distribution of that information to those who need it. Thirdly, the ultimate disposition of information through archiving or deletion.

4.4.2 Neutral Data Formats

The difference that data structures and data models (i.e. how information is stored and represented) proprietary data formats have is the issue behind lack of interoperability. When exporting information, the receiving application must be able to read and interpret the information in order to use it. Therefore, work with standards and neutral data format have been conducted so that translation becomes possible.

An advantage with a neutral data format is that parties along the value chain are not required to use the same kind of applications, which widens spectra of potential users and decreases duplication work. Thus, the component manufacturer would be able to provide a library of all his components in a format every customer is able to use (ibid.). Drath, Luder, et al. (2008) also highlights the benefits of neutral data formats regarding information exchange between manufacturing engineering tools as it enables interoperability between the tools. Therefore, neutral data format is a central part of the vision of reaching a seamless value chain (Drath, Luder, et al., 2008; Thapa et al., 2006). However, information losses normally becomes an issue when converting into neutral data formats. (Dimitrov and Valchkova, 2011; Xu, 2009)

4.4.3 Neutral Data Formats-AutomationML

A neutral data format currently being developed for supporting file exchange across IT-tools is AutomationML. It is developed by the companies Daimler, ABB, Siemens, Rockwell, Kuka, Zühlke, netAllied and the universities of Magdeburg and Karlsruhe. It is meant to serve as a data exchange enabler between manufacturing engineering tools and therefore it supports the interoperability between them. Currently, information silos that are heterogeneous regarding syntax and semantics tend to be created throughout the life-cycle of plants. (Süß, Strahilov, and Diedrich, 2015) Therefore, AutomationML intends to become an enabling technology for VC, since VC concerns the reunification of interdisciplinary engineering results which currently are spread to different tools. (Drath, Luder, et al., 2008)

AutomationML follows the object-oriented programming paradigm, which means that it describe real plant components as data objects, with appropriate attributes. Examples of data objects could be grippers, values, signals, robots, tanks or complete manufacturing cells. These objects contain information about plant topology, geometry, kinematic, logic, behavior description and references & relations to other objects.(Kong et al., 2011) However, as tools and therefore data formats already have been developed for each of above mentioned objects, AutomationML aims at recover required functionality from existing data formats and possible extensions of them. In short, AutomationML extracts information from its host tool. Furthermore, the extracted data becomes neutralized. Hence, engineering investments otherwise bound to the tools is protected. Therefore, AutomationML facilitates issues with intellectual property and the data format can be seen as the glue between otherwise separated engineering information. (Drath, Luder, et al., 2008)

4.4.4 Neutral Data Formats-CAD

Within the CAD domain, the work with data exchange has been conducted for a long time. The need surged due the way of working in the engineering workflow implying that one organization might develop the CAD model, another all analysis work of the same model and the third party might be the one responsible of manufacturing the product. There are numerous different CAD tools on the market, that differs in e.g. functionality, but most importantly in regards of interoperability they differ in data structures and data formats. (Xu, 2009) Therefore, standard formats like IGES, STEP, DXF and Parasolid have been developed. However, there is always some loss of information when translating data from one CAD data format to another (ibid.). Even if neutral data formats were designed to solve this problem,
there is currently no format that completely can eliminate all translation issues (Dimitrov and Valchkova, 2011).

4.4.5 Neutral Data Formats—Behavioural Models

There are several languages available to describe the behaviour of mechatronic components. PLCOpenXML, Matlab/Simulink (a toolset with the language Matlab) and Modelica are some and not necessarily all of the languages that exist. There are differences between the languages regarding possibilities to perform co-simulation, calculation and if they are open source or proprietary languages. PLCOpenXML fails with co-simulation and cannot include differential equations which implies that only simple behaviour models can be made. In Matlab and Modelica, differential equations and co-simulation is possible and both tools can import and export their models as FMUs and to execute co-simulations using FMI, which is explained in 4.1.4 Co-Simulation and 4.1.3 Model Exchange Methods. Additionally, as mentioned in Model Exchange Methods 4.1.3 FMU is considered appropriate as format for behaviour models of mechatronic components. Therefore, Matlab and Modelica are preferred to PLCOpenXML. However, Matlab is a proprietary language and can only be used by one tool whereas Modelica is an open source language that enables a variety of tools to use it. (Süss, Strahilov, and Diedrich, 2015)

4.4.6 Interfaces

The work with interfaces between applications is also in progress. Since it would require companies massive investments (both in time and money) in new IT-infrastructure to enable seamless information flow, it is favorable to work on possible tool chain integration instead (ibid.). An interface within computing is defined as a shared boundary which two or more separate components of a computer system exchange information across. Thus, the exchange can be between hardware, software, peripheral devices, humans and combinations of these. Between applications, application programming interface (API) is usually used and could be said to be a set of clearly defined methods of communication between various software components.

4.4.7 Intellectual Property

IP concerns intangible creations of the human intellect and protection of these is partly the foundation of willingness to invent and develop (Goldstein, 2008). Artistic works like discoveries, inventions, and designs, can all be protected as IP. Deployment of such information (i.e. intangible property) is considered harmful and difficult to control, since its information can be "consumed" by an unlimited number of people. In contrast, traditional property can be secured by e.g. fences and guards to control it (Reese, 2008). IP protection’s main purpose is to encourage the creation of intellectual goods by giving people and businesses property rights to the information and intellectual goods they create. The possible profits that can be made from these intellectual goods serve as economic incentives that are expected to stimulate innovation and contribute to the technological progress (Goldstein, 2008). In addition, Süss, Strahilov, and Diedrich (2015) express that it is a challenge for component manufacturers to share information without revealing confidential data. The authors argue that provision of models containing the behaviour of their products may imply a risk that competitors analyze them resulting in a loss of competitive advantage.

4.5 Usability

Usability as field of action that treats the work of making simulation results accessible, especially for non-simulation experts so that the decision making processes during plant operation can be made with better information ground. Thus, integration of simulation into the plant operations must be developed further. (Oppelt, Barth, and Urbas, 2015)
Non-Technical Fields of Action

The non-technical fields of action are work-flow, acceptance, education and collaboration. They mainly concern soft factors regarding simulation and the research focus on organizational shortcomings.

4.6 Work-flow

Work-flow refers to the process or method that an organization use during the plant engineering process (see figure 3). Oppelt, Barth, and Urbas (2015) concluded that four actions within work-flow must be addressed. Firstly, the general need to question current work-flows and establish an information structure that enables simulation to become a standard in the organization. Secondly, make VC a standard process within each automation project. Thirdly, that the VC activities should start already in the design and planning phase. In short, make sure that the VC activities are accounted in the early development phase of the product the organization is aiming to bring to the market.

Nowadays, engineering of specialized production equipment is characterized of sequential and separated processes. The engineering process is initialized with the mechanics, proceeding with the electrics and ending with the automation design (see figure 27 (Drath, Luder, et al., 2008; Neugebauer and Schob, 2011; Westkämper et al., 2012)). To enable simulation (and simulation will be inevitable since requirements regarding time managements (shorter time frames) will increase) a concurrent design methodology is often stressed to be inevitable. (Neugebauer and Schob, 2011).

As explained in 3 Introduction to Virtual Commissioning, the target of the commissioning step is to reach a plant that is capable of production. Nowadays, the commissioning process is mainly conducted manually and prior to the start of commissioning, the correct function of the system must be tested. This testing consists of four parts and is normally separated into hardware and software tests. The software test includes three parts. Firstly, the factory acceptance test (FAT) that analyzes if the process control system and its software is according to its specification. Thus, the production equipment is mounted on site at the PEP and then dismantled and shipped to the customer (OEM). Secondly, the site acceptance test (SAT) which is a test to test the final production site after delivery generates the same results as with the FAT. Effectively, the production equipment is mounted again on site at the customer and the same tests as in the FAT are conducted. Thirdly, site integration test (SIT) where testing of multiple systems and whether they are integrated and interact with each other is conducted. The commissioning ends with plant start up, proof of performance and continuous and stable production is conducted.

The goal with implementation of VC is to not to find any errors in the FAT and thus shorten the commissioning and decrease the need of manual (physical) testing. (Oppelt and Urbas, 2014)
However, VC is currently seen as an additional step towards the end of the development phase and is associated with effort, time and costs. Hence, the ongoing research concerns how to make VC an integrated and a continuous part throughout the whole engineering work-flow (Oppelt and Urbas, 2014). Oppelt and Urbas (ibid.) argue that making VC an integrated part of the automation phase would reduce the threshold to use it as continuously building the simulation model would decrease the effort by breaking it down to small steps. In addition, the automation engineer will be able to test each function immediately after implementation and benefit directly from the simulation. Therefore, errors will be found at the earliest point in time leading to cheap correction. Hence, VC can be seen as an engineering support tool, and not only a simulation tool.(ibid.)

Drath, Weber, and Mauser (2008) presents an evolutionary concept for a practical and realistic technical approach for introduction of VC. For this, the authors formulate five major industrial requirements that must be dealt with in order for VC to become widely accepted by the industry.

Firstly, the control code for PLC, robots and HMI must remain unchanged while embedding it into the VC environment, i.e. no modification between the mediums should be required. This would reduce the internal resistance towards using VC. Secondly, existing engineering tools and languages for PLC, robots and HMI ought to be intact since it would enable re-usability of existing libraries and standard solutions. Thirdly, the VC environment should be seamlessly embedded in the existing engineering work-flows to minimize the additional effort of creating simulation models. Fourthly, the VC environment ought to be brand neutral, due to the large variety of e.g. PLC brands on the market. Fifth, PLC programs must be able to run on virtual controllers that behave exactly as the corresponding real controller. At the time of writing the article An evolutionary approach for the industrial introduction of VC, the authors found no commercial tools that covered all of the mentioned requirements.(ibid.)

In addition, Oppelt and Urbas (2014) also suggests requirements that must be fulfilled by the tools used in VC. First of all, only three tools ought to be needed: simulation, planning and automation engineering tool. Arguably, every additional tool will increase the complexity. The simulation tool should support four domains. Efficient simulation design by templates and import interfaces, scalable simulation model ranging from simple signal simulation up to process simulation, usability concept designed for automation engineers and support for HiL and SiL configurations. The planning tool ought to support management for test cases and documentation and export of process layout as basis for simulation tool. Ultimately, the automation engineering system must enable export of hardware configuration to connect to the simulation system and that it can be stimulated by a simulation system through HiL-or SiL configurations.

4.6.1 Project Capability

Commissioning of machines is a project based activity. One of the most important questions for any project based organization (PBO) is how to develop its project capabilities. For example, Turner (2009) suggested a four-step model of building project capabilities: comprising variation, selection, retention and distribution of project management (PM) practices. In another four-step model, Davies and Brady (2000) focused on the key role of vanguard projects and subsequent achievement of the economy of repetition as the core component of project capability building. Later on, they refined the model by linking it to exploration and exploitation of knowledge and differentiating between project-led and organization-led learning activities (Brady and Davies, 2004). Melkonian & Picq (2011), in turn, viewed project capabilities as bundles of various capabilities at different organizational levels and proposed a more nuanced view of project capability building. In all of these models, organizational project capability building is strongly relying on effective inter-project learning and knowledge management. Thus, how can PEPs and OEMs develop its inter-project learning and knowledge management in the commission of the necessary machines, were VC is the incremental step needed to raise the project capability.

The tacit component of knowledge taken in an organizational perspective is embedded in distinct routines and stored within its memory (Brady and Davies, 2004; Pemsel and Müller, 2012). To utilize the embedded component it is important to transfer the knowledge from tacit to explicit (see figure 28). According to Brady and Davies (2004), this is done by focusing on the outcomes from learning through double-loop reflections, and could be used by either individuals or organizations (ibid.). Furthermore, Brady and Davies (ibid.) introduce a project capability-building model, consisting of two levels of learning: bottom-up and business-led. The bottom-up level consists of three phases. The first phase is strictly exploratory, the learning occur when companies move into a new market or new technology. Phase 2 is when lessons learned are transferred between projects, and phase 3 is when companies increases
its capabilities to deliver many projects. Business-led learning is present when strategic decisions are taken to create and perform increasingly predictable and routine project activities. Done by utilizing organization-wide resources and required capabilities (Brady and Davies, 2004).

![Diagram](image)

**Figure 28:** The types of knowledge and how its categorized.

## 4.7 Acceptance

Refers to how to gain acceptance from the management to use simulation tools. In order to reach a success within simulation, it is important to enable a trust and acceptance with the tools being used throughout the organization.  (Oppelt and Urbas, 2014)

The reasons why acceptance differ within the organization, as well as along the value chain, can be derived from the different viewpoints on the benefits from VC.

From the perspective of the PEP there are two benefits with shorter commissioning and ramp-up time. Firstly, the OEM will have less time to submit changes in the order to the PEP. Secondly, shorter time of capital and assembly area lockup at the supplier’s plant due to faster SAT and SIT (Reinhart and Wünsch, 2007).

From the OEM perspective, a shorter time-to-market offers a competitive advantage with differentiating oneself from the competitors, which implicitly secures market shares as a short time-to-market is one of the most important drivers in the OEM market (ibid.).

### 4.7.1 Acceptance within Small and Medium sized Enterprises

Acceptance vary due to the size of the organization (Moeuf et al., 2017). According to OECD (2017), SMEs (Small and Medium sized Enterprises) are non-subsidiary independent firms that employ a given number of employees, i.e. they are classified as SMEs if they are within the predefined limits. Moeuf et al. (ibid.) highlight several aspects why it is relevant to understand the day-to-day operations for manufacturers part of the SME segment. Moeuf et al. (ibid.) highlight two common problems commonly occurring for SMEs. Firstly, despite the existence of methods to create production planning and control management (i.e. to synchronize flows), these methods have proven difficult to implement for SMEs. Lack of expertise and leadership are the faulty aspects. Secondly, the implementation of computer IT-tools, e.g. ERP-systems, are complex and costly to implement and give a rigid setting to the manufacturer once installed. (ibid.) However, despite that the Industry 4.0 concept is based on the deployment of new technologies that require large investments and high level of expertise, Moeuf et al. (ibid.) argue that solutions linked to Industry 4.0 suits SME since it promise a more flexible approach with decentralized information and decision-making. Nonetheless, Moeuf et al. (ibid.) are ambivalent in their conclusion. On the one hand, introduction of new technologies and practises offer great possibilities that would
suit SMEs. On the other hand, these investments are risky and demanding for SMEs. (Moeuf et al., 2017)

4.8 Education

Education refers to the development of a common methodology and terminology concerning simulation and associated activities. The development should be used to create knowledge on how to easier integrate data and tools, and thus ease the technological aspects of integration (Integration 4.4). In addition, to continuously develop the educational program towards simulation for process and automation engineers, is a necessary action, to benefit, and quicker reach, simulation as a standard.

To conduct VC, software tools and engineering know how is needed (Oppelt and Urbas, 2014). Major vendors offer tools for VC, but they tend to require a high level of training or in-house secondment of specialists from the vendor. Effectively, mostly large enterprises (e.g. in the automotive industry) choose to conduct VC. Therefore, “Digital Factory” solutions do not tend to be suitable for SMEs, since they normally do not have the resources to use these techniques. There is a need of improved model building methods to minimize the effort and expertise required to build a model. As models on this detailed level require high level of expertise and considerable effort regarding technical knowledge and time, VC is not viable for SMEs. (Hoffmann et al., 2010)

4.9 Collaboration

Collaboration refers to the collaboration across companies to provide and exchange simulation models. As mentioned in Integration 4.4 and Work-flow 4.6, the parallel work when creating simulation models in isolated environments makes it difficult to obtain efficiency in modeling. Therefore, Oppelt, Barth, and Urbas (2015) suggest that a collaboration model should be developed in order to enable the exchange of simulation models between companies. Furthermore, the author suggests that the simulation model should be created by one company and shared through the collaboration model to other companies. This is important, since a distribution of the modelling would enable the appropriate company to be involved in the design, engineering and commissioning of a manufacturing plant. However, there is currently no collaboration model that addresses these issues. (ibid.)

4.9.1 Business Ecosystems

A trend within strategy for the past years has been an increased interdependence between different organizations and activities, which has resulted in the emergence of the term Business Ecosystem (BES) in strategic management (Adner, 2017). Compared to the traditional industry concept, BES implies a more rich and flexible understanding of the business environment.

Iansiti and Levien (2004) describe how companies such as Wal-mart and Microsoft developed competitive advantages by having a strategy to build a BES around their value proposition. Along the same line, Moore (2006) present how Sun and AT&T in the eighties joined forces and promoted interoperable hardware based on the same software, Unix. The plan was to create a community of smaller companies that would offer interchangeable hardware. This would be a game changer according to the Sun and help the two companies to jointly enter the oligopoly marketplace – controlled by giants, such as, IBM, Digital Equipment Corporation, and Hewlett-Packard – on Sun and AT&T own permissions.

Iansiti and Levien (2004) further conceptualize BES and its strong parallels to biological ecosystem. They highlight the health of the ecosystem and state that individuals within the biological ecosystem will thrive, only when the biological ecosystem is healthy. In contrast, the participating individuals will suffer if the biological ecosystem is unhealthy. This goes for BES as well, because business networks are intertwined in mutually dependent relationships.
5 Results

This section will provide a summary of the answers from the interviews. This summary is our own interpretation of the answers and is meant to give a combined picture of how each part of the value chain relate to each field of action. An elaborated and granular depth of these results will be provided in the Discussion & Analysis (section 6).

Each field of action was investigated through a set of questions destined to provide an explanation about how companies relate to each field of action. The same questions were used in all interviews in order to obtain comparable answers. However, the questions were modified without changing the meaning to fit the interviewee and his perspective. The questions can be found in section 7.3.

The summary is divided into the three parts of the value chain: Component Manufacturers (CMs), Production Equipment Providers (PEPs) and Original Equipment Manufacturers (OEMs). Each part starts with a summary of the characteristics of the company and their views on advantages and disadvantages with VC. Thereafter each field of action follows with a summary of how the companies relate to the questions asked.

First and foremost, a clarification regarding the vocabulary in this chapter. All models concern virtual/digital models if nothing else is mentioned. However, virtual/digital is occasionally combined with "model" to clarify for the reader what we mean. If the model or the context is not virtual/digital, it is clarified with the words "real" or "physical". In addition, we make a distinction between simulation models and models. A model is a component (electrical or mechanical), machine, cell, factory/plant and the level of abstraction can vary.

A simulation model can be a single model or several models put together in order to perform a simulation (virtual experiment).

A digital twin is as the name suggests, an identical virtual/digital replica of a component (electrical or mechanical), machine, cell or factory/plant. Thus, all levels of abstraction are covered.

Virtual manufacturing refers to activities that involves manufacturing activities performed on computers with the aid of software. Thus, it concerns virtual/digital activities within companies that supports real manufacturing or other real manufacturing related activities. Thus, VC, CAD, robot simulation, flow simulation, process simulation and other similar are included in the term "virtual manufacturing".

High level of maturity within virtual mfg implies that the company has experience, developed methods and processes and use virtual manufacturing frequently in their daily business.

Production equipment implies all equipment used for production. It concerns machines, robots, fixtures, sensors, motors etc.

5.1 Component Manufacturers

This subsection will introduce the summarized view of the Fields of Action from the CM perspective.

5.1.1 Summary of Interviews with Component Manufactures

CMs provide PEPs and OEMs with spare parts, software and associated services. Our interviews were mainly with people who worked with software in terms of development or selling. Nonetheless, they had deep insights regarding electrical components and their corresponding virtual models. The perspective the interviewees had in terms of abstraction level varied, ranging from plant and cell level down to electrical aspects of components.

Their viewpoint of advantages with VC is that it will reduce the overall risk in projects and that VC is likely to decrease the total commissioning time compared to conventional commissioning. In addition, VC will enable an optimized and mature system early in the production phase, i.e. an overall higher quality of the production equipment. Due the possibility to test many scenarios virtually, it can be seen as a learning activity about the production equipment. Furthermore, earlier involvement of different disciplines and engagement of operators in the development process will be possible. Effectively, if errors
are found virtually early, the cost of fixing them is lower than to detect and correct them on site during the commissioning phase.

The main drawback with VC is that it currently implies extensive effort and that VC will require investment in time, education of personnel and in software prior to successful implementation. A new type of skill among engineers is necessary and new ways of working will require organizational change. Since VC concerns simulation and is an interdisciplinary field, the engineer’s knowledge about simulation ought to increase and different engineering disciplines must collaborate more than previously. In addition, disciplines need to know and understand other disciplines better than they do today.

Concerning the organizational change, a concurrent design methodology must be developed and early adopters ought to lead this development. It will require both dedicated people and engaged top management, so that the entire organization supports this process. Therefore, it is crucial that companies have a clear purpose and goal with VC and not to aim too high too quickly.

5.1.2 Model Re-Use

CMs rarely build simulation models themselves. However, in projects that include a delivery of a production systems, the corresponding simulation model is delivered. Nevertheless, virtual manufacturing is considered to be a new interesting business for CMs. The idea is to support PEPs and OEMs in the creation of models and simulation models.

Software provided by CMs often includes standard libraries with generic, and in some cases, specific virtual components. These can be parameterized upon implementation in a simulation model to fit the specific simulation needs. Their vision is to enable re-use as much as possible. In addition, CMs are investigating the possibility to provide behavioural models to the components. Nowadays, solid (dead) 3D models are usually (but not always) offered and users must add kinematics themselves.

5.1.3 Modeling Efficiency

As said before, CMs do not create simulation models or models on regular basis. However, the interviewees argued that the overall issue with creating models is not to create each part of the VC model i.e, the PLC-code, the emulation of components and the behaviour model. These can be kept in libraries or information management systems and thus enable re-use. The major issue is putting all different components together in a 3D simulation model. Components developed in different applications must fit together, and the work to make them fit together must be reasonable (i.e. low EMP). Thus, applications and file formats must be able to work together, i.e. be interoperable, and not be vendor specific.

CMs offer software and solutions within each part of a VC model (PLC-code, the emulation of components, the behaviour model and putting it all together). They are currently investigating to offer detailed emulation of components, both vendor specific and generic with corresponding behavioural models. According to CMs, this step will reduce the modeling effort for downstream parties in the value chain, since the behavioural model nowadays must be created by the user of VC. This service has not been offered previously (mostly due to the absence of a demand from the market). Nonetheless, this service will raise new question for the CM regarding how to handle IP.

Historically, a black-box solution of the component (solid CAD model) with a detailed virtual control that emulated the behavior has been sufficient. However, to achieve full benefits of VC, both PEPs and OEMs argue that this black-box solution might have to change in favor of more detailed models.

CMs that currently offer virtual components (not always detailed) offer them within the software. These components are therefore property of the software company and a license must be purchased before the customers get access to the components. In addition, questions regarding IP can also be solved by e.g. protecting files and PLC-code, a feature offered within the softwares and is mostly used by PEPs. However, OEMs often require the possibility to see the code and have access to all files.

If a CM develops a vendor specific component to a specific customer, a NDA can be prepared and the model becomes property of the customer (usually a PEP).

Responsibility of updating component models (offered by CMs) is the CM’s, and more precisely, their product development team.
5.1.4 Integration

CM describe interoperability as one of the major issues with virtual manufacturing. Usually, interoperability is developed between applications from the same vendor (not always), but interoperability between different vendors is not always the case. Therefore, file formats normally must be exported to standard formats in order to enable import into other applications. This export usually implies information losses and this information must be added back to the model. Standardization is often the suggested solution to interoperability. However, CMs naturally have some degree of reluctance towards opening up their software to other CM-vendors due to business related incentives.

5.1.5 Usability

CMs do not simulate themselves, their software is used by PEPs and OEMs.

5.1.6 Work-flow

CMs stress that the work-flow within the plant engineering process is characterized by sequential work, i.e. each discipline do their part in a specific order. The same applies to simulation. Usually each discipline simulates their work in their specific software and makes sure that it works followed by passing it on to next discipline. It is when the combined work of all disciplines is put together that design flaws can be detected.

Some industries have reached a high level of maturity in virtual manufacturing concerning their working process. These companies aim at using work done in earlier phases to enable simulation throughout the entire developing process. In companies where simulation is considered a standard tool in the developing process there is normally some kind of strategy concerning how to make use of modeling efforts from earlier developing phases. However, this strategy tend to be one sided and seen from upstream to downstream. Hence, product development rarely takes into account the work done by the production equipment people resulting in that design changes in the product might imply changes in the production equipment. In other words, product design changes are not simulated to fit the current production equipment.

5.1.7 Acceptance

There is economical value with VC if the cost savings from early error detection and time saved in the commissioning is lower compared to the cost from pursuing conventional commissioning. VC must be compared with the time it takes to create the simulation model, and the value the simulation model generates. Another intangible value is that the quality of the delivery can be higher already from the start.

5.1.8 Education

CMs, and especially sales people within those companies, work with educational activities for customers (PEPs and OEMs) and offer support.

5.1.9 Collaboration

All interviewees argue that there is collaboration along the value chain. This collaboration mainly concerns opening up software, projects with customers and providing behavioural models of components. There is a trend among CMs towards becoming more of a software company than a hardware company since this service will become essential in the business. This poses great pressure on creating interfaces with other vendors (CMs) to facilitate modeling and seamless flow of information for the users. Furthermore, PEPs and CMs tend to work as partners when learning and developing methods and tools. Recent initiatives made by one CM is to be able to offer standard components with behavioural models in their software, e.g. in Mechatronics Concept Design.
The collaboration with other vendors (CMs) regarding opening up software is upheld and filled with friction due to that companies are unused to work together in this way. The difficulty to quantify the benefits of collaboration makes it difficult to change the organizational attitude. There is a difference of opinion regarding providing detailed models of components among CMs. All agree that it will be an inevitable part of the future business models to offer virtual models. However, they disagree on how detailed and close to reality they must be as it becomes an issue with IP. Another issue to solve is how pricing of these models should be made. There must be a value proposition for each party in the value chain and the cost must be distributed.

The benefit of a close collaboration is argued to be overall improved quality of the end product, faster development of and distribution of knowledge.
5.2 Production Equipment Provider

This subsection will introduce the summarized view of the Fields of Action of the Production Equipment Provider-perspective.

5.2.1 Summary of Interviews with Production Equipment Provider

PEPs support OEMs with the engineering and construction of production equipment. The interviewed PEPs are compared to the OEMs and CMs small companies in terms of revenue, employees and enjoys low profit margins. There are different types of PEPs and they differ in which kind of service they offer. Some build entire production systems, machines or cells whereas other just offer virtual manufacturing services. Our interviews with PEPs covered this whole spectra. However, PEPs that work frequently with the automotive industry have a higher level of maturity in virtual manufacturing tools, e.g simulation, than the rest. Therefore, the answers from the interviewees varied.

The amount of commissioning projects that PEPs execute per year ranges from ten to fifty and the time needed to complete a project varies. It depends on the complexity and size of the project and can range between two days to one year. Commissioning is described as a resource intensive activity and that it is difficult to estimate and predict the cost.

The PEP’s maturity in using simulation as a standard in their working process varies and tends to be a consequence of which type of OEM they mostly work with. The most mature PEPs are the ones that frequently work with the automotive industry.

Generally, PEPs work with simulation in their daily business. However, the type of simulation they use varies. Most PEPs use robot simulation as a standard simulation activity whereas other types of simulation, e.g. flow simulation, process simulation, assembly simulation and PLC-simulation is dispersed. None of the interviewed companies use VC regularly. However, several of the interviewed companies, especially those who work with the automotive industry, are investigating VC and develop methods to be able to use VC. Among our interviewed PEPs it is expected that they in a near future increasingly will be forced to use VC since OEMs will require it.

The advantages with VC according to the PEPs are: shorter commissioning time, validation of code and mechanical constructions, early error detection, educational purposes and enable early involvement of different engineering disciplines. It should be seen as front loading of the project to reach the goal quicker and also to be able to optimize the solution prior to real commissioning. Furthermore, investments in VC can also be seen as measure to stay ahead of competition, or even a prerequisite to stay competitive. It enables the possibility to keep a high level of expertise in-house and still lower costs. Instead of being forced to outsource certain tasks to low wage countries since the price of commissioning will decrease as VC increasingly is used. Thus, if you do not have the capability to conduct VC, your profit margin of the project will be lower.

The main disadvantages with VC is not the technology itself, but the barriers towards being able to conduct VC. It will require PEPs to educate personnel and also to change the way of working within the organization, which will need investment in time. In addition, as software will be an enabler of VC, investment in software is inevitable. Currently, VC is accomplished by combining several softwares, using HiL or SiL solutions where each software implies a license cost and required know-how about the software. The combination of software from various disciplines needed for VC also leads to interoperability issues internally for PEPs as not all software have interfaces. In addition, interoperability issues with external parties is also a barrier.

PEPs that work with OEMs that require delivery of models of everything delivered physically are somewhat forced to keep many softwares (that offers the same functionality). Each OEM usually has a unique set up of softwares and PEPs normally have to deliver the project in the file format chosen by the OEM. Therefore, the PEPs must have the ability to deliver in many file formats.

Furthermore, the modeling depth needed for a successful VC is unclear and it is also unclear which parts that ought to be investigated virtually and which parts to be investigated on site.
5.2.2 Model Re-Use

The PEPs that use simulation build their own simulation models and models are either created from scratch or retrieved from libraries. The most common simulation conducted by PEPs is concept-based where the customer is shown how an idea can be realized. Then, the model can be developed to verify that requirements like, e.g., cycle times, the robot’s range and reach are met with the suggested solution.

They strive towards re-using models already built and all models are saved in data bases. However, each project tends to be unique and thus, re-usability becomes complicated. Normally, standard components, mechanical fixtures and standard blocks of PLC code is re-used and just modified to fit the task at hand. Occasionally, models of components can be downloaded from the suppliers’ website. However, these models usually lack kinematics and must be parametrized.

5.2.3 Modeling Efficiency

The creation of a simulation model usually starts with a 3D layout of the area. This layout is normally created during the negotiation process with the OEM. However, sometimes only 2D layouts are available and the project must start with the creation of a 3D model. The steps that follow involve the modeling of fixtures, components, actuators, sensors, and robots. These are either created from scratch in a CAD software, 3D-scanning, retrieved from libraries in-house or downloaded from libraries from suppliers. Nonetheless, components provided by suppliers (CMs) normally have to be modified. They usually lack the behavioral model and I/O, which must be added to components prior to simulation. However, within the robot models, kinematics is usually offered by the suppliers.

The last step involves putting above mentioned models together in a simulation model. This is crucial for VC since mechanical features, electrical design, robots and automation is simulated jointly. However, this last step is rarely done by PEPs and among the interviewed companies only one had completed a pilot project where this last step was tested.

As modeling is considered one of the major barriers towards the utilization of VC, modeling efforts must be eased as much as possible. Most of the PEPs state that a clearly structured and well communicated working process with all parties involved would improve their modeling. Furthermore, working with standards is considered crucial and softwares must have interfaces to decrease issues with interoperability. In addition, work done in virtual environments must be directly transferable into the real world so that no extra time in translation must be spent. Modularized concepts to enable combination of different modules is also considered important.

In summary, the goal is to achieve plug-and-play solutions (modules), work according to standards and to have libraries with standard components, with logic and behavioral models to enable re-use and decrease modeling effort. This is the main challenge with virtual manufacturing.

Another interesting barrier is that PEPs hesitate to invest in VC since they do not want to invest time and money in software that only might enable them to service certain companies that use the same software. There is currently no dominant design concerning VC, and to be an early adopter is risky as the softwares are expensive. Additionally, the requirement to use VC has not yet come from OEM.

Ownership and updating of the model is usually the OEM’s responsibility. Since the model often is part of the delivery (especially within the automotive industry), the OEM owns the model when it is completed. However, the PEPs are usually not contractually obliged to delete the model and can therefore re-use parts of the model in similar projects. The updating of the simulation model as the reality change is done by the OEM. Since the PEPs do not use the simulation model after delivery, it is not updated. Nonetheless, models, e.g., components and fixtures that the PEP use when creating simulation models are kept by the PEP. An interesting aspect concerning models is that when these models are entered to the simulation software, the connection with the original file disappears. Therefore, updates in the original file are not transferred to the simulation model and vice versa.

5.2.4 Integration

Interoperability is an issue according to the interviewed PEPs. Nowadays, there is no easy solution to this, and shifting between different vendors is usually a problem that implies information losses that in
turn requires extra work (re-work).

PEPs use software from many vendors, e.g. Siemens, ABB, Kukha, Atlas, Festo och Servo, to be able to serve several customers. These are not fully compatible with each other, and it will become an issue when the PEPs will commence with VC. The PEPs do not see VC as a technical issue, but an organizational issue where no CM is interested in opening up their software. The perceived attitude is that the CMs wish to sell their software and are not interested in helping a competitor. Effectively, PEPs must work around the issue, which often implies duplication of work.

They work with neutral data formats to enable export and import. However these tend to require more computational power than original file formats and information normally disappears when exported to standard formats.

IP is not considered an issue. This is not an issue since the PEPs do not produce any "products", but production equipment according to the order by the OEM. They argue that the competitive advantage is the ability to offer complete solutions, and not just parts e.g. PLC-code. However, if 3D-models are delivered, these come at a price and nothing is delivered without payment.

5.2.5 Usability

Since PEPs simulate to validate solutions and ideas during the development phase of the project, simulation results are used immediately and decisions are based on them. Hence, the results from the simulation are valuable immediately.

5.2.6 Work-flow

As simulation will become an important tool for engineers, a structured way of working throughout the plant engineering phase will become necessary. However, from answers among the majority PEPs it is clear that there is still development needed before a suitable methodology/work-flow is achieved. Mainly, the work-flow should be based on a strategy regarding how modeling efforts from early steps can be used in later steps, i.e. refinement of the work. The PEPs argue that no strategy is clearly documented, but that it is common sense among employees that information is refined along the work-flow and that suitable feedback normally is provided to earlier steps. Furthermore, PEPs aim at creating models and code that can be usable in future projects.

One PEP with a high level of maturity regarding VC argued that they have a clear strategy where modeling is seen as a chain of continuous improvements along the process. They have a clear information structure where information easily can be shared within the organization. Additionally, they use as few different softwares as possible in order to avoid issues with interoperability.

5.2.7 Acceptance

The perceived economical benefits with simulation are varying among PEPs. According to one half of the interviewed PEPs the economical value is clear. However, the other half argue that economical benefits are difficult to prove and thus unclear. An argument used by one PEP to stress the economical value is: "aerospace and automotive does nothing without virtually verifying firstly". Implying that it therefore must be economical. In addition, the value of saving time and get it right from start justifies simulation, despite time and money must be spent on modeling.

Nonetheless, those who cannot see the benefits argues that the initial investment in software and education is a large cost since 10-20 brands from different vendors must be handled in order to serve all of customers. However, it should be mentioned that this was perspective was presented by a line builder that generally must use various tool in their work. Other PEPs e.g. machine builders that use fewer tools in their project did not stress this issue. In addition, as project tend to be unique, modeling efforts might be difficult to re-use in other projects. However, it is believed that money can be saved by simulation. Especially if parts of the project that are sensitive of, or associated with large risk, are simulated.
5.2.8 Education

Most of the PEPs participate in workshops or other educational activities in order to increase the knowledge about VC.

5.2.9 Collaboration

The overall perceived impression among the PEPs is that no clearly stated collaboration exists along the value chain regarding simulation. However, it has been some development throughout the years. Fifteen to twenty years ago there was more time during production for commissioning of product- or production equipment changes. However, the time frame has become more and more tight concerning commissioning and problem solving, which has pushed the need for simulation.

Normally, it is the OEM that demand the simulation model and historically, PEPs have argued that it is too arduous to create these models. Hence, the OEMs have paid a substantial sum of money to obtain these models. However, overall market trends towards shorter time frames have shifted this viewpoint. Therefore, PEPs increasingly have to use simulation in order to comply with the requirements and demands of the OEMs.

However, some OEMs have high demands in the accuracy of the models, i.e. specification of requirements. This implies high costs of creating these models which raises the question of “how should these models be priced and who should pay?” In addition, the OEM ought to be more involved in the creation of models. Only written demands and specification of requirements is usually not enough. Increased involvement would enable simulation based on real data and effectively, all different test cases could be covered.

Currently, the collaboration with CMs is developing. The collaboration mainly concerns provision of 3D-models of their components, which lowers the threshold to create models. However, the delivery of corresponding behavioural models is still lacking. Generally, CMs are considered the least involved and developed partner in the collaboration. They do not get the full picture of the system PEPs deliver to OEMs. Thus, they do not understand what the OEMs need to succeed. CMs would need better insight in how their products are used and how their products interact when used in the work of OEMs and PEPs. In addition, PEPs stress more collaborative efforts from both sides (CM and OEM) since they feel alone in the development of VC.

Generally, the work with standards ought to be better. Software have been developing freely over time, which has led to many different file formats and major actors should take command and dictate standards. Therefore, a better collaboration between PEPs and CMs regarding software development would enable development according to feedback.

Furthermore, the software offered by CMs are expensive, and for PEPs, an investment in these is a major event financially. One PEP argued that the price and payment of the software ought to be reviewed by the CM in the initial stage. Mainly so that the PEP can see the benefits and learn how to use the software prior to take on the entire investment.

The major barriers against collaboration with external parties are the distribution of the cost and the benefit of the collaboration. OEMs want a model/simulation model delivered, since they can use it in their operations. The PEPs are increasingly required to deliver the model/simulation model, even tough they themselves do not benefit from all parts nor need the great level of detail.

The major benefits of collaboration is a better end product and mutual understanding throughout the project. In addition, the development of better and more knowledge regarding simulation that is distributed along the value chain.

The idea of offering more virtual manufacturing services to OEMs, i.e. deliver a digital factory, is considered interesting for PEPs. Modeling of these models/simulation models is regarded as important knowledge that ought to be kept in-house. Therefore, PEPs do not want to hire external parties to model for them, and it is more likely to hire personnel to model.

However, the purchasing of models, i.e. components, is acceptable. Actually, it is often already done through licenses. Additionally, in the event of absence of specific models, PEPs can consider purchasing these instead of model it themselves. However, if and only if it is a customer requirement to deliver a this specific model.
5.3 OEM

This subsection will introduce the summarized view of the Fields of Action of the OEM-perspective.

5.3.1 Summary of Interviews with OEM

OEMs are manufacturing companies that use production equipment to produce desired products. Half or our interviews were with representatives from automotive companies and the other half with different types of manufacturing companies. Generally, the interviewed automotive companies have a higher level of maturity in virtual manufacturing tools, e.g simulation, than the rest. Therefore, the answers from the interviewees varied.

When product changes occur or when new products are developed, changes to the existing production equipment, or design of new production facilities, are usually needed. Additionally, changes of the production equipment can also be the result of discovered improvements, e.g. productivity increase. However, OEMs rarely build or perform major changes to their own production equipment. Instead, PEPs are hired to build and commission production equipment.

The size of projects that PEPs are hired to perform varies. Some projects may require two years of planning and one year to implement. Furthermore, a few OEMs had the required knowledge to integrate smaller machines and to manage minor changes to production equipment without the help of PEPs. Nevertheless, all OEMs hired PEPs on a yearly basis. Moreover, the complexity of the projects varies too. They can range from implementation of one robot cell to twenty robot cells or design of completely new product-lines.

Commissioning is considered a resource intensive activity that is difficult to predict and quantify in terms of time and cost. However, as downtime in production is costly, a lot of resources are used during commissioning. Historically, PEPs have been responsible to deliver and integrate e.g. machines into the production system during a planned installation slot. However, as the industry is becoming more and more digitalized, virtual manufacturing, e.g. simulation is increasingly becoming a part of OEMs standardized work-flow. Therefore, the required delivery from the PEPs is changing.

Today, it is becoming increasingly important for OEMs (especially those with a high level of maturity regarding simulation) to obtain a model of the production equipment as well.

There are several advantages with models and simulation. The interviewees argued that the model gives them an opportunity to virtually test the new production equipment and therefore understand how it will work together with the current production equipment in the facility. In addition, models facilitate communication between OEMs and PEPs since the model works as a common platform, where e.g. geometry, movement and PLC-logic can be analyzed. Effectively, a smoother acceptance-phase between the PEP and the OEM is enabled. Furthermore, the softwares used to conduct VC will enable error detection, balance the changeover time, find optimized utilization rates and enable an infinity of resources to experiment with. Hence, the automation engineer will obtain a tool that enables work in risk free virtual environments.

Despite the advantages with VC, none of the interviewed OEMs are currently using VC in their everyday business. However, many OEMs are investigating and researching VC and are trying to assess the value of VC. Currently, OEMs are unsure of how to balance efforts to conduct VC against the benefit the VC will generate.

Furthermore, finding people with adequate competence to manage VC is difficult. The complexity of the models is high and therefore a holistic understanding on how relationships within the model affect other disciplines is needed. Additionally, deciding on which level of detail (abstraction level) the model should be built on is not obvious. Another drawback is the fact that the machine needs to be built twice.

5.3.2 Model Re-Use

Most of the OEMs create their own simulation models. The ones who do not create their own simulation models, buy the simulation models from PEPs. Most of the simulation models are used to assess the production flow, were the level of detail of the models vary among the OEMs. Some build 2D-models but OEMs with high maturity level build 3D-models. The general goal with the more detailed 3D-models of
e.g. production cells, is to verify the geometry within the production cell. Furthermore, the simulation is used to assure that it is possible to produce the planned product or to simulate if changes to an existing product will have any impact that requires action.

OEMs strive to re-use simulation models as much as possible and usually have a plan concerning how they should re-use simulation models. The re-use is achieved by documenting projects and saving them internally in PLM-systems or other central databases. The PLM method assure that work is carried out based on the latest and correct version of a simulation model. However, the OEMs that only had a central database to store files in, struggled to assess the most recent version of the simulation model, which decreased the modeling efficiency. Re-use is also accomplished by using libraries with models of standard components. Nonetheless, as models usually are part of the delivery from the PEP, the focus on model re-use is not crucial for the OEM, but rather the PEP.

5.3.3 Modeling Efficiency

OEMs generally do not create models themselves. Nowadays, PEPs are hired to create, and commission the production equipment and to deliver corresponding model. Therefore, the OEMs do not have to model themselves.

However, the quality of the model that is delivered depends on the quality of the specification of requirements, which in turn correlates with the maturity the OEM has regarding the use of virtual manufacturing methods and especially simulation. OEMs with high degree of maturity require the PEP to verify the entire installation virtually in 3D prior to the start of real commissioning. Additionally, this model must be delivered after the commissioning. Furthermore, the PEP is required to model in a specified way and use certain softwares. For example, it is specified how the models must look, how is should be structured within the software, which signals to include, naming convention of variables and which functions that can be used in e.g. robot-code and PLC-code. This implies that it is often the PEP that creates the e.g. PLC-code, the emulation of the components and their behavioural model.

Nevertheless, OEMs occasionally create models themselves. The method of creating the models varies among the OEMs, but generally it commences with a conceptual phase in 2D and sometimes in 3D. This is followed by construction of CAD-models of e.g. fixtures, components etc. and can be done from scratch manually, via 3D scanning or retrieved from libraries. Models of standard components can be obtained from suppliers or received as part of the delivery from the PEP. However, these are often dead CAD-models and occasionally simple components like cylinders contain some kinematics. These models are suitable and sufficient for constructors, but not for automation engineers. Therefore, one automation engineer argued that it would be appreciated if components were delivered as well structured CAD models with kinematics and signals instead. Nevertheless, nowadays the OEMs usually have to add kinematics and signals themselves. Models of more advanced components like motors are usually black-boxes with surface geometry, but these are normally sufficient for the task at hand.

In the event of creating PLC-code, OEMs normally retrieve this from standard blocks of code or re-use of functions from other projects. It can also be created from scratch based on the function the machine should have and the code is written accordingly.

The above mentioned work is delivered to the simulation engineer who inserts them into a simulation software. e.g NX, Proces Simulate, Robmatix, Robot Studio or Sinematik. However, it is argued that it ought to be easier to integrate different disciplines in the simulation software.

To become more efficient in the modeling OEMs highlight several important areas: global standards, improved interoperability, libraries, re-use of models, plug-and-play solutions, modularity of models, suitable levels of abstraction and improvement of internal processes.

Global standards refers to the use of standardized ways of working, the usage of standard file formats and common definitions within the simulation terminology. This facilitates the work with simulation and improve interoperability. In addition, it is argued that interfaces between different applications ought to improve to increase interoperability.

Libraries with standard components would improve re-use and thus model efficiency. Furthermore, better models from the suppliers are requested, e.g. black-box solutions and behavioural models so that plug-and-play solutions becomes possible. In addition, modular concepts would also enable plug-and-play solutions and improve re-use.
Suitable levels of abstraction ought to be investigated so that the correct level is modelled, since the level of detail correlates with the modeling effort.

The OEMs stress that improvement of internal processes also is important. Mostly that all parts of the project should know what to do, what their job is for and to know what is expected from the simulation. Thus, internal clear goals must be communicated so that correct data is used and a suitable level of abstraction is chosen.

However, only a few of the interviewed OEMs had ongoing projects to attend to above mentioned areas.

Clearly stated ownership of the models is mostly the case among OEMs that have a high degree of maturity regarding working with virtual manufacturing. The OEM owns the model in all phases, but it is shared in the construction phases of the production equipment with the PEPs. There is a clear ownership structure internally of where the model is kept and which department that is responsible for updating the model. However, the updating of models is not carried out with the desired or required frequency to keep them close to reality.

An interesting aspect is that one OEMs with high simulation maturity argued that the model of the production equipment ought to be considered the "original". Thus, the reality should match the model, and not the other way around.

OEMs with a lower degree of maturity regarding working with virtual manufacturing have not yet achieved clear ownership structures or responsibility of updating. They usually have structures for real systems, products and segments of the line, but the digital models do not follow this structure. However, it is argued from a hypothetical perspective that it ought to be a combination of central process owners and local ownership in the factories that constitutes the ownership structure.

All OEMs work with some kind of data base or PLM-system where company information is stored.

5.3.4 Integration

Interoperability issues are common among the OEMs and they tend to work with many different softwares and "one-engineering environments" do not exist. Work done in one environment normally requires extra work or re-work when exported to another environment due to information losses. The information that tend to disappear is the smartness of the model, i.e. kinematics etc.

OEMs express an uncertainty regarding how interoperability issues should be solved for VC and argue that software developers ought to take a greater responsibility. Many OEMs have found ways to work around the issue or just accepted that duplication of work is required. One OEM argued that seamless information sharing does not exist and there is always a customized solution or API in the background that enables information distribution. Furthermore, another OEM considers that it is standards that ought to solve interoperability issues. However, the same OEM has an understanding concerning the complexity in implementation of standards.

Nowadays, OEMs usually require specific formats in their specification of requirements, but this requirement normally implies an extra cost and in some cases it can double the invoice price. In addition, working with standard CAD formats is common among OEMs and several OEMs use formats like STEP, IGES, XML or JT. Additionally, one OEM mentioned that AutomationML is an interesting format in the future for VC.

Which format they receive depends on how the specification of requirements is written. The clarity of the specification of requirements correlates with the digital maturity and especially, the simulation maturity the company have. Thus, companies with a more mature simulation level receives the desired format whereas those with less mature level can receive a mixture. One OEM stressed that they had guidelines concerning their preferred formats. However, the lack of strict requirements led to that they usually received undesired formats and had to convert them, with information losses as a consequence.

IP is not a major issue for the OEMs since they receive the models that PEP creates and CM provides. When we asked the OEMs how they think PEPs relate to his issue, they argued that is was a more pressing issue previously for them. Historically, the PEP wanted to protect their know-how and was reluctant to share the models. However, this is changing since the PEPs know that it is required to
deliver the model and that it in the future will be an inevitable requirement. Furthermore, trust and NDAs has helped changing this attitude and thus made sharing less complicated.

However, during the engineering phases when the PEP creates the production equipment they use information from the OEM. One OEM stressed that the information they receive must be controlled, since it otherwise risks leakage of insider information. Specific production data e.g. production rates can be sensitive since it can affect stock price. Sharing of other kind of information, e.g PLC-code, with non-competitors it is not a problem since it is solved with trust and NDAs.

When using component models from CMs, the OEMs argue that they just need the geometry and functionality, not exact information on e.g. internal workings of the motor. Some CMs delivers black-box solutions which are sufficient. However, tools from e.g. Atlas Copco can be delivered as a digital twin, which is insignificant in the context and it makes them computationally demanding.

5.3.5 Usability

The general opinion among OEMs is that simulation is a support tool during the engineering process and that simulation results are used as feedback for corrective measures. In short, it is a tool that provides information that can be used to make better decisions.

However, it is not always appropriate to simulate. For example, flow simulation models can be complex and require data that is difficult to acquire. A few OEMs stated that the effort to find realistic input to the flow simulation model is so time consuming that a decision and action is taken when the simulation results arrive. Furthermore, simulation implies a cost. One OEM argued that the model used in commissioning projects only ought to take 1-2 weeks to build and cost 10% of the total project cost. Otherwise it becomes difficult to justify.

5.3.6 Work-flow

For OEMs with a high simulation maturity, simulation is considered a standard in the work-flow and simulation is used along the plant-engineering-process. However, none have adapted a standard working process for projects linked to VC. Work done in the early phases of the plant-engineering-process, e.g. CAD models from R&D, are passed on to later phases. Nevertheless, the work-flow is sequential and each phase is isolated. One effect of this is for example that R&D can make product changes without considering existing equipment. However, OEMs were reluctant to explain in detail how the strategy actually was carried out. The answers were short and somewhat vague. Therefore, it was difficult to assess how work in the early stages would gain the later stages of the plant-engineering-process.

As OEMs do not perform commissioning nor construction of production equipment, these parts of the plant-engineering process is not covered in their work-flow. The contact with the PEP starts with the order including all specified requirements of the production equipment. Then, it is up to the PEP to have a strategy of how to refine modeling efforts and build the model.

5.3.7 Acceptance

The opinion among OEMs whether simulation activities have an economical value is rather aligned. They tend to agree that there are savings to be made in time and money due to simulation, but that it is difficult to quantify and prove these savings. One OEM compared simulation activities with several alternative costs that probably would arise if no simulation was done. Another OEM viewed simulation activities as an "insurance" and argued that it gave them a 80% risk reduction. It was further exemplified as, "we only need to find one error per year to justify simulation activities." The general issue with proving and quantifying the effect of simulation is that there are normally just two alternatives to choose from: simulate or not. Thus, it is difficult to compare the effects. In summary, many of the OEMs argue that there are economical benefits with simulation. However, few OEMs specified any KPIs (Key Performance Indicators) to measure and thus justify simulation activities with.

There is generally high acceptance within the companies of OEMs to work with simulation tools and many departments supports the usage. The high acceptance originate from many years of working with simulation tools, e.g. many of the OEMs consisting of the automotive industry have been simulating.
in more than 15 years. However, operators and people working close to the production might have less interest in simulation, mainly because they do not see the value it creates.

5.3.8 Education

OEMs with high simulation maturity work with internal and external education (education of suppliers) with the aim to increase the understanding of simulation tools. However, none work with established education packages linked to VC.

5.3.9 Collaboration

The majority of the interviewed OEMs claim that there is collaboration along the value chain to facilitate simulation. OEMs with high simulation maturity are mostly working together with PEPs to develop a better collaboration regarding VC. It is the PEPs that do the commissioning since OEM’s organizations usually lack resources and know-how to perform the commissioning themselves. Therefore, it is natural that OEMs with high simulation maturity meet with PEPs on a regular basis to discuss the future needs of commissioning, i.e. VC. The OEMs consider the collaboration with the PEP to be important, and are concerned with achieving long term relationships and in some cases partnerships. This will lead to an extensive and professional PEP-portfolio, i.e. have many suppliers. In turn, this will make it easier to collaborate, e.g. make it easier to negotiate prices in the future. However, none of the OEMs specified an ongoing partnership.

OEMs educate PEPs in their way of working so that the collaboration will become more facilitated. In addition, the OEMs argue that there is inadequate communication in several domains between them and the PEPs, which results in sub-optimal collaboration. There are mainly two areas of improvement: data sharing methods and order requirement specification. Data sharing methods refers to the sharing of design data that is used by the PEP to create the production equipment and to build the models. The issues with current sharing methods is that the OEM and the PEP not always use same data. Discrepancies in data is often the result of poor data integrity, e.g. that updates from the OEM are not automatically stored in a shared data base. Order requirement specification refers to the listed requirements that the OEM specifies in the order of the project to the PEP (in this case specification of the virtual model). OEMs that devote much effort in the specification of requirement and are clear with their request, enjoy better deliveries of the model. For example, the right file format, correct naming convention and the correct functions used in the robot code. This is a two-way collaboration, i.e. the PEP must be better at understanding the need the OEM has, and the OEM must understand what they need. Firstly, OEMs must understand the technology before it is possible to specify requests in the orders. One OEM is currently developing a check-list of technical requirements in order to facilitate ordering of VC models.

The collaboration between the CM and OEM mainly consists of maintenance and spare parts whereas CMs and PEPs have a closer collaboration according to one OEM. The same OEM argues that they just buy a solution from the PEP. Thus, the collaboration is not natural with the CM and is argued to be more natural between PEPs and CMs. However, the OEMs stress that CMs both in terms of software providers and component manufacturers ought to become more present throughout the value chain. Regarding the development of the software, the software ought to handle more file formats. Concerning provision of virtual components, they ought to consider the simulation needs of the OEMs to a greater extent. Nevertheless, the OEMs did not specify what CMs should attend to more precisely.

There are many barriers towards collaboration with external parties regarding simulation. One of them is already discussed, the sharing of data and to use the same data base or PLM-system. Which is both a technological issue and a matter of giving access to internal systems. Additionally, interoperability issues depending on utilized systems and the lack of understanding of needs, i.e. specifying requirements. Ultimately, that the modeling is associated with time and costs. However, models are already normally included in the price of the delivery and if the PEP can not deliver the model, the price of the model is discounted.

When asked if externals could be in charge of virtual models and digital twins, i.e. managing them and updating them, the answers are dispersed. As production is the core competence of the OEM and the digital twin should manage the virtual production, many of the interviewees are negative to the idea of having an external company managing the digital twin. In this line of reasoning, some OEMs want
to keep information generated from the digital twin in-house as part of core competence. Additionally, confidential or delicate information about the production might leak and thus pose a threat. Therefore, all models should be completely owned by the OEM. However, the issue with confidential data could be solved by managing access in the PLM-system and one OEM argued that automation is not sensitive to share, since it is the product *we make money on.*
6 Discussion & Analysis

The eight fields of action that must be addressed to facilitate the use of simulation and thus VC was the premise that formed our research questions, purpose and research design (see Fields of action 4). In this section, an analysis of our results from the interviews coupled with theory from the literature review is provided. This will form the discussion that is destined to give answers to our research questions and lead to our conclusions and recommendations.

6.1 Summary

Traditionally, engineering disciplines have worked in an isolated and sequential manner (see figure 27). However, the tendency of shorter time frames in the industry forces companies to change towards a more integrated and concurrent approach. Adoption of information and communication technology (ICT) into the industry enables information exchange between systems and machines which supports this integrated and concurrent approach. Mainly, automated information exchange becomes possible (Wollschaeger, Sauter, and Jasperneite, 2017). However, the need to connect software, machines and systems in order to enable information exchange poses high demands on interoperability (see Integration 4.4). In addition, virtual manufacturing is increasingly becoming important in the industry. Thus, many engineering activities are performed with software and currently, simulation is an activity that is being used frequently. In our interviews we found that companies utilize several simulation activities e.g. flow-, robot-, PLC-code-, assembly-, process and ergonomic simulation. However, none of the interviewed companies used VC or had completed a commissioning project completely virtually. Nonetheless, a few companies conducted projects concerning VC with the objective to learn and investigate the technology.

In short, VC is simulation of the combined work from mechanical, electrical, robotic and automation design. All discipline’s work is put together in a simulation model and the objective is validation of the work by each discipline and also to test if all the requirements are fulfilled. It can concern the validation of a machine, line or an entire production system. Throughout the years, different engineering softwares have been used by engineers to facilitate and make their work more efficient. For the mechanical engineers, CAD became an important tool early, electrical and robotic engineering disciplines also obtained software early. However, a software designed for the automation engineer has not been on the market for a long time. As VC concerns testing of above mentioned disciplines, the work conducted in each software needs to be tested jointly in a simulation environment. Thus, VC requires a high level of interoperability between softwares.

There are several advantages with VC and being able to validate the combined work from all disciplines prior to real commissioning. The interviewees agreed that VC enables early validation of involved disciplines which reduce risk, time and cost of the commissioning. As one PEP stressed: “Nowadays it can be rather stressful towards the end of the project and we are very vulnerable to disturbances as e.g. sickness etc. Just finding 75% of the errors would be valuable.”. Furthermore, one OEM stressed that the virtual environment provides unlimited amount of material to test with. Therefore, scenarios associated with large risk in the real world can be tested. In addition, the interviewees highlighted that systems becomes more optimized and mature early where e.g. cycle times and output is optimized before commissioning. Effectively, VC can be regarded as a learning activity about the system and it becomes easier to involve the customer early.

One PEP that is in the initial stages towards implementing VC in their projects argued that: “We want to make more in the office than on site and thus save time, resources and money. We want to stay competitive without having to outsource labour to low wage countries in order to meet requirements higher requirements to a lower price coming from OEM. We want to keep our high level of expertise at a lower cost by using virtual methods.” We believe that this view summarizes and highlights important arguments in favor of the general need to adapt to virtual methods, and especially VC.

However, despite that VC offers many advantages, it is also associated with several issues. All interviewees agree that VC itself does not imply any issues, it is the work that must be done in order to perform VC that is troubling. The major issues that our interviewees discussed can be divided into technical and non-technical issues.

The technical issues concern the level of detail of the model, modeling efforts and interoperability.
As will be discussed in *Modeling Efficiency* 6.2, the level of detail correlates to the modeling effort. However, if the simulation is not performed on a sufficient level of detail, important errors might be undetected. One OEM argued that CAD-models that are not exact enough normally leads to unexpected errors during the commissioning. Nonetheless, one PEP stressed that certain errors might be difficult to discover no matter how exact and detailed the level is. An example of this was when they used a simulation model during the design phases of a project. The commissioning went well, but soon the production equipment quit working. They later found that a window in the facility let the sun in, which blinded the photoelectric sensors which disturbed the signal. This example serves as a reminder of the delicate balance of modeling effort versus value, known by academia as the EMP (see, *Modeling Efficiency* 4.2). Both OEMs and PEPs discussed this issue and one OEM stressed that “...modeling everything can take more time than to build the real machine.” Furthermore, both PEPs and OEMs claim that they face issues regarding interoperability between softwares from different vendors.

The non-technical issues concern education, processes, organizational factors and a common definition of VC. The CMs argue that VC requires skilled people that have knowledge about simulation and all engineering disciplines. As one OEM put it: “you must find the golden person who can manage all knowledge needed to conduct VC”. In addition, there is no common process concerning VC established yet. Currently, there are many different softwares to perform VC with, which makes it difficult to collaborate (due to interoperability issues). Furthermore, if the OEM requires a specific file format, and the PEP must use a new software and learn how to use it, the price increases for the OEM. Furthermore, one CM argued that different disciplines must collaborate more and that a new concurrent design methodology must be developed which the organization supports. Ultimately, the PEPs stressed that there is no clear definition regarding what VC actually is and what should be included in the notion. Hence, questions regarding how much should be done virtually and how much should be left to be done on site is not clear. As one PEP put it: “How far should one go in order to conduct a VC? We have the knowledge and know-how in order to do VC, but the requirement has not yet come from the OEMs so we do not get paid for our time.”

### 6.2 Model Re-Use

*Model re-use concerns the ability to recycle simulation models, models and code. Thus, simulation models, models and code developed during the plant development process ought to be re-used in later stages and to various projects. As modeling requires much effort, re-use is desirable and a measure to improve modeling efficiency. In this section we will discuss how companies work with re-use and how it relates to current research.*

In our interviews we found that model re-use is sought by all companies in the value chain and they strive to re-use both models and simulation models as much as possible. However, the role each part (i.e. type of company) has regarding modeling and re-use varies and it affects their attitude towards the activities.

CMs rarely build simulation models nor models since they focus on supporting PEPs and OEMs in the creation of models and simulation models. Therefore, CMs supply them with software that enables model creation and libraries containing generic models of components embedded in the software. The models can be parameterized upon implementation in a simulation model and CMs are currently investigating the possibility to provide behavioural models of the components. PEPs that use simulation in their workflow build their own simulation models and frequently delivers these to OEMs as part of the delivery. In addition, they create and deliver models too and these are either created from scratch or retrieved from libraries. Re-use is mainly done from standard components (downloaded from the CM’s data-base), mechanical fixtures or standard blocks of PLC-code. However, downloaded models usually lack kinematics and must be parametrized, which is considered to be an issue among the PEPs. Most of the OEMs create their own simulation models and those who do not create their own simulation models buy these from PEPs. Generally, re-use is accomplished by documenting all work in PLM-systems, or similar data-base. However, models of components are normally re-used from libraries provided by CMs. Nevertheless, as models usually are part of the delivery from the PEP, the focus on model re-use is not crucial for the OEM, but rather the PEP.

Model re-use is difficult due to several reasons and since projects tend to be unique, the complete re-usability of models, simulation models and associated work within those becomes complicated. Therefore, researchers have investigated techniques to improve re-usability.
Mainly, research concerning modular concepts i.e. plug-and-play has been conducted (see Modular Concepts 4.1.1). However, this modular approach will demand development of a commonly accepted modelling and co-simulation standard accepted by both vendors and users. In addition, this must be combined with development of a standard for model exchange between different simulation tools.

In our interviews only three companies discussed modularity. Two of the companies, one OEM and one PEP, had a low level of maturity in virtual manufacturing, especially concerning simulation. The last company was a PEP with high level of maturity. However, none of them currently used modules, i.e. plug-and-play solutions. Thus, their answers were on a hypothetical level rather than a description of their current business. The OEM argued that re-use of models ought to be accomplished by standardized models on a modular level and the PEPs claimed that all work should be modularized to make it possible to combine modules. Nonetheless, no solutions on how to accomplish this modular concept were presented by the interviewees. Therefore, we will discuss potential solutions later in this section based on the research presented in Modular Concepts 4.1.1.

Re-use through libraries is often highlighted as a suitable solution to re-usability and nowadays provision of libraries with standard components is common. Actually, the majority of our interviewees state that they accomplish re-use by using library solutions. However, these models normally lack the behavioural model, which causes much extra work for the PEPs and OEMs. Therefore, they would appreciate the delivery of the behavioural model too.

The problem for CMs is not to provide behavioural models of components. Actually, from our interviews we found that one CM currently is working with a project to provide behavioural models. Interestingly, Oppelt, Barth, and Urbas (2015) predicted that CMs would pursue this direction.

“Currently, we are discussing this to build a compelling business case and to find time and money from management to offer this. We are in the early beginning of this, but we believe that in the future that we will offer a complete library with generic components and their corresponding behavioural model.”

Business Development Manager for a global VC software at Company A2

Nevertheless, the problem with providing models is to enable customization and model exchange methods of these models. The customization possibility is important since the user on the one hand does not always use all functions of a mechatronic component and on the other hand, the effort for the CM to provide a customized component with specific functions for each user is immense. In research conducted by Süß, Strahilov, and Diedrich (2015), the authors investigated the possibility to provide behavioural models as modules with customization possibilities. Effectively, users of the model can modify it to suit their needs. The author’s research concerns the use of UBM and MBM and standardized interfaces of MBM that can be stored as FMUs (see Behavioural Models as Modules 4.1.2).

In addition, the provision of models with corresponding behavioural models requires suitable model exchange methods. Therefore, FMI was developed to enable exchange of dynamic models as well as its co-simulation (see Model Exchange Methods 4.1.3 and Co-Simulation 4.1.4). FMI enables both vendors and the users of the models to use different tools and the standardized format makes simulation easier. Thus, FMI offers sustainable behaviour simulation within VC by using open source and standardized formats solutions. One of the interviewed CMs currently used FMI/FMU in order to provide behavioural models. Hence, their software is compatible with FMU platforms and their models can be stored and exported as FMUs. Thus, they can import a model as a FMU and reversely export a FMU, which can be imported e.g. into a competing vendor’s software.

Furthermore, the FMI standard enables simulation of different FMUs in a approach called FMI for co-simulation (ibid.). Therefore, co-simulation enables joint simulation of the already established tools and semantics and that they are simulated with their suitable solvers.

The research conducted by Süß, Strahilov, and Diedrich (ibid.) concerning MBM, UBM and standardized interfaces of these, jointly with the development of FMI conducted by MODELISAR and their Functional Mock-up Interface Standard (2018), enables a sustainable behaviour simulation approach within VC. Firstly, modeling and simulation is separated which facilitates re-use of models. Secondly, the customization of models and the distribution of the burden of modeling along the value chain is addressed.
Summary

All parts of the value chain strive to re-use models, simulation models and code through library solutions, documentation in PLM-systems or other similar data-bases. However, researchers stress that modular concepts ought to be used, but among our interviewees, only three argued that this was important for them. In addition, OEMs and PEPs request models with corresponding behavioural models from CMs to improve re-use and model efficiency. Currently, CMs are developing solutions to provide this. Furthermore, researchers that investigate model exchange methods stress that standardized solutions ought to be used and present a method with FMI/FMU and co-simulation. The CM that aims at providing models with behavioural models use this technology. However, the CM does not provide these as a modifiable solution, e.g. MBM.

Conclusion & Recommendation

To improve re-use of models, modular approaches ought to be used more frequently. Therefore, CMs ought to consider provision of MBMs (models with behavior model) with standardized interfaces that can be stored as FMUs. This would enable better re-use of models and for PEPs to modify these, i.e. create UBM’s suited for their needs. Additionally, this approach would enable co-simulation of different FMUs according to the “FMI for co-simulation” concept. Effectively, model exchange and simulation would become facilitated and companies along the value chain would have less problem with interoperability delimitation in the complex landscape of IT-tools.

6.3 Modeling Efficiency

Modeling Efficiency concerns the initiatives towards decreasing the effort of modeling since it requires much effort and is considered one of the major technical barriers towards simulation (VC). Therefore, areas concerning automatic model generation, libraries for devices as well as for processes and suitable levels of abstraction are being researched. In addition, organizational factors concerning management of simulation models throughout the life-cycle and the management of change in simulation models are reviewed. In this section we will discuss how companies work with above mentioned areas and how their work relates to current research. However, the focus will be on automatic model generation and level of abstraction since library solutions are discussed in Model Re-Use 6.2.

The model creation method (i.e. models, simulation models and code) is similar between the PEPs and the OEMs and their method is manual. CMs on the other hand do not normally create models the same way, since they do not work with modeling for specific projects. However, as each part of the value chain has a different role in the creation and usage of models, simulation models and associated work, their attitudes towards how to become more efficient varies. Therefore, we will provide an elaborated comparison between the answers from the different companies along the value chain.

PEPs are normally hired by OEMs to build and commission production equipment. In addition, delivery of virtual models is increasingly becoming usual. Therefore, OEMs do not always model themselves, but when they do, their method is the same as the PEP’s. Nowadays, both PEPs and OEMs usually start the creation of a simulation model with a 2D- or 3D layout of the area. Thereafter, modeling of fixtures, components, actuators, sensors and robots follows. These are either created from scratch in a CAD-software, 3D-scanning, retrieved from libraries in-house or downloaded from libraries from suppliers. Nonetheless, components provided by suppliers (CMs) usually lack the behavioural model and I/O, which must be added to components prior to simulation. In addition, the OEMs claim that the delivery they receive from PEPs occasionally lack behavioral models too. However, within the robot models, kinematics is usually offered by the suppliers. In the event of creating PLC-code, both PEPs and OEMs normally retrieve this from standard blocks of code or re-use of functions from other projects. It can also be created from scratch based on the function the machine should have and if the code is written accordingly. Ultimately, the above mentioned work is delivered to the simulation engineer who inserts them into a simulation software. e.g NX, Proces Simulate, Robmatix, Robot Studio or Sinematik.

The models, or emulation of components can be obtained in many different ways (see Emulation of Components & Behavioural Model-Challenges 4.2.3). One method is to retrieve them from suppliers and currently there is a discussion concerning that manufacturers of mechatronic components should provide the behaviour models in libraries too (Westkämper et al., 2012). From our interviews we found that this currently is occurring and it is an important step that will facilitate simulation activities. This is further discussed in Model Re-Use 6.2. Additionally, as an automation engineer at an OEM argued,
the current models that are delivered (dead cad-models) are suitable and sufficient for constructors, but not for automation engineers. The same automation engineer stressed that it would be appreciated if components were delivered as well-structured CAD models (i.e. with a complete operation tree) with kinematics and signals instead of current dead models.

However, models of advanced components, e.g. motors, are usually delivered as black-boxes (i.e. no knowledge of its internal workings) with surface geometry. One CM explained that these are controlled by an emulation of the virtual control that replicates the exact behavior of the e.g. robot. Thus, there is no need to see the exact design of the component. One OEM agreed and argued that these normally are sufficient for the task at hand since too precise models is not adding value and can cause computational issues. However, the CM argues that these black-box solutions might have to change in favor of more detailed models due to the requirements that VC implies. Nonetheless, the correct level of detail is difficult to define and a pressing issue within modeling, but this will be discussed below in this section (Level of Detail). Additionally, concerning detailed models is that sharing detailed information about components without revealing confidential data is a challenge. Süß, Strahilov, and Diedrich (2015) have conducted research on this topic, and it will be discussed in Integration 6.4.

In summary, both researchers and companies seem to agree that library solutions are suitable to improve modeling efficiency. Nevertheless, PEPs and OEMs currently have to add kinematics and signals themselves which complicates the use and reduces the efficiency. However, as we can see this starting to change and CMs will start to provide behavioural models too.

**Automatic Model Generation**

There are many researchers that investigate methods that are destined to automate the modeling of mechatronic components with behavioural models, PLC-code and simulation models. Westkämper et al. (2012) present a type of library solution that can be used to automate modeling of mechatronic components and still provide the flexibility of the mechanical side (see *Emulation of Components and Behavioural Model- Automation through Libraries* 4.2.4). The method enables a semi-automatic model generation where information about components that is created during the design phases of product development is used. Briefly, the idea is that the mapping between the ECAD-component and the logical behavior model is done once and then combined with the 3D-CAD model via an interface. Thereafter, the PLC can then be connected to the behavioural model. Additionally, the creation of PLC-code among PEPs and OEMs is mainly done by re-using code from previous projects and one PEP stated that they had used the same code-block for the past ten years. Thus, PLC-code is not highlighted as a major concern in the modeling. However, there is research concerning automatic PLC-code generation and two methods developed in MATLAB is presented in *Programmable Logic Controller Code* 4.2.2. Furthermore, Neugebauer and Schob (2011) present a method to automate the generation of simulation models in a method called MDA, see *Simulation Model-Model Driven Architecture* 4.2.5. MDA is an approach that enables consequent use of models by defining key aspects of software applications where activities performed by a simulation engineer are formalized and put into rule-based algorithms. Thereafter, the transformation of information from digital files into a simulation model is based on the rules that represent the knowledge and ability of the simulation engineer to find patterns. However, none of our interviewees used any of these approaches.

As discussed previously, PEPs and OEMs do their modeling manually in software in a sequential manner. In addition, shifting of software environment often implies re-work since information disappears, which will be further discussed in Integration 6.4. Therefore, one OEM argued that it ought to be easier to integrate different disciplines in the simulation software, and one of the CM’s agrees. When asked “How to become more efficient in the modeling?” this CM argued that one of the major issues with modeling is putting all different components together in a 3D simulation model. “Components developed in different applications must fit together, and the work to make them fit together must be reasonable.” Therefore, applications and file formats must be able to work together, i.e. have interoperability, and not be vendor specific. In addition, provision detailed models (both vendor specific and generic) with corresponding behavioural models is considered important according to this CM since it reduces the modeling effort for downstream parties in the value chain. This is discussed in *Model Re-Use* 6.2 where potential solutions are provided.

When PEPs and OEMs were asked the same question their answers were aligned. A summarized version of their answers concerning activities to make them more efficient will be provided below. However, only their opinion regarding level of abstraction will be elaborated in this section.
Both PEPs and OEMs stress that standardized and structured ways of working that are well communicated internally with all parties involved would improve their modeling. Mainly, that all participants of the project should know what to do, what their job is for and know what is expected from the simulation. Thus, internal goals must be communicated. Effectively, correct data is used and a suitable level of abstraction is chosen. Additionally, OEMs stress that common definitions within the simulation terminology is important to improve communication, and as discussed in Summary 6.1 no clear definitions currently exist. Furthermore, PEPs stress that work done in virtual environments must be directly transferable into the real world so that no extra time in translation must be spent. This will be discussed in Work-flow 6.6. In addition, both PEPs and OEMs consider standards concerning file formats and interfaces between software to be crucial to decrease issues with interoperability. This will be discussed in Integration 6.4.

Furthermore, PEPs and OEMs both agree that modularized concepts to enable combination of different modules is important. Additionally, better models from the suppliers are requested, e.g. black-box solutions and behavioural models so that plug-and-play solutions becomes possible. This is discussed in Model Re-Use 6.2. Furthermore, as discussed earlier, OEMs argue that libraries with standard components with behavioural models would improve re-use and thus model efficiency. Ultimately, one OEM stresses that suitable levels of abstraction ought to be investigated. It is crucial that the correct level is modelled, since the level of detail correlates with the modeling effort. Several attempts to agree on modeling levels have been made by both companies and researchers. However, there is currently no common definition of which level of detail models and simulation models should have.

Level of Detail

The level of detail that the model must have depends on the test cases the user is interested to analyze. Oppelt and Urbas (2014) suggest a vague, but eloquent guideline: “a simulation model for VC is sufficient if the automation system cannot notice the difference in the connection with the simulation model than with the real production system” (ibid., p. 2567). Thus, modeling every aspect and detail is not necessarily the case in order to reach the goal, see Level of Abstraction 4.3.

The interviewees did not discuss level of detail frequently during our question concerning modeling. However, it should be clarified that we did not ask specific question regarding level of detail since it originally was outside our scope. Nonetheless, comments concerning appropriate level were occasionally mentioned by our interviewees and we decided to discuss the matter since it correlated to the modeling effort. For example, the CM that discussed their black-box solution with only surface geometry, argued that an exact virtual control could replace the need to obtain exact models. Nonetheless, this CM believed that more detailed levels would be needed in the future, but did not specify exactly how detailed. Currently, they deliver solid CAD-models, but occasionally these contain a few parts in the assembly to offer the possibility to add kinematics. However, a virtual control that is a digital twin of the real control system is used to mimic the exact behavior of the model. Thus, the CM do not have to deliver the exact behavioural model nor exact models that demonstrates how the e.g. motor is constructed. Nevertheless, the CM agrees that other requirements concerning models of mechatronic components might apply in the future. In this regard the CM argued that increased requirement of detail might be solved with encapsulation of the behaviour, i.e. if you deliver certain input, certain output is received. Effectively, there is no need to see the inner structure since the functionality will be the same. This approach is similar to research conducted by Puntel-Schmidt and Fay (2015) where models are divided into Dead-Time-Models and Device and Kinetic-models, see Level of Abstraction-Current Research 4.3.1. In this case, the classification of Dead-Time-Models applies. The Dead Time Model can be seen as black-boxes that describes a mechatronic system, but ignores its inner structure. Additionally, control input is simply delayed by a dead-time and transformed to an output and no physical characteristics are considered. In addition, this idea is similar to the work a PEP explained that they use. The PEP replace models of e.g. valves controlling cylinders with code that replicates the behaviour by delaying output based on the input. Furthermore, another OEM used even simpler models where only booleans were used to mimic sensors.

However, if testing of e.g. collisions and layout is important, Device and Kinetic-models ought to be used. These can be seen as white-boxes that describe the inner structure of a mechatronic system. Additionally, these are divided into to three different types: Simple-, Ordinary and Complex-Device and Kinetic-models, see Level of Abstraction-Current Research 4.3.1. For example, Complex-Device and Kinematic-models are used to describe free movement in space and emulates reality so that that cases like possible collisions between objects and other structural elements are simulated. The classification of models and their capabilities are presented in Defined levels of detail and their comprised model types (ibid.) figure 26.
Furthermore, simulation can be made on several different levels of abstraction and as manufacturing plants can be simulated at any level of detail, a wide range of models can be considered. In addition, the more complex and detailed level the model must have, the more detailed databases are needed for their creation and the more CPU-intensive the simulation becomes. However, there is a difference of opinion concerning how the classification of abstraction level should be defined and which type of models that should be used. One of our interviewed CMs divides the hierarchy of a plant is into: production plants followed by production cells, machines and machine components (see figure 18 in Level of Abstraction 4.3). In addition, researchers have investigated suitable model types within the plant hierarchy. Lasa et al. (presented in Oppelt and Urbas (2014)) suggest that the levels should be divided into: state level, the system level, network level and the finite level. Manske and Lotz (presented in Oppelt and Urbas (ibid.)) divide the models into the levels: Input-Output model, Model without dynamics, Model with dynamics and physical model. Puntel-Schmidt and Fay (2015) division of model (discussed above) types concern mechatronic components more than higher levels of abstraction. However, their classification is a suitable guideline to follow in order to decide an appropriate level of detail.

In addition, the virtual model could be built to support scalability, i.e. being able to raise the level of detail locally while maintaining global coherence, see Level of Abstraction-Current Research 4.3.1. The principle of the magnifying glass implies that certain parts of the production equipment can be detailed and others less detailed. Thus, parts that are complex and associated with risk could be modeled in detail whereas less complex e.g. conveyors can be Dead-Time-Models and only have surface geometry. Effectively, the simulation model is a mixture of macroscopic (time behaviour) and microscopic (individual behaviour and interaction) models called a mesoscopic model, that also supports the magnifying glass principle.

For example, one PEP discussed this and argued that conveyors do not have to be modeled in detail since these are standard components in production equipment and rarely cause trouble. Therefore, modeling of these in detail is not valuable. However, complex parts e.g. robot cells or machines that never been created before are suitable to model in detail. Nonetheless, here again not all parts must be on the level of e.g. ordinary device and kinematic models on microscopic level as suggested by Puntel-Schmidt and Fay (ibid.). This level implies that free movement in space and material properties of for example mass, measurements and heat transfers is considered. According to Manske et.al this level would correspond to level four i.e. a dynamic model with rigorous physical and chemical behaviour and to Lasa et. al the Finite Level. It becomes obvious that it is not sustainable nor valuable to model on this level of detail in projects where the production equipment is e.g. a complete production line. It would require too much time and effort. Therefore, the mesoscopic model that supports the magnifying glass principle is an important concept to bear in mind.

In another example, one PEP discussed a project where they created a complete production line that was designed to pack goods on pallets. This project was not commissioned virtually and the conventional method was used. They used several conveyors, robot cells and special machines since this palletizing method was a newly developed method. One of the special machines included a gluing station where the pallet was glued together. In addition, the glue needed a few seconds to settle. However, the settling time varied with the temperature the glue had when is was applied to the surface. Furthermore, the temperature the glue was allowed to have was a narrow temperature interval. Otherwise, the glue did not flow at the desired speed needed for the correct amount of glue to be applied, since excessive amount delayed the settling time and insufficient amount lead to weak pallets. Additionally, since they did not have a way of controlling the strength nor dryness of the glue, the automation program relayed in a fixed amount of settling time as the signal to next event. Therefore, the right conditions were important. Furthermore, the conventional commissioning approach implied that the production equipment was mounted on site at the PEP and the FAT was performed. During the FAT, errors that were discovered was corrected and the production equipment was dismantled and shipped to the OEM for SAT. However, certain errors that occurred at the PEP and thus were corrected, reoccurred during the SAT at the OEM as a consequence of the correction. The moral of the story is that not all errors are present in all environments. Especially those that concern physical en chemical behavior. It was not specified in this example if the errors concerned the gluing station. However, the other example we provided in the beginning of the Summary 6.1, with the sun and photoelectric sensors, is an illustration of indoor environment differences. Therefore, it is not obvious that high level of detail is valuable in all cases.

In closing, we conclude that the principle of the magnifying glass ought to be kept in mind while modeling. Therefore, not all parts of the model must be detailed. In order to decide the correct level of detail, the desired test cases and parts of the production equipment that are complex ought to be taken
into account. Since the goal with VC is to not encounter any errors during the FAT, the test cases specified in the specification of requirement or the FAT ought to be simulated. Secondly, parts of the production equipment that are associated with large risk, i.e. they affect other parts or risk to delay the commissioning, ought to be simulated.

In addition, the level of detail each model of the production equipment should have ought to be individually evaluated. As discussed, in the case of standard parts e.g. conveyors, a Dead-Time-Model or Simple device and kinematic models might be sufficient. Thus, model on level two and three as suggested by Manske et.al and Lasa. et.al, see figure 19. However, in the case of complex machines, Ordinary and Complex device and kinematic models ought to be used. Hence, model on level three and four as suggested by Manske et.al and Lasa. et.al, see figure 19. Therefore, each part should be evaluated based on the aspects that are desired to test, example of aspects can be found in figure 26. In addition, the level of detail and which aspects to simulate must to be critically evaluated since the EMP otherwise might be to severe. In figure 29 we illustrate our idea of locally being able to raise the level of detail and to use a Mesoscopic simulation model. Thus, various levels of abstraction, as suggested by Manske et.al and Lasa. et.al, are represented in the model. In addition, e.g. conveyors are modelled as Dead-Time-Models, complex machines and complex parts within that machine as Ordinary-or Complex device and kinematic models.

Figure 29: Scalability by the principle of the magnifying glass and suitable level of detail

Nonetheless, it is difficult to argue that VC could replace the FAT and thus start directly with SAT in the early stages of VC due to the difficulties with finding all errors with simulation. Skipping the FAT and start directly with commissioning at the OEM would be risky since the commissioning time at the OEM is expensive. Despite this, if VC enables an error free FAT it would shorten the commissioning. Therefore, we argue that VC initially should be used to limit the errors in the FAT, but that the FAT currently cannot be skipped. However, the long term goal with VC ought to be that the technology and knowledge is so developed that a successfull simulated FAT is on a par with a conventional FAT.
Ownership and Updating

When asked about ownership structures and updating responsibility it was clear that this was a question of virtual maturity and varies among the interviewed companies. CMs have ownership structures and assigned updating responsibility internally of their models. However, PEPs do not have comprehensive ownership structures nor updating responsibilities since they work more project based. OEMs with high simulation maturity have clear ownership structures and assigned updating responsibilities whereas OEMs with a lower degree of maturity have not yet achieved clear ownership structures or responsibility of updating. As discussed in Interoperability and Information Management 4.4.1, information management concerns three aspects. Firstly, the acquisition of information from one or more sources. Secondly, the custodianship and the distribution of that information to those who need it. Thirdly, the ultimate disposition of information through archiving or deletion. We argue that these simple aspects could serve as guidelines during the implementation of ownership structures.

Summary

Modeling is considered one of the major barriers towards simulation due to the effort it requires. Westkämper et al. (2012) stress that modeling effort currently is saved by omitting certain models since it would require the model to be very detailed, see Modeling Efficiency 4.2. Thus, all signals from the PLC-program are not used in the model. Therefore, two scenarios can occur (1) the PLC code must be adapted to VC, i.e. not the real PLC-code, or (2) the model must be very detailed in order to use the real PLC code. The first scenario is not aligned with the goal of VC: to test the real PLC-code (Hoffmann et al., 2010; Puntel-Schmidt and Fay, 2015; Westkämper et al., 2012). Thus, the need of effortless setup of detailed models and definitions of how detailed the model must be is needed.

The focus on modeling efficiency measures mainly applies to PEPs and OEMs since CMs do not model frequently to certain projects. Nowadays, PEPs and OEMs use a manual and sequential method and their main focus on becoming more efficient is to re-use from previous projects and to use libraries with components. They stress that definitions and common terminology is lacking which makes it difficult to communicate between companies. In addition, the lack of a definition of what VC is makes it difficult to agree on a suitable level of abstraction and which level of detail the models should have. Furthermore, ownership structures and responsibility of updating is important, and currently companies with high maturity regarding simulation has implemented clear structures whereas less mature companies have not.

Conclusion and Recommendation

In a short-term perspective concerning model efficiency, it can be concluded that libraries containing models with behavioural models ought to be developed and provided by CMs. In addition, it ought to be easier to create simulation models in existing software. Therefore, FMI/FMU solutions coupled with co-simulation is recommended.

In addition, before commencing a modeling project, a suitable level of detail ought to be decided. In order to do this, a common terminology and definition must be created and agreed upon. Therefore, we stress that future work should focus on this. Additionally, companies ought to have clear objectives concerning the test cases that are supposed to be analyzed in the simulation since it dictates the level of detail needed. Therefore, PEPs and OEMs should have a purpose and goal with the simulation prior to initializing the modeling. Furthermore, we argue that simulation models should be created based on the idea of locally being able to raise the level of detail and to use a Mesoscopic simulation model.

In order to enable re-use and thus improve return on invested modeling effort, ownership structures and responsibility of updating should be implemented. Preferably a specific department should own and update the model (since people can quit). In addition, a plan of updating containing e.g. frequency of updating, responsible person, checklist of what to control etc. ought to be used. Ultimately, we conclude that the aspects of information management provided in Interoperability and Information Management 4.4.1 ought to serve as guidelines during the implementation of ownership structures.

In the long-term perspective, companies ought to implement automatic model generation methods, e.g. MDA. CMs primarily will provide models of standard components within libraries. Therefore, PEPs and OEMs ought to have efficient methods of creating models suitable for simulation when a special case appears.
6.4 Integration

Integration in this thesis refers to the ability to share models and data seamlessly between different IT-tools, both internally within the organization and externally between other companies. It is an important field of action as data exchange is a significant bottleneck within the engineering value creation chain today. To address this issue, academia and companies are investigating solutions with neutral data formats and interfaces between applications to increase the interoperability. In addition, as information becomes increasingly digitalized and sharing of data increases, IP becomes an important subject. Therefore, we will discuss how companies and researchers relate to interoperability and IP in this section.

All interviewees states that interoperability is an issue. However, their approach to avoiding it varies. CMs strive to achieve interoperability between their own applications, but interoperability with competing CM’s software is not always the case. PEPs and OEMs solves interoperbillity issues by converting proprietary file formats into standard formats to enable export/import into other applications. However, this conversion usually implies information losses and the information must be added back to the model.

Interoperability

The virtual manufacturing domain is currently characterized by a broad heterogeneous tool landscape with limited interoperability. In addition, there is strong separation of phases in the plant engineering process and each phase/engineering discipline uses variety of specialized engineering tools. In addition, software to support engineering activities, i.e. computer-aided engineering is widely used and has been on the market for a long time. Effectively, companies have over time created an IT-landscape that is complex and heterogeneous resulting in immense interoperability challenges.

Now that virtual manufacturing (especially simulation) increasingly becomes an important part among companies in the industry, applications must strive to support seamless information exchange (see Interoperability and Information Management 4.4.1). However, this seamless vision is ambitious. One OEM argued that “seamlessness does not exist, there is always some kind of customized solution behind.” Nonetheless, we argue that the idea of reliable seamless information exchange that enables automation of information is the guiding principle the increasingly digitalized industry, which also Wollschlaeger, Sauter, and Jasperneite (2017) stress.

From our interviews we can see that companies work with solutions to achieve this idea of reliable seamless information exchange. Effectively, one CM is currently investigating solutions to create interfaces to competing vendor’s software. An interface within computing is defined as a shared boundary which two or more separate components of a computer system exchange information across (see Interfaces 4.4.6). This CM agrees that applications must support seamless information exchange. Therefore, the CM stress that increased collaboration vertically with competitors must be developed. Otherwise development of interoperability will occur regardless of consent or not, which may cause unnecessary tensions. Since it would require companies (PEPs and OEMs) massive investments (both in time and money) in new IT-infrastructure to enable seamless information flow, it is favorable to work on possible tool chain integration instead (Süß, Strahilov, and Diedrich, 2015).

Another CM argues that standards concerning file format, i.e. neutral data formats is their focus (see Neutral Data Formats 4.4.2). They have developed own file formats that they consider to be standard and strive to make others use them. However, that is the issue, the vast majority must use and agree on a specific format before it becomes a standard. Therefore, CMs must stop develop and promote own “standards”, since that kind of action oppose the creation of real standards. Therefore, they ought to strive towards complying with existing standards or agree with other CMs on the standard. However, this is a distant reality since there is few business incentives in favor of not promoting own file formats and software. Additionally, OEMs must also support standards and use them. Thus, OEMs must be prepared to change their way of working in order to realize a commonly accepted standard.

AutomationML is a standard that has been developed by several large CMs (see Neutral Data Formats-AutomationML 4.4.2). The above discussed CM is currently involved in this development and their software supports AutomationML. Both PEPs and OEMs stress that information losses within models is an issue that results in re-work when shifting between applications. However, AutomationML enables recovery of required functionality from existing data formats and possible extensions of them. Therefore, AutomationML is a format that solves the issue of the heterogeneous tool landscape as it reunifies
Discussion & Analysis

Engineering results which currently are spread to different IT-tools. Effectively, AutomationML is an interesting file format that could become an enabling technology for VC.

The majority of the PEPs and OEMs stress that interoperability currently is a daily problem. Nonetheless, one PEP argued that it on rare occasions works to share information successfully and that when it works it is beneficial. However, this PEP stressed that they use different softwares from different vendors to be able to serve many customers and most of the time they can not exchange information successfully. For example they used sofware from Siemens, ABB, Kukha, Atlas, Festo, Servo etc. and claimed that they are not compatible with each other. Since VC requires simulation of many different disciplines, limited interoperability will become an issue when the PEPs want to start with VC. Another PEP agrees and stress “in the future when we are going to connect more tools I can already see problems with it”. In addition, one PEP argued that interoperability is not a technical issue, but an organizational. The perception of this PEP was that none of the CMs are interested in working with the issue. In their own words “They want to sell their software and are not interesting in helping a competitor”. However, as we can see from the discussion above, one CM is currently working with opening up their software and another is working with AutomationML capabilities. Therefore, we can see that interoperability issues are being investigated by CMs and that they agree that interoperability must increase in the future.

However, an interesting perspective that one PEP discussed is that neutral data formats normally require more computational power than proprietary formats. Therefore, they want to keep the model in its original file format. In addition, this PEP stressed that the connection between the original file disappears when the file is converted or inserted into e.g. a simulation software. Thus, updates in respective environment do not transfer automatically. According to this PEP, CAD-software have reached far in the development concerning keeping the models in its proprietary format and still provide the possibility to transfer the file into other CAD-software. This might be a result of how CAD activities are conducted. For example, one company might develop the CAD-model, another all analysis work of the same model and a third party is responsible of manufacturing the product. Hence, simulation might take a similar way in the future. However, there are still neutral formats within the CAD domain that are frequently used (see Neutral Data Formats-CAD 4.4.4). Among our interviewees the majority use neutral CAD formats often, but OEMs with high level of maturity concerning simulation usually require a specific format.

The current way of business between PEPs and OEMs is that when PEPs deliver e.g. models to OEMs they develop them in the required file format that the OEM has specified. However, if the file format is not specified, the PEPs deliver in their preferred format or in standard file formats. Effectively, valuable information is lost e.g. the kinematics, I/O and the operation tree of the model, resulting in a solid model with only surface geometry. Of course the severeness of the information loss depends on which format you convert from and which format you convert to, but normally, above mentioned information loss is the case.

The specification of requirements that for instance dictates the required file format, correlates with the level of maturity the OEM has concerning virtual manufacturing. Therefore, OEMs that intend to use the model in their continuous operation and for simulation are particular in their choice of required file format so it will suit their IT-landscape. Effectively, they have to worry less about information loss, which improves their modeling efficiency. An example of an OEM that has not implemented strict specification of requirements said “We sometimes obtain STEP, IGES, XML and convert them...always information losses. We obtain many formats, and we try to have guidelines to control which formats we obtain. If we get a format we do not recognize we just google for a converter and then notifies the supplier that we want another format next time.”. On the contrary, one OEM with high maturity level in virtual manufacturing stressed that “we want a language that all softwares can use e.g. AutomationML. Nowadays, PEPs are paid to deliver our required format, since exporting leads to information losses”. In addition, to solve the issue with interoperability another OEM argued that it is standards that ought to solve the problem. However, this OEM is aware of the difficulties in achieving standards and gave an example where a comparison between robot simulation and PLC simulation was made: “robot simulation nowadays have a standards, but prior to that it was impossible to work with different tools. Currently, the same problem is present with PLC, and there are far more PLC vendors than robot vendors.”

Furthermore, research regarding programming languages that enables neutral data format of the behavioural model is currently developing (see Neutral Data Formats-Behavioural Models 4.4.5). Effectively, there are possible solutions with neutral data formats concerning information losses of the behavioural model. Languages like PLCOpenXML, Matlab/Simulink and Modelica are available and describe the
behaviour of mechatronic components (see Neutral Data Formats-Behavioural Models 4.4.5). However, only Matlab and Modelica can import/export their models as FMUs and to execute co-simulations using FMI (see Model Exchange Methods 4.1.3). Nonetheless, Matlab is a proprietary language and can only be used by one tool whereas Modelica is an open source language that enables a variety of tools to use it (Stüß, Strahilov, and Diedrich, 2015). Therefore, Modelica is preferred from an interoperability perspective. Furthermore, as discussed in Model Re-Use 6.2, FMU is considered appropriate as format for behaviour models of mechatronic components. Therefore, library solutions with models of e.g. mechatronic components, stored as FMUs or in AutomationML and could be a suitable solutions to information losses and interoperability.

In addition, this approach also reduces the importance of the level of maturity concerning simulation the firm has since the specification of requirements do not have to include requirements on file formats. The delivered format supposedly is interoperable regardless of IT-landscape. Thus, the comprehensiveness of the specification of requirements decreases, but only in terms of required file format, not the available information in the files. Library solutions, FMU/FMI and co-simulation is further discussed in both Model Re-Use 6.2 and Modeling Efficiency 6.3.

Intellectual Property

The opinion whether IP is an issue when sharing models or not varies among CMs, PEPs and OEMs. Among the CMs there is a difference of opinion. One CM argues that there is not an issue to share exact models with behavioural models of standard-or proprietary components. However, another CM argues that provision of exact models, in this case actuators and robots, could imply IP issues. PEPs on the other hand do not considered IP to be an issue. They argue that their competitive advantage relies on the ability to offer complete solutions of production equipment and not specific parts of it (including models). OEMs on the other hand normally receives models as part of the delivery from PEP, which limits their issue with IP. However, during the engineering phases when the PEP creates the production equipment they use information from the OEM which can be sensitive. Therefore, OEMs are cautious with which kind of information they provide PEPs with.

The questions regarding IP are important to discuss since IP concerns intangible creations of the human intellect and protection of these is the partly the foundation of willingness to invent and develop (see Intellectual Property 4.4.7). Therefore, IP is an important area to consider when sharing of data among companies increases. Nevertheless, the attitude regarding IP varies among CMs, PEPs and OEM.

One of the interviewed CMs provide models in libraries and stress that these models are their property. However, when the software is purchased, the right to use these models is sold too. These models are not vendor specific but generic. Nonetheless, these can be made equivalent to a specific component/motor by entering parameters provided in data sheets from producers. Occasionally, modeling of specific components to customers is conducted. During those events a NDA with the customer is signed so that the customer company can provide information concerning the machine or components. Nevertheless, it is argued by this CM that it is in the interest of CMs to provide “digital twin” of their products e.g. predefined, parametrized and with kinematics. The CM argues that “it is in their interest since PEPs are likely to ask for this due to that their need for digital validation will increase. Effectively, they will need this kind of data and either they model it on their own, or obtain it from us (the CM)” . Another CM explained that they deal with IP by removing all blueprints and technical documentation associated to their CAD-models so that they can not be copied. Additionally, all models of mechatronic components are delivered as black-boxes with a virtual control as discussed in Modeling Efficiency 6.3. However, they currently have discussions internally concerning delivery of digital twins in the future and how to handle IP of these. Drath, Weber, and Mauser (2008) discuss that AutomationML can be used to address IP issues since the extracted data becomes neutralized. Hence, engineering investments otherwise bound to the tools are protected. Therefore, AutomationML facilitates issues with IP and the data format can be seen as the glue between otherwise separated engineering information. However, there is an uncertainty among the OEMs regarding digital twins from CMs. One OEM argues that current models where geometry and functionality is included are sufficient. They claim that they do not need exact information on e.g. internal workings of the motor. On the contrary, too detailed models can be an issue with computational power. Currently, one CM offers web-based libraries where digital copies of e.g. robots can be downloaded by users. Embedded in the digital copy (i.e. the downloaded file), the behaviour models and robot control code are inaccessible by users. Nonetheless, the user is still able to fully (offline) program their robot model and thus lower the commissioning time (i.e. partially a VC). However, one OEM stress that everything they buy must be suitable for simulation and is unsure if the e.g. robot controller can
be hidden in the future when they pursue more comprehensive VC projects. Therefore, we believe that black-box solutions with an emulation of the virtual control is an appropriate short-term solution that suits the current need of the OEM and protects the CM. It is currently an appropriate structure on how CMs should see their role were detailed functionality is needed, but exact information is not necessarily needed to be accessed. Additionally, we concluded that it was appreciated by the interviewees if a digital copy could reached from web-based libraries, since collaborations should base on interdependent platforms (such as the Internet) (Moore, 2006).

In addition, a third CM explained that the software offer the possibility to protect e.g. PLC-code, which protects the PEP. However, the end customer (OEM) thus obtains limited access to the models and therefore limited capability to modify the model, which is not appreciated. Furthermore, information in PLM-system can be encoded and have restricted access. This CM discussed problems with the current business model and that incentives for modeling efforts must exist, i.e. payment which is in line as Goldstein (2008) concluded regarding IP. Therefore, the CM concluded that there must be a payment for obtaining this kind of information in the future.

The majority of the PEPs do not consider IP to be an issue. One PEP argued that “we do not deliver patents, the unique thing we do is to put it all together and it is not a secret. We do not protect code etc. We argue that it is difficult to copy the ability to offer complete solutions.” Occasionally some PEPs hide specific parts of the model and in some cases NDAs are used. One of our interviewees (PEP) explained that reluctance towards delivery of models was a bigger issue before. However, this has changed since the overall trend towards virtual validation from the OEM increases and PEPs are forced to comply. One OEM discussed that the PEP sometimes can be reluctant to share, but that they normally require them to share either way. Additionally, another OEM had the same experience that PEPs occasionally do want share complete 3D documents. However, in cases when they find it reasonable to demand it, it is added as a requirement in the order. In short, the PEPs are increasingly required to deliver models of everything delivered physically and the required level of detail is increasing. In addition, the PEP is nowadays not reluctant to share, as long as they are paid for their modeling efforts. In addition to this line of reasoning, an interesting comment a PEP expressed, which reveals an underlying attitude the PEPs might have when delivering models was: “We know that some companies in certain countries tend to copy much, but if we do not do the work someone else will.” Therefore, we also conclude that incentives along the value chain for creating and delivering models must exist. This will be further discussed in Collaboration 6.9.

An interesting view concerning the correctness of models that one OEM discussed was if they will need a complete original when conducting VC in the future. Their line of reasoning was that “if the PEP do not want to share the real original, what digital twin will be delivered?” Therefore, they are critical towards the current excessive focus on digital twins in the industry since they argue that less exact models still can be valuable. They OEM stress that they are satisfied with a model that enables testing of code and concepts and are currently discussing with PEP how close to reality the model must be. Their conclusion is that an exact replica is not needed. Their argument is that the real production has top priority, not the digital twin meaning that “If the reality of the machine does not comply with the model, no one will stop the production to correct it. In the end, it is the production that we make money from and not the model.” The OEM concludes that it is IT-people that exaggerates this need of a digital twin, and stresses that it is the delicate issue of finding balance between input versus output that must be addressed. Therefore, we once again stress the need of a common terminology and definitions concerning simulation and especially VC. In addition, users of simulation must have a purpose and goals so that correct level of detail is chosen.

Summary

Interoperability is a major issue that hinders the possibility to connect different IT-tools. All interviewees claimed that they suffer from interoperability issues and want solutions from the CMs. Currently, PEPs and OEMs use neutral data formats as a solution, but it is not an optimal solution according to them since information disappears. In addition, PEPs and OEMs must re-work (duplication of work) models frequently as they shift between IT-tools. Effectively, re-use is difficult and thus the modeling efficiency is decreased. In response to this, the CMs are currently working with creating interfaces between applications and are striving to establish standard file formats that are designed to preserve information as the model is transferred between tools.

IP is not considered a major barrier towards sharing of models, simulation models and code among our interviewees whereas researchers present IP as an important issue. However, in general we conclude that
Discussion & Analysis

all companies are reluctant to share information to some degree, but not to receive. CMs want to restrict the possibility to see internal workings of the e.g. motor. PEPs are mostly concerned with the return on investment regarding the modeling, i.e. payment from the OEM for the delivery and require models from the CM. OEMs want detailed models suitable for simulation at a low cost and are careful with what type of information that is shared with PEPs during the design phases.

Conclusion and Recommendation

We found that interoperability issues are being investigated by CMs and that they agree that interoperability must increase in the future. This can be accomplished in two ways: interfaces and standard file formats. Standard file formats must support preservation of information, e.g. AutomationML. Effectively, AutomationML is an interesting file format that could become an enabling technology for VC. Therefore, we recommend continued work with interfaces and continued development of AutomationML and that CMs, PEPs and OEMs increasingly start to use it so it becomes a standard. This is important and it is not only the CMs that are responsible for a standard becoming a standard, PEPs and OEMs must be prepared to change their way of working too.

In addition, library solutions with models of e.g. mechatronic components, stored as FMUs or in AutomationML solves two issues. Firstly, information loss is supposedly eliminated and interoperability is increased. Therefore, re-use and modelling efficiency is improved. Secondly, this approach also reduces the importance of the level of maturity concerning simulation and thus how comprehensive the requirements of specification are. Since the delivered format supposedly is interoperable regardless of IT-landscape. Therefore, a suitable standard for CMs, PEPs and OEMs to commit to is FMI/FMUs and AutomationML. In addition, AutomationML can be used to address IP issues since the extracted data becomes neutralized and engineering investments are protected. Therefore, AutomationML also decreases issues with IP.

Concerning IP we believe that black-box solutions with an emulation of the virtual control is an appropriate short-term solution that suits the current need of the OEM and protects the CM. It is currently an appropriate approach for CMs where detailed functionality is needed by PEPs and OEMs, but exact information is not necessarily needed to be accessed. However, we once again stress the need of a common terminology and definitions concerning simulation and especially VC. This is important since common terminology and definitions are needed preconditions to create specification of requirements that support VC. In addition, users of simulation must have a purpose and goals so that correct level of detail is chosen. Ultimately, we also conclude that incentives along the value chain for creating and delivering models must exist so that a sustainable business model that supports the implementation of VC in the industry is created.

6.5 Usability

Usability refers to the work of making simulation results accessible, especially for non-simulation experts so that the decision making processes during plant operation can be made with better information ground. In this section we discuss how the interviewed companies utilize simulation results.

From our interviews it is clear that simulation is seen as an engineering support tool that is used to test e.g. mechanical design and code iteratively. Thus, the simulation results are utilized immediately in the engineering work-flow. None of our interviewees claimed that they had any issues with accessing simulation results nor making them useful in their decision processes.

Nonetheless, simulation requires a simulation model, and this model requires modeling efforts that must be justified by a business case. However, none of the interviewees could point to any KPI (Key Performance Indicator) that was used to assess the value of their simulation activities. Hence, they stressed that it was difficult to present strong business cases. In addition, one OEM argued that the lack of a clear KPI makes it difficult to measure the value. However, once becomes VC a standard, this OEM believes that check-lists will be suitable to evaluate VC since it is easy to check if certain parts of the model work/do not work.

In addition, two interviewees discussed the need of a purpose and goals with the simulation and the following quote from Lewis Carroll was highlighted by Company A1 and Company C8.

“Would you tell me, please which way I ought to go from here?”
“That depends a good deal on where you want to get to”, said the Cat.
“I don’t much care where”, said Alice.
“Then it doesn’t much matter which way you go”, said the Cat.

Lewis Carroll, Alice’s Adventures in Wonderland

Metaphorically speaking, if Alice knew her destination, the Cheshire Cat could have assisted her. The moral of the story in the context of simulation serves as a reminder that without a purpose and goals with the simulation, the simulation is less likely to be valuable. In addition, suitable level of abstraction becomes difficult to decide. Therefore, we believe that simulation goals, i.e. measurement of how to reach ones destination is important.

Furthermore, we argue that the interview study made it clear that few of the interviewees were able to address these crucial measurement perspectives. We believe that there exists two reasons for this. Firstly, actors within the value chain are unable to assess and institutionalize internal simulation KPIs. The reason to institutionalize the knowledge is to make the measured KPIs accessible by non-simulation experts. These KPIs works as a communication tool, and increased communication will eventually lead to that the overall work is less sequential (see Usability 4.5). Secondly, companies within the value chain are overburdened by work and therefore unable to reflect on how the results of the simulations should be used in a long-term perspective (see Project Capability 4.6.1). Both mentioned problems (lack of KPI and excessive work load) are important. No matter which problem that is the cause of the inability to address crucial measurement perspectives, both issues ought to be dealt with.

One OEM stressed the need to know “why” a simulation takes place. This OEM’s opinion regarding simulation is to virtually test something prior to doing it physically. Therefore, there should be a purpose with the simulation model, a goal with the simulation and an awareness that it implies a cost to create models and to simulate. However, relevant KPIs are difficult to assess, therefore success stories must be shared among the companies in the value chain. We believe that CMs are suitable to enable such communication, since their role is cross-functional in the entire value chain. For example, they could be working with defining suitable abstraction level in VC models. Therefore, we suggest that CMs that encounter success stories concerning how others achieve relevant KPIs should help OEMs and PEPs in their development of KPIs.

Summary

It is important to have a purpose and goals with simulation. However, few of the interviewed companies currently reflect on this.

Conclusion and Recommendation

We conclude that companies within the value chain currently lack relevant KPIs to evaluate simulation with. Therefore, we recommend that OEMs should spread and document success stories of VC in order to develop KPIs and e.g. defining suitable levels of abstraction.

6.6 Work-flow

Work-flow refers to the process or method that an organization use during the plant engineering process. Oppelt, Barth, and Urbas (2015) concluded that four actions within work-flow must be addressed. Essentially, the goal with the actions is to assure that modeling from early development phases ought to gain later phases concerning VC. In this section we will discuss the work-flow within our interviewed companies and how they relate to the four actions.

Nowadays, both PEPs and OEMs use simulation during their plant-engineering-process and among those with high level of maturity in simulation, it is considered a standard. However, a common view concerning work-flow within the plant-engineering-process among our interviewees (that also match what research concluded) is that it is characterized by sequential work (see Work-flow 4.6). Interestingly, this sequential approach applies to simulation too. Effectively, each discipline simulates their work in their specific software and makes sure that it works and then it is passed on to next discipline. An automation engineer OEM highlighted this issue and resulting complications in his work due to the lack of understanding for other disciplines.

“... we receive models created by construction engineers that are unaware how their operation tree affect the modelling of kinematics. We (my discipline) often have to restart the modelling
The majority of both PEPs and OEMs lack a documented strategy concerning how modeling efforts from early phases should benefit simulation activities in later phases of the plant engineering process. Generally, simulation results are utilized directly by the simulation engineer who does not take later phases into account when modeling. However, these PEPs and OEMs claim that it is common sense that the same model is refined throughout the project and that suitable feedback is provided to involved parties. On the other hand, one PEP argued that they will have to develop a better strategy when VC becomes a standard and a requirement. Additionally, one CM argued that early product development phases rarely take into account existing production equipment. Vice versa, development phases of the production equipment do not take products into consideration. Effectively, companies that simulates the production system and test e.g. robots so they do not collide with fixtures are not necessarily taking the product into consideration, despite that products affect the production equipment. Furthermore, if product development makes a new detail, it might imply that the production equipment must be adjusted. In conclusion, there does not exist any information strategy today regarding collaboration and communication between these phases. In addition, one OEM agreed and stressed: “it is a challenge and today since there are watertight compartments between the phases and each phase do their job isolated. R&D make CAD models that we can use, but they rarely care about the production of these. We would like to have a way for R&D to test changes or new products against existing production equipment. To see if there are any collisions and also if assembly will have issues with mounting etc.” In conclusion, a two-way modeling strategy must be implemented.

However, one PEP with high level of maturity regarding virtual manufacturing claimed that they have a clear strategy. “Preferably, it is a chain of continuous improvements along the process. We have a clear information structure where information easily can be shared within the organization. Also that we want to use as few different softwares as possible in order to avoid issues with interoperability that causes a lot of extra work.”

Additionally, when asked about issues with VC, one OEM highlighted that they tend to start late in plant engineering process with VC and thus all benefits are not captured. Oppelt and Urbas (2014) also stress that VC currently is seen as an additional step towards the end of the development phase and argue that VC ought to be an integrated and a continuous part throughout the entire engineering work-flow, see figure 3. Therefore, PEPs and OEMs ought to implement a strategy along the plant engineering process so that the VC starts early and that modeling efforts are refined along the process. In addition, this strategy should be documented and communicated to all involved parts along the plant-engineering-process.

Furthermore, CMs ought to develop software for VC in accordance with the five major industrial requirements proposed by Drath, Weber, and Mauser (2008) (see Work-flow 4.6). One OEM claimed that the code they use in the for PLC in the real factory can not be used for simulation, and vice versa. Nowadays, only robot code can be directly transferred. Therefore, they want all part of VC to follow the same principle as the robot domain do: same in the virtual world as in the real. This is in accordance with one of the requirements that Drath, Weber, and Mauser (ibid.) stress. Namely that the control code for PLC, robots and HMI must remain unchanged while embedding it into the VC environment, i.e. no modification between the mediums should be required. This would reduce the internal resistance towards using VC.

Summary

None of the interviewed companies have a documented strategy concerning how early engineering phases should model to benefit and support later phases in the plant engineering process when pursing VC. However, there is a general agreement within the companies that information is refined along the process, but without consideration to simulation.

Conclusion and Recommendation

Therefore, we conclude that PEPs and OEMs ought to implement a strategy concerning how early engineering phases should model to benefit and support later phases. Thus, VC would be able to be initialized early and modeling efforts would therefore be reduced. In addition, CMs ought to develop software in accordance with Drath, Weber, and Mauser (ibid.) five major industrial requirements.
6.7 Acceptance

Acceptance refers to how to gain acceptance from the management to use simulation tools. In order to reach a success within simulation, it is important to enable a trust and acceptance with the tools being used throughout the organization. In this section we discuss how PEPs and OEMs relate to the economical benefits from simulation and the current business model.

The general acceptance for simulation tools is high among the interviewed companies. However, there is a difference of opinion regarding the importance of its economical value, especially concerning VC. The interviewees stress that it is difficult to assess the value quantitatively and thus it is difficult to build strong business cases. However, intangible benefits, e.g. higher quality of PLC-code, are still considered important.

The PEPs and OEMs that see clear economical benefits with VC argue from a hypothetical position that they save time and money if they get it right from start. The PEPs that see economical benefits tend to work frequently with the automotive industry. Vice versa, the OEMs that see economical benefits tend to be automotive companies or other companies with much experience of simulation. However, one PEP argued that they cannot see economical benefits. They stressed that it implies a large investment in software that also leads to a "lock in effect", i.e. tied to one software vendor. In addition, they argue that they have to manage 10-20 brands from different vendors in order to serve all of their customers. Effectively, it is difficult to justify the VC investment. Furthermore, another PEP discussed that the uniqueness of the projects makes it difficult to benefit from modeling efforts between projects. Another interesting perspective that was highlighted was that "...money can be saved with simulation. Not by simulating the entire project, but parts that are sensitive of, or associated with large risk...". This reasoning is also in line with our suggested design of simulation models that is based on the idea of locally being able to raise the level of detail and to use a Mesoscopic models, see figure 29.

It is difficult to quantify the savings that can be made from simulation. Since there are only two options, simulate or not, a comparison is not possible. Therefore, EMP is a major concern that companies bear in mind (see Modeling Efficiency 4.2. To address this issue, reference project ought to be used. In this line of reasoning it would be interesting to conduct projects both with VC and without VC in order to compare the projects. In addition, the projects ought to vary in size and complexity, i.e. some projects where a single machine is commissioned and some where a complete production line is commissioned. This would help to decide where VC really is valuable and where it is less valuable. The current estimation of a time reduction of 75% with VC is based on experimental results of a simple setup of a machine with a certain type of PLC and cannot be directly extrapolated to larger projects (Reinhart and Wünsch, 2007). The experiment involved 60-test persons and each person had to independently develop a control program for the same machine. Half of the test persons used standard development tools, whereas the other half was allowed to additionally use a simulation model to conduct VC of their control software before the real commissioning. The results from this experiment was that the control software quality in terms of fulfilled requirements was improved by more than 100% and the commissioning time was reduced by 75% if VC was used. Despite that the experiment was well conducted, the results are not applicable to the vast variation of commissioning projects that exist. Therefore, we argue that more reference projects made in a similar way as above experiment ought to be conducted. Preferably, CMs should do this since they promote the technology and to gain trust they ought to develop these reference projects as a proof of concept and selling argument. It is an expensive activity to perform and it must be made jointly with an PEP or OEM. However, one must spend money in order to make money.

Nonetheless, one OEM claimed that the question regarding economical value can be formulated in two ways: “How much did we save by simulating or, how much did we lose by not simulating?” Each question can give different answers and it can also be easier occasionally to find answer one or the other. As discussed earlier, there are no KPIs to measure VC with. However, in our interviews we found two OEMs that reasoned according to above mention questions and each OEM reasoned according to one of them.

The OEM that reasoned from the “How much did we save by simulating?” argued that:

“We have 80% risk reduction when we simulate and we only have to find one error per year to justify the simulation. It must be seen as an insurance, even if you do not want to fail with the commissioning, it is inevitable, you will fail in some part…”

Senior Automation Engineer at Company C9
The OEM that reasoned from the “How much did we lose by not simulating?” argued that:

“We have just compared costs if we must return to the PEP if the test-run is not accepted. We can be told that everything is ready for a test-run, and when we arrive, it is not. Improved quality and shorter commissioning time is our most valuable output.”

Early Equipment Manager at global truck manufacturer C8

However, one OEM also mentioned that they cannot spend unlimited amount of time and money on models and simulation. They discussed a project where they excluded the model that accounted for 15% of the total project cost. Simply because the PEP that was hired to perform the project could not answer the question “How do we know that the model is a replica of the reality?”. According to this OEM the model (in this case a model of a machine or robot cell) should only require one week extra work to a cost of 50-100 000 SEK (i.e. labour) or around 10% of the project cost. Otherwise the cost becomes difficult to justify. Currently, this OEM manages to create models in two- to three weeks, depending on the project. Therefore, they strive to become more efficient.

It is also interesting to discuss the business model regarding modeling in the context of the size of companies (number of employees, revenue and profit). PEPs are primarily the actor that is supposed to conduct VC in future projects since OEMs will require them to do so. In addition, as already discussed, modeling is costly and the model must have the required level of detail needed for true validation of the demanded test cases in order to be valuable. Otherwise errors may remain undetected and the invested modeling effort risk to become for nothing. Furthermore, the EMP makes users aware of the risk with VC economically.

The current business model is that the CMs sell VC software to both PEPs and OEMs. PEPs make the models and must comply with specification of requirement from the OEM. Hence, if unexpected errors occur, despite that VC has been conducted, the PEP is obliged to solve them, which decreases the return on investment of the model i.e. EMP. In addition, VC software is expensive. For a PEP which compared to a OEM or CM is a small company, i.e. a SME (see Acceptance within Small and Medium sized Enterprises 4.7.1), an investment in software can be the same amount as one year’s profit. Therefore, they must be able to justify the investment and obtain a decent return on the investment i.e. not lose money on it in the long run. Otherwise it is not a sustainable business model. In this regard, one PEP discussed this issue about the initial investment. They stressed that they find it difficult to justify the investment prior to knowing the benefits. The EMP coupled with the required knowledge to use the software makes this PEP reluctant to invest. They argue that the software ought to be cheaper in the initial stage so that they can perform a pilot project and thus assess VC. This line of reasoning is logical, but also common and we believe that we, despite being independent KTH students conducting our thesis project at Siemens AB, occasionally during our interviews suffered from subtle criticism towards Siemens. We stress that the concept of a sustainable business model is a two-way responsibility. Therefore, CMs, PEPs and OEMs must all benefit from the collaboration within the business model. In this case, the PEP must benefit from using the software that enables VC, but the CMs must also make money on their products. Despite that it might be difficult to justify the investment prior to knowing the benefits, not investing can also be the first step towards loosing in future competition. However, we still agree that the payment of the software could be modified in the initial stages and that it would benefit both parties.

Summary

The perceived economical value with simulation varies among the PEPs and OEMs and they all agree that it is difficult to quantify the economical impact and the EMP is a constant issue that companies discuss internally. Furthermore, simulation is an expensive activity and its cost must be justifiable since each project (e.g. new production equipment) must be profitable. In addition, the cost of modeling must be shared, i.e. the company that models must be paid for this service.

Conclusion and Recommendation

To attend to the perceived economical value we argue that more reference projects ought to be conducted. Preferably, CMs should do this since they promote the technology and to gain trust they ought to develop these reference projects as a proof of concept and selling argument. It is an expensive activity to perform and it must be made jointly with an PEP or OEM. However, one must spend money in order to make money.
In addition, we conclude that sustainable business models must be implemented in order to create incentives for CMs and PEPs to create models and for OEMs to use the models. This is a prerequisite for the implementation of VC.

6.8 Education

Education refers to the development of a common methodology and terminology concerning simulation and associated activities. In this section we discuss how companies conduct educational activities and how they reason about the required knowledge that VC implies.

Currently, internal education activities to increase the general simulation knowledge is present among the most interviewed companies. However, since VC is in its early stages none of the interviewees worked with educational activities linked specifically to VC. We found that it is either CMs or OEMs that plan educational activities (i.e. workshops) to enable VC within the value chain and PEPs get invited to increase the transparency of what is seen as future issues by CMs or OEMs. We found that it is either CMs or OEMs that plan educational activities (i.e. workshops) to enable VC within the value chain and PEPs get invited to increase the transparency of what is seen as future issues by CMs or OEMs. However, CMs and OEMs have different agendas/motives for the knowledge increasing activities. OEMs want to assure higher quality of the specification of requirement and thus obtain a smoother commissioning phase with the PEP. The smoothness is reached by addressing future software needs and knowledge that the PEPs must adapt to. However, the needed knowledge is difficult to obtain and as one OEM put it:

“To find the correct VC competence is a challenge. The complexity of the model is rapidly increasing, therefore, the VC model creates new levels of know-how on how the different VC parts relate to each other. The needed competence can be exemplified as a ‘tulip rose’.”

*A tulip rose is a Swedish expression, metaphorically explaining an impossible hybrid

Global Strategy and Process Developer at Company C4

In similarity to the above quote, Oppelt and Urbas (2014) highlight that VC will pose new requirements concerning knowledge. In addition, the authors stress that increased competence about VC is crucial for its success, but also that appropriate know-how is difficult to obtain. The problem is a type of catch-22 problem that until solved will keep educational perspective inactive. The actors within the value chain must collaborate in order to articulate a common terminology and definitions since knowledge always is tacit before it has been explicitly articulated for the organization. Once that articulation is accomplished it is possible to create education packages that can be utilized to spread the knowledge. Therefore, since VC is in the early stages it is impossible to conclude what the common methodology and terminology is in terms of VC.

Summary & Conclusion

Since none of the companies in the interview study have adapted to VC activities on a daily basis, the internal VC knowledge is not sufficiently mature to be transferred into educational packages. In order to increase the knowledge needed, collaboration and discussion between the actors within the value chain must occur. Without the initial effort and investment in time and thus being forced to reach new levels of internal knowledge, the education packages will always be sub-optimal. Therefore, an initial step could be that OEMs and PEPs agree on specification of requirements together. These can be developed interatively through conversations during the learning process of VC.

6.9 Collaboration

Collaboration concerns the ability to exchange simulation models across companies in a collaborative manner. The collaboration can be horizontal along the value chain, e.g. collaboration between a CM and a PEP or vertical, e.g. collaboration between two CMs. Collaboration is important since distribution of the modelling enables the appropriate (best suited) company to be involved in the respective phase, e.g. design, engineering and commissioning of production equipment. However, there is currently no collaboration model according to Oppelt, Barth, and Urbas (2015). During our interviews we investigated company’s view on collaboration and in this section we discuss their answers.

The overall opinion whether collaboration exists along the value chain or not varies among the interviewed companies. However, several companies discuss future needs regarding simulation with each other. CMs
expressed a focus on vertical collaboration, to enable software interface and to provide libraries with models of components. OEMs expressed that they participate in horizontal collaborative activities with PEPs frequently. In contrast, PEPs did not express any active collaboration and claimed that there was no clearly stated collaboration within the value chain.

As already mentioned, CMs are currently providing library solutions and one CM is investigating to provide the behavioural model of components. Furthermore, they are creating interfaces with competing vendor’s software to increase interoperability and they enter partnerships with PEPs. Within the partnerships CMs and PEPs meet regularly and CMs teach PEPs how to use their products. In turn, the CMs obtain valuable market intelligence since the PEPs are in direct contact with OEM and can help CMs understand how to better serve both them and OEMs. The CMs stress that if the end customer know what they want, i.e. have explicit knowledge, a close collaboration is usually the case (see figure 27).

Additionally, one CM discussed the general trend in increased use of software in the industry, which we also can see in figure 2. Therefore, CMs in the future will become more like software companies than hardware companies, which will affect the current ways of collaboration and future collaboration must adapt to this change.

“We deliver hardware, but it is the software that will be the difference in the end. Therefore, we must transform into a software company since it is increasingly important to be able visualize and simulate operations. The manufacturing of a e.g. motor is not difficult, it is well known and can be made wherever in the world. However, software and service is what is difficult and thus, we must change our culture and reevaluate our role in the value chain. The same applies to PEPs and OEMs, the successful companies in the future are the ones that adapt to virtual manufacturing.”

IT Specialist of global Robotics Software Company A3

The general opinion among PEPs is that there is no stated collaboration concerning how it should be formed, i.e. responsibilities or liabilities. Some PEPs highlight their partnerships with CMs, but despite this, one PEP considers the CM to lack an understanding regarding the business between the PEP and the OEM. The PEP stresses that CMs ought to have a better understanding of the system PEP delivers to OEMs, and what the OEMs need to succeed. Thus, CMs should have better insight in how their products are used and how their products interact when used in the work of OEMs and PEPs. This is valid criticism, but PEPs also have a responsibility to provide feedback to the CMs and give the the right preconditions to understand. The CMs must be prepared to listen and strive to understand. An example of when this feedback and listening collaboration has worked is the demand form PEPs concerning increased provision of 3D-models with the behavioural model. In this regard, the CMs have listened and are currently working on provision of complete models with behavioural models.

In addition, both PEPs and OEMs stress that the work with standards ought to be better. Since software have been developing freely over time, there are many different file formats which lead to interoperability issues. Therefore, one PEP argued that CMs should take command and dictate standards. We found that this currently is occurring with the development of AutomationML (see Integration 6.4). Furthermore, as discussed in Acceptance 6.7, the price of the software from CM was mentioned by one PEP. They were currently in a partnership with a CM and the CM introduced them to VC. However, the up-front payment was too high initially, especially prior to knowing its potential. They claimed that “We would probably enter if the price was lower initially so that we could start slowly and learn and test if this is suitable for us.” In addition, this PEP argued that some OEMs seem to require simulation without knowing why: “The OEM might read some flashy brochure about simulation and ask us if we can simulate. However, they do not understand that it will increase the price, and when they find out, the simulation is no longer interesting.” Effectively, the PEP’s reluctance towards investing time and money in software to conduct VC is both based on the initial investment and that the demand from the market is not yet established. In addition to this line of reasoning, a quote from a PEP highlights another aspect concerning the current view on collaboration among the PEPs: “We stress more collaborative efforts from both sides since we feel alone in the development of VC.”

However, it is natural that PEPs feel this way and have a certain skepticism towards VC. PEPs have limited resources to develop their internal organizations i.e. new technology or organizational change whereas CM and OEMs normally have departments appointed for these activities. Hence, the question
of company size as discussed in Acceptance 6.7 is important. However, PEPs ought to prepare and adapt to the new requirements in the future concerning increased virtual manufacturing. CM and OEM do their part, i.e. develop software and implement virtual manufacturing in their business. Therefore, PEPs must do their part too, i.e. invest in virtual manufacturing education and software. Otherwise they may risk to lower their competitiveness.

The OEMs stress that they have collaboration with PEPs to a larger extent than with CMs. Hence, OEMs with high level of maturity concerning virtual manufacturing educate PEPs in their way of working and strive to achieve long-term relationships. In addition, the OEMs stress that they ought to be clearer in their communication with the PEP and have clear requirements regarding the models. Therefore, their current collaboration mainly concerns which requirements that will come in the future and one OEM stressed that CMs ought to be more involved in these discussions. This is not an unreasonable idea since it would increase the understanding among the CMs about e.g. VC. One of the interviewed OEM with high level of maturity currently has a collaboration with a CM and a PEP concerning the creation of technical requirements of models that can be used to enable VC. This is according to us a suitable method since all parties together can discuss and understand each others businesses. Effectively, the quality of the specification of requirements will increase and a common terminology will be developed. However, one OEM highlighted the need to create sustainable requirements and business models meaning that “...if we are too demanding we might end up without suppliers (PEP).”

All interviewees agree that collaboration is beneficial. They highlight advantages like increased knowledge due to collective learning and therefore better communication is established. Effectively, a CM highlighted improved quality of the end product as an important outcome. In addition, not all companies in the value chain must have the resources and know-how to model simulation models, since the service can be purchased. Effectively, simulation will be used more frequently. However, there is a difference of opinion regarding which barriers towards collaboration between CM, PEP and OEM that are the most pressing.

A general conclusion is that the traditional roles of companies within the value chain constitutes a barrier itself to cooperation concerning models and simulation models. Mainly because the traditional roles create an unbalanced cost distribution in the value chain, especially now when the demand regarding the virtual delivery increases. In addition, one CM argue that it is difficult to convince companies that there are advantages with collaboration. Mostly because it is difficult to quantify the advantages financially and that companies are unused to collaborate together. For example, this CM claims that the attitude within CMs normally is negative towards collaboration with competitors.

In addition, there are three other problems that constitutes a barrier towards collaboration: a business incentives problem, a first-mover problem and a resulting business model problem.

One CM argued that the business incentives problem concerns the lack of an agreement regarding both the pricing and who should pay for the models. A PEP confirms these issues and additionally stress that the question “Who should take the cost and who gets the benefits?” must be addressed. Furthermore, this PEP argues that the OEMs want a model to continue working with, preferable detailed, and the PEP does not see the benefit to work with great level of detail. The first-mover-problem according to the CM is that the PEP want the OEM to require VC and show them their requirements specification. Prior to that, the PEP is unwilling to invest in software and education for VC.

The combination of the business incentives and first-mover problem leads to a problem with the current business model. Mainly that the current business model leads to unbalanced cost distribution and that the lack of collaboration leads to poor communication regarding specification of requirements. Effectively, concerning cost distribution, one PEP argued that “If the cost of creating models was lower, then we would cope with low return on investment in order to learn and test. But now it is too expensive for us. If we could learn it at our pace it might be us to offer customers simulation services, and not them asking us for it.” This is further discussed in Acceptance 6.7. Additionally, one PEP discussed the current communication within the business model and argued that software developers want to promote their products and OEMs are sold the idea of VC. Thus, PEPs must deal with both actors, i.e. OEMs with their demands (order requirement specification, software requests) or CM’s products (components, software offerings). In addition, OEMs want a simulation model that is adaptable to their current production, but lack the ability to express the needed requirements. Effectively, the PEPs must manage unclear requirements and therefore, they demand better instructions. However, at the same time, OEMs argue that PEP should take a greater responsibility to understand OEM, which results in agitated relations. Therefore, we argue that a sustainable business model, i.e. a business model where all actors within
Discussion & Analysis

benefit from collaboration must be developed. Hence, modeling efforts must be financially rewarded and investments in education and software must be profitable. We argue that a possible solution to this would be that CMs offer smoother initial investments for PEPs, but that CMs must be increasingly paid for their software as PEPs increase their return from using it. In addition, PEPs ought to be financially rewarded by OEM from their modeling efforts.

Another interesting idea would be to allow CMs and PEPs to increasingly offer virtual manufacturing services to increase their return on investment. However, when the interviewees were asked questions concerning purchasing-or offering of virtual manufacturing services, i.e. pay another company to e.g. model components or to deliver a digital twin of current production equipment, the answers were dispersed.

CMs are positively inclined to offer modeling services to specific projects in the future, e.g. offer a digital factory and consider provision of their current product portfolio in a digital version to be an interesting business, i.e. being paid for it. PEPs also find the idea to offer modeling service, to e.g. OEMs, compelling. However, they do not like the idea of that they themselves should purchase services of complete modeling since “We want to have that knowledge ourselves and it is more likely that we will hire someone to do it for us within the organization.” Furthermore, they welcome the idea of CMs offering libraries with detailed models. However, they do not want to pay for them and argue that “It is a hygienical factor of CM to offer this.” OEMs argue that they already purchase models from PEPs as part of the delivery of production equipment and if the PEP cannot deliver the model, the corresponding cost for the OEM to model it is discounted from the price. Generally, there is a negative attitude towards expanding their purchasing of virtual manufacturing services, mainly regarding letting other companies manage updates in the models due to change within the factory. The OEMs argue that it would be difficult for an external person or company to do this, since there is so much that is changing in the facility all the time. Therefore, it would require a full time employee. In addition, it would also lead to lost competence regarding simulation, which they are keen to have.

In summary, CMs are positively inclined to increase their virtual manufacturing services and want to sell library services. PEPs that themselves stress that they would benefit in their modeling from libraries are not interested in paying for this services and they are not interested in using virtual manufacturing services. Additionally, PEPs are interested in expanding their virtual manufacturing services i.e. offer updating of models and/or creating digital twins of production equipment. You could argue that this would increase their return on investment from software, since they can expand their current business with new services. However, OEMs are not interested in increasing their use of external companies concerning this type of virtual manufacturing services. Nevertheless, OEMs require the PEPs to increase the virtual delivery, but to our understanding, they did not want to pay more than they already do.

Thus, PEPs and OEM are not interested in increasing their purchasing virtual manufacturing services, but both CMs and PEPs want to increase this service as part of their future business. In addition, PEPs want increased library offerings from CMs without paying for it and OEMs want increased virtual delivery from the PEPs without increasing the payment. Hence, it is a question of “who should bear the cost?”, or as in the colloquial expression “You can’t eat your cake, and have it too” (referring to the impossibility of having something both ways, if those two ways conflict) that must be addressed. Therefore, we conclude that this attitude must change. Otherwise a sustainable business model will not be developed.

Summary

It is mainly organizational barriers behind the lack of collaboration and CMs, PEPs and OEMs tend to blame each other as the guilty part. However, they all stress that collaboration is important. One CM argued the collaboration implies that all parties involved will benefit. The collaboration leads to a new level of knowledge since more competence can be reached within the collaboration and effectively, they can increase their offerings. As one OEM stressed “Industry 4.0 is based on partnerships”. Therefore, we suggest to follow the examples highlighted in Business Ecosystems 4.9.1, namely to collaborate more between CMs, PEPs and OEMs to deal with the with technical and non-technical problems associated with VC.

In addition, collaboration leads to agreement concerning e.g. terminology, definitions, and requirements of specification which is crucial for the successful implementation of VC. Therefore, a suitable initial stage of the collaboration in order to agree on above mentioned areas is to follow the approach suggested by Brady and Davies (2004). Namely to use reflective sessions where tacit knowledge is transferred to explicit knowledge by focusing on the outcomes from learning through double-loop reflections (see Project
Furthermore, our results confirm what Oppelt, Barth, and Urbas (2015) stated (see Collaboration 4.9), namely that there are no collaboration models currently concerning simulation and model exchange. Additionally, we did not find any literature addressing how such a collaboration should be structured. Therefore, future work ought to focus on development of a collaboration model. In addition, this model ought to be support a sustainable business model, i.e. that all parts of the value chain benefit from the collaboration financially. However, discussed examples of suitable roles within a potential collaboration are summarized in figure 30. Our recommendation suggests how the traditional roles within the value chain could change to enable collaboration. The collaboration model is built on a common foundation that means to fulfill our recommendations in terms of interoperability, namely to choose interfaces and standard file formats that enable sharing, horizontally and vertically within the value chain.

**Figure 30:** Our suggested Collaboration model, that should be interpreted as an overview of what actions actors within the value chain should attend to

Furthermore, we have tried to express how the actors should act in relation with its upstream and downstream partner, to level the cost of modeling. Starting in the top left arrow (figure 30, we suggest that CMs should find alternative pricing to enable a smoother transition for PEPs to gain knowledge with VC.

Such a subvention from CM would isolate parts of the problem and "only" assess modeling knowledge, which in itself is complex enough.

Secondly, due to CM's position as a cross-functional party, we believe they have a suitable position to help with finding common (i.e. best-practise) benefits of VC, making it possible to share benefits. Eventually, such information would enable a assessment of the monetary value of VC. Thirdly, to create a sharing of models interdependent platforms are needed to easily access reliable models. Therefore, we suggest CMs to assist the value chain with web-based libraries. Fourthly, we suggest PEPs to support CMs in this and show the value PEPs receive by paying for access to a web-based library-service. Moving over to the top right arrow (PEP to OEM), firstly, we suggest that both PEP and OEM carry out internal activities where they create KPIs, to assess where they want to go. Secondly, they should ventilate internal knowledge to raise the quality of their requirements specification work, so that when they share information between one-another it is done in higher pace and with smoother information flow. Secondly, we suggest that PEP should continue with delivery of models, but shift it so that they are ready-to-simulate for OEM. Thirdly, OEMs should pay CMs and PEPs to provide services linked to Virtual manufacturing, to raise their return of investment. Lastly, the third arrow on the bottom of figure 30, in the same manner as
helping PEP, we want CM to assist OEMs with addressing the financial benefits as well. Secondly, since OEMs are the ones that will handle the model during its life-cycle, it is highly important that they provide feedback to CMs on how the original files could be altered to suit the users need.

**Conclusion and Recommendation**

It does not exist any collaboration model currently that supports simulation model and model exchange. This is due to organizational barriers where companies are stuck in traditional roles and the fact that no one wants to bear the cost of modeling. Effectively, the lack of collaboration hinders the development of common terminology and definitions regarding simulation. Therefore, the implementation of VC becomes difficult.

We recommend that companies collaborate more frequently and support a sustainable collaboration model as presented in figure 30.

In addition, as Drath, Weber, and Mauser (2008) stress in the *Modeling Efficiency 4.2*, it is during the introduction of VC that businesses are the most sensitive due to the EMP. Therefore, we suggest that CMs current role towards PEPs should change in two ways. Firstly, instead of selling the VC software to PEP in the initial stage and require full payment, the CM should offer a lower price initially. Effectively, the PEP can perform a pilot project and learn the technology and its benefits, and thus reduce the EMP. Secondly, as is highlighted in *Integration 6.4* CMs should enable standard components in web-based libraries.
7 Conclusion

In this section the conclusions based on our RQ can be studied. In addition, our recommendation on how actors within the value chain should address to the barriers and needed future work is included within this section.

To answer our RQ (What barriers within the eight fields of action are preventing VC from gaining momentum and becoming widely used by the industry?) we conclude that it generally is the non-technical fields of action that contain barriers that prevent VC from becoming widely used in the industry. Especially, it is the organizational related barriers that are most severe. Nowadays, there exist technical solutions that enables VC and the technical fields of action mainly treat modeling efficiency improvements. However, interoperability is considered to be the most severe technical barrier towards VC and an important area to improve. Nonetheless, we conclude that the technical barriers are considered less severe compared to the non-technical in terms of enabling VC to becoming widely used. Our conclusions are provided in detail within their corresponding field of action in Discussion & Analysis 6 and below are the summarized version of our conclusions. Therefore, for readers who want to read the nuanced view and understand how we reached these conclusions, we recommend to study the section Discussion & Analysis 6

7.1 Barriers to Virtual Commissioning

- We stress the need of a common terminology and definitions concerning simulation and especially VC.
- To improve re-use of models, we suggest that modular approaches ought to be used more frequently. Additionally, this approach would enable co-simulation of different FMUs according to the "FMI for co-simulation" concept. Effectively, model exchange and simulation would become facilitated and companies along the value chain would have less problem with interoperability delimitation in the complex landscape of IT-tools.
- In a short term perspective concerning model efficiency and model re-use, libraries containing models with behavioural models ought to be developed. In addition, it ought to be easier to create simulation models in existing software. Therefore, FMI/FMU solutions coupled with co-simulation is recommended. In the long term perspective concerning model efficiency, companies ought to implement automatic model generation methods. CMs primarily will provide models of standard components within libraries. Therefore, PEPs and OEMs ought to have efficient methods of creating models suitable for simulation when a special case appears.
- Before commencing a modeling project, a suitable level of detail ought to be decided. To decide a suitable level, common terminology, definitions, required test cases, purpose and goals need to be established. Furthermore, we argue that simulation models should be created based on the idea of locally being able to raise the level of detail and to use a Mesoscopic simulation model.
- To enable re-use and thus improve return on invested modeling effort, ownership structures and responsibility of updating within the organization is important.
- Interoperability must increase and two suitable methods are interfaces and standard file formats. Several barriers are solved with library solutions with models of e.g. mechatronic components, stored as FMUs and/or in AutomationML. Firstly, information loss is supposedly eliminated and interoperability is increased. Therefore, re-use and modelling efficiency is improved. Secondly, the importance of the level of maturity concerning simulation and thus how comprehensive the requirements of specification are becomes less important.
- Concerning IP we believe that black-box solutions with an emulation of the virtual control is an appropriate short-term solution that suits the current need of the OEM and protects the CM. In addition, AutomationML also decreases issues with IP.
- We conclude that companies within the value chain currently lack KPIs to evaluate simulation with. In addition, knowledge is not institutionalized and actors within the value chain are either unqualified to assess this knowledge or overburdened by work which limits their time to reflect over how the results of the simulations should be used with a long term perspective.
Conclusion

- None of the interviewed companies have a documented strategy concerning how early engineering phases should model to benefit and support later phases in the plant engineering process when pursuing VC.
- It is difficult to quantify the economical impact simulation implies and currently no one is able to present benefits quantitatively, only qualitatively.
- The lack of common terminology, definitions and that internal knowledge is not transferred from tacit to explicit makes it difficult to conduct educational activities regarding VC.
- There is currently no collaboration model that all actors within the value chain agree on, but all actors agree that collaboration is important. In addition, the current business model and the direction that the development this business model is going is not sustainable, i.e. that all parts of the value chain benefit from the collaboration financially. We conclude that current business incentives for creating and delivering models must change as the requirement on the virtual delivery increases. Otherwise, the business incentives will disappear or be insufficient. Furthermore, we conclude that the current roles in the value chain are inadequate and caused by out-dated views on the roles. Therefore, we suggest an updated role structure, a new collaboration model that enables a sustainable business model. This is visualized in figure 30.

To answer our sub-RQ (Which actions and factors must be addressed in order to reduce the barriers?) we recommend that the following areas ought to be addressed.

7.2 Recommendation to value chain

- To create and agree on a common terminology and definitions all actors within the value chain ought to cooperate and transfer tacit knowledge into explicit. This is also a prerequisite for enabling educational activities.
- To enable model re-use and increase model efficiency in a short term perspective, CMs ought to consider provision of libraries containing standard components created as MBMs (models with behavior model) with standardized interfaces that can be stored as FMUs. This would enable better re-use of models and for PEPs to modify these, i.e. create UBMs suited for their needs. In the long term perspective concerning model efficiency, companies ought to implement automatic model generation methods, e.g. MDA.
- To agree on test cases of the production equipment so that a suitable level of detail of the model can be decided.
- Implement ownership structures and responsibility of updating within the organization concerning models and simulation models.
- We recommend continued work with interfaces and continued development of AutomationML and that CMs, PEPs and OEMs increasingly start to use it so it becomes a standard.
- We recommend continued use of black-box solutions with an emulation of the virtual control in as a short term solution that suits the current need of the OEM and protects the CM. It is currently an appropriate approach for CMs where detailed functionality is needed by PEPs and OEMs, but exact information is not necessarily needed to be accessed.
- PEPs and OEMs should find measurable KPIs that can be used to evaluate simulation, by e.g. comparing alternative costs to simulation and evaluate simulation results.
- We recommend that PEPs and OEMs ought to implement a strategy concerning how early engineering phases should model to benefit and support later phases. In addition, this strategy ought to be used both ways, i.e. early phases should consider later phases and later phases should consider earlier phases.
- Reference projects ought to be conducted where the project both is conducted with and without VC. Effectively, the economical impact that VC has could be quantified by comparing the outcomes.
- We recommend actors within the value chain to develop the future collaboration based on the ideas we suggested in figure 30.
7.3 Future Work

- Modular concepts with customization capabilities must be further investigated. Preferably, the idea of MBM, UBM and PBM with standardized interfaces ought to be tested in a case study.

- There is still much research to be conducted concerning automatic modeling methods. It will pose high demands regarding company’s internal databases that they are detailed and well structured. Therefore, automatic modeling methods also implies organizational factors.

- The definitions of level of abstraction and level of detail models must have is still lacking. Therefore, future work of investigating suitable level of abstraction and level of detail is needed. Mainly, that the levels must be defined and that each level is categorized into suitable areas of use. Effectively, simulation engineers will be able to evaluate the project at hand and decide which parts of the production equipment that ought to be detailed and which parts that is enough to keep at a low level of detail. Arguably, the required test cases could be a suitable guiding principle initially. However, future research is needed since level of detail is correlated to the modeling effort.

- More research regarding AutomationML, FMU/FMI and co-simulation is required. Especially as a case study where a VC project is carried out with these file format.

- More reference projects must be conducted where different kinds of commissioning projects e.g. commissioning of a machine, a robot cell or an entire production line is commissioned both with conventional commissioning and with VC. This would enable comparison of the projects and quantified results could be created. In addition, KPIs to measure simulation results must be developed too.

- A concurrent plant engineering process must be developed where disciplines collaborate more. In addition, a strategy regarding how modeling should be conducted to support simulation must be developed.

- As companies gain more competence and knowledge about VC, we suggest that future work should investigate how educational packages should be structured, the most efficient and effective research, would be if it was done by the help of companies who have done at least a couple of pilot projects linked to VC. It is important to continue research within this field, since the sharing of achievements and best practice is highly needed.

- Continued work with our suggested collaboration model must be conducted. The list of responsibilities and liabilities must be supplemented so that the role that each actor ought to have is clear. In addition, new businesses regarding virtual manufacturing services ought to be investigated so that the business model develops and becomes sustainable.
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Appendix

Enclosed questions were sent to the interviewees before the interview with the description so that participants were allowed to read and examine the questions, but not obligated to do so.

Introduction

To ease the understanding of the coming interview a short introduction and the Virtual Commissioning definition will follow. Note that the questions might change during the interview, depending on if we find something (in your answers) that we didn’t know we were going to find.

In short, Virtual commissioning (VC) is a simulation tool that is used to create e.g. a more efficient and risk free commissioning on e.g. newly bought machines, that in the future will be integrated into a production facility (i.e. plant).

In our report, we define and use VC only when it is linked to automation. VC simulates how a PLC (Programmable Logic Controller) control a machine model, actuator or sensor, who in turn control the virtual plant. Therefore, to achieve VC four parallel cornerstones follow; the virtual model that is going to be commissioned needs to be modelled, the behavioral of the machine needs to be determined, an emulation of the mechatronic components is necessary and lastly, the writing of PLC-code needs to be created. These components are then integrated into one simulation model to be able to virtually validate the future commissioning.

The interview will follow two parts. To be able to make sure that we make all our questions during the interview, we might interrupt you if we see that you have answered our question.

Choice of word: During the interview, questions regarding simulation from a general perspective will follow. For such scenarios, the word simulation and simulation model will be used. This includes all types of simulation, including VC. In specific question regarding VC, the word “VC” will be used in the question. Furthermore, the word model and modelling will be used frequently. This is used to describe the virtual copy of a component, system or machine and the creation of such virtual copies.


Interview Date:
Interview Question

Part 1 - General Questions
Do your company work with simulation in any way?
Do you work with VC?
IF Yes
What advantages do you see in this technology?
What disadvantages do you see in this technology?
IF No
Can you specify why you do not work with VC?
Can you see any clear disadvantages with VC?
Can you see any clear advantages with VC?
IF Maybe/Partly
Can you specify how a traditional commissioning is done?
Can you specify how a traditional commissioning is done?
How frequently do you commission?
How long time does it take for you to commission, on an average?
How much resources do you insert in a normal commissioning project?

Part 2 - specific questions
Model Reuse
Do you model your own simulation models?
IF Yes
What are the simulation models used for?
Do you reuse the models that you have created?
If Yes
How do you achieve the re-use of the models?
If No
Do you get/buy models for other stakeholders?
If Yes
Are these models created after you specifications or do you need to change standard parts to fit your own need?

Model Efficiency
How do you create your own simulation models?
How do you create your own VC-models?
How do you create PLC-code?
How do you create
How do you create the behavioural model?
How do you create the 3D-model?
What should be done to be able to be more efficient in your modelling?
Do you do anything to achieve this vision?
Who is in charge/responsible of the simulation model? before, during, and after the model life-cycle?
Who is in charge of updating and changing of the simulation model?
Is there any central database where simulation models are saved?

Integration
How do you handle interoperability between softwares?
Do you use any neutral data format?
How do you transfer simulation model files, internal? external?
How do you handle questions regarding material rights of models?

Usability
How do you guarantee that the results of your simulations are used?

Work-flow
Do you use any simulation or modelling along the plant-engineering-process?
IF Yes
Do you have a strategy in how the modelling work, in early process, should be used in a later stage?

Acceptance
Who within your organization would you say is most keen that you use simulation tools? least keen that you use simulation tools?
Are there any clear economical benefits that can be derived from simulation as a working tool?

Education
Do you work with any educational activities for personnel to increase the knowledge on simulation? In particular with staff linked to automation or mechanical.

Collaboration
Is there any collaboration throughout the value chain to ease simulation?
If yes
How is the collaboration achieved?
If no
How do you think such a collaboration could work?
What are the biggest barriers to collaborate with external parties, linked to simulation?
What are the biggest perks with a collaboration with external parties, linked to simulation?
How would you react if an external stakeholder want to access the original copy of a model?
Do you think you would be likely to pay for a digital copy of what you buy physically? I.e. you won’t have to model it yourself.
If yes
What simulation models would you priorities?
If no
Do you know who in your organization who might be able to answer?