THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Towards a holistic methodology of efficient virtual preparation and commissioning for production systems

A work flow methodology based on insights and lessons learned investigating the development process for production systems at Volvo Cars

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To my lovely wife and daughter.

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Abstract

The industry elaborates on the possibilities of applying virtual engineering work to excel in production system development. For example, Virtual Commissioning as a concept for testing and validating system performance in advance of on-site commissioning has proven beneficial in multiple areas of development. Some areas include reducing on-site commissioning time, guaranteeing functional behavior, and removing potential errors, resulting in a smoother integration of new and upgraded systems.

Nevertheless, it has been hard to prove the financial benefits and actual gain from VC compared to the more trusted traditional methods. The lack of standards mixed with the increasing complexity of systems and experience from prior attempts is one of many reasons.

This thesis has identified different vital areas crucial for adopting virtual elements into the value chain of the development process within the automotive industry. It is of the highest importance to understand the prerequisites of a project's ability to integrate virtual preparation for efficient commissioning and further break down the technical requirements of modeling and simulation in a multidisciplinary digital architecture.

With more quantified data and insight from Virtual Commissioning attempts, it is possible to adopt knowledge to future projects and find ways to increase the utilization of the invested virtual engineering work.

The thesis investigates the challenges of implementing virtual preparational methods for efficient commissioning to achieve flawless launches for all implementation projects of production systems. In addition, the research aims to find ways to increase the utilization of the constructed models, decrease the cost of virtual development and testing, and verify functionality and accuracy for optimal levels of simulation.

Keywords: modeling, digital architectures, virtual preparation, virtual commissioning, industrial development.

List of Publications

This thesis is based on the following publications:

[A] **Anton Albo** and Petter Falkman, "A standardization approach to Virtual Commissioning strategies in complex production environments". *Published in Procedia Manufacturing, Volume 51*, (pp. 1251-1258), 2020.

[B] **Anton Albo**, Kristofer Bengtsson, Martin Dahl and Petter Falkman, "A framework concept for data visualization and structuring in a complex production process". *Published in Procedia Manufacturing, Volume 38* (pp. 1642-1651), 2019.

[C] **Anton Albo**, Ludvig Svedlund and Petter Falkman, "Modular Virtual Preparation method of production systems using a Digital Twin architecture". *In 2021 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, (pp. 1-8), 2021.

[D] **Anton Albo** and Petter Falkman, "Integrating efficient Virtual Preparation and Commissioning into traditional production system development work flow". Submitted to CIRP Journal of Manufacturing Science and Technology.

Other publications by the author, not included in this thesis, are:

[E] Ludvig Svedlund, **Anton Albo**, Bengt Lennartsson, "Co-simulation of Rigid Interactions Using Differential Algebraic Equations". *In 2021 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, (pp. 1-7), 2021.

[F] Endre Erős, Martin Dahl, Atieh Hanna, **Anton Albo**, Petter Falkman and Kristofer Bengtsson, "Integrated virtual commissioning of a ROS2-based collaborative and intelligent automation system". *In 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, (pp. 407-413), 2019.

[G] Martin Dahl, **Anton Albo**, Johan Eriksson, Julius Pettersson and Petter Falkman, "Virtual reality commissioning in production systems preparation".

In 2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), (pp. 1-7), 2017.

[H] Julius Pettersson, **Anton Albo**, Johan Eriksson, Patrik Larsson, Kerstin W Falkman and Petter Falkman, “Cognitive ability evaluation using virtual reality and eye tracking”. *In 2018 IEEE International Conference on Computational Intelligence and Virtual Environments for Measurement Systems and Applications (CIVEMSA)*, (pp. 1-6), 2018.

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Acronyms

DM:	Digital Model
DT:	Digital Twin
FMU:	Functional Mock-Up Unit
MDMF:	Multi Domain Mixed Fidelity
OEM:	Original Equipment Manufacturer
OPC:	Open Platform Communications
PLC:	Programmable Logic Controller
RFQ:	Request For Quotation
VC:	Virtual Commissioning
VP:	Virtual Preparation
VPC:	Virtual Preparation and Commissioning

Contents

Part I

Overview

CHAPTER 1

Introduction

The automotive industry has over the years shown an increased interest and willingness to adapt and integrate virtual engineering strategies and methods to improve production efficiency and be a competitive business on a global market [1].

The operational development teams at Volvo Cars also acknowledge a new technological era of digitalization where virtual tools are the key enablers to find and solve problems as early as possible to secure a higher qualitative development process to achieve flawless launches. Furthermore, a thoroughly tested and verified production system will allow a faster ramp-up and significantly reduce the non-value-added time during physical installation and commissioning [2]–[4].

It has proved advantageous to apply virtual work in the preparation phases for new installations or upgrades of production systems, both for visualization of constructions, programming of control systems, and robots that can identify and prevent possible errors in the development phase. Moreover, it is of the highest value since the cost of unsolved problems during the development process, both for the product itself and for the production system, has an exponential growth for each new development phase [5].

Today's technology makes it entirely possible to make very detailed and accurate models of equipment and larger production systems [6]–[8]. However, the question remains if the highest accuracy and performance results in the highest added value for verifying all kinds of production systems and applications. For example, a system with a rather deterministic or "simple" behavior is easier to verify than a more complex system with multiple constraints and interconnected systems with discrete and continuous dynamics [9].

Virtual Commissioning (VC) is not a new concept anymore, and even though it has some clear advantages, many project attempts fail to make it profitable and financially justifiable. One reason for this is the lack of standards, both technological and cross-functional, between disciplines and systems.

As a result, there can be misconceptions of what the digital model can do, how detailed it needs to be, and its purpose during the production system life cycle [2].

Virtual Commissioning is also not an add-on feature that can be easily applied for verification just before the start of construction and commissioning of the physical system. The concept requires integrated preparational work from the very start of the development process. The virtual work needs to be considered during the prestudy and development of the RFQ (request for quotation) if working towards a contractor/line builder.

The conducted research within this thesis has identified five key areas to investigate the potential integration of virtual preparation. The key areas are:

- prerequisites for integrating virtual preparation and commissioning
- modeling of multidomain systems
- realization through digital architectures
- RFQ preparation and procurement
- virtual testing, verification, and commissioning
- utilization of the invested digital model

In other words, the thesis aims to investigate the challenges of implementing virtual preparational methods for efficient commissioning to achieve flawless launches for all types of production system implementation projects. Furthermore, the research will investigate and find potential ways to increase the utilization of the constructed models, decrease the cost of virtual development and testing, and verify functionality and accuracy for optimal levels of simulation.

1.1 Research questions

The thesis will resolve what defines virtual preparation and commissioning, for whom it is of interest and value, how it will be carried out, and last but not least, why we should do it. The research questions are formulated as follows;

RQ1 *How can virtual preparation and commissioning be integrated into the current preparational work to optimize workflow and save physical commissioning time when requesting, developing, and implementing new production systems?*

RQ1 is explained further in papers A and D.

RQ2 *How can modeling a complex production system be specified and simulated using different levels of details to reduce developing time by applying the right level of detail according to desired verification accuracy?*

RQ2 is explained further in papers A, C, and D.

RQ3 *How can the utilization of collected process data and virtual model libraries be increased to improve the developing procedure of future production systems?*

RQ3 is explained further in papers B, C, and D.

RQ4 *How can virtual preparation be utilized to verify and test a large variety of interconnected and complex systems?*

RQ4 is explained further in papers A, B, C, and D.

1.2 Scope and delimitation

The research scope for this thesis has focused on the prerequisite and crucial parameters for development projects using virtual preparation and commissioning. Furthermore, the definition and requirement for modeling a production system and the structure of the digital architecture to meet its requirement for virtual testing and commissioning are also elaborated. In addition, the procedure of executing a virtual development project and finally evaluating the possibilities to further utilize the outcome of the virtual work developed during a project has been investigated and how it may be used for continuous improvements and development for future Virtual Commissioning attempts.

The research is mainly from the perspective of the manufacturing development team at the company side (OEM), focusing on the challenges and problems most relevant for the said company.

When creating digital models of the production system, the possibilities are relatively limitless and can be applied to multiple-use areas. However, this research will only evaluate the potential for further use beyond the development phase as an argument to justify the cost and mainly elaborate on how the developed models could be re-used for future virtual commissioning projects.

1.3 Scientific approach

Relevant knowledge and process data have been obtained and evaluated from different sources to support the research objectives and goals. As standard practice, literature studies of historical research have been carried out in interviews and over ten years of personal experience within the company. In addition, cross-sectional field studies from historical, ongoing, and planned implementation projects at Volvo Cars have been compared to similar attempts within research and the industry community.

A cross-sectional research approach is suitable due to the multiple fields of technological disciplines required to collaborate to design, construct and deliver a new production system using virtual preparation and commissioning methods [10], [11].

Standardization is crucial for efficient work between separate disciplines to ensure qualitative work given a specification of a complex and interconnected system in a new virtual environment. Therefore, a least common denominator analysis between involved disciplines can provide an initial prerequisite based on requirements, constraints, and expected outcome to address where the research needs clarification, proof, and guidelines to meet general expectations and delivery.

A quantitative research approach is necessary to analyze and compare obtained data [12]. Therefore, the conducted case studies will aim to construct and divide the development process into several smaller sub-tasks, both technological and project management-wise. In this way, each task is described for its specific purpose, with a clearly defined input and consequently an expected delivery. A task can be measured by time spent on it, staff involved, additional cost, or absence of any resource at any given instance. This approach will also benefit the scheduling of tasks to enable parallel workflow or optimize the consecutive order in which the tasks are carried out, resulting in a measurable outcome for comparison and conclusion.

In addition, experimental studies have been conducted to solve technical obstacles and challenges or as proof of concepts to strengthen further the contribution to the general framework concept regarding virtual preparation and commissioning.

1.4 Contribution and impact

The thesis consists of an explanatory insight into the different challenges a manufacturing company can face when introducing the concepts of virtual preparation and commissioning concepts. A resulting methodology is presented focusing on quantifying the wide arrange of different technological and operational activities to be integrated with a future project to provide enhanced data to be analyzed in future research.

The concrete outcome from the research is a standardized framework made for structuring the different technical domains that constitute a production system. Furthermore, concepts are presented regarding the definition and ways to represent multidomain models with a mixed level of fidelity used for Virtual Commissioning. In addition, a proposed concept is explained for how virtual preparation and commissioning is integrated into the current development process at Volvo Cars and which prerequisites there are for different scenarios.

1.5 Outline

The thesis consists of two parts. Part I features an overview and summary of the research with concluding remarks. Part II contains the publications that constitute the basis of the first part. Part I starts, following the introduction in Chapter 1, with Chapter 2 that provides a brief understanding of the prerequisites for applying virtual preparation and commissioning towards the industrial use case.

Chapter 3 will present a concept of how multidomain production system modeling can be specified, designed, and constructed. Furthermore, Chapter 4 elaborates on the digital architectures required to realize these multidomain models for development and simulation.

How the models are tested and implemented using the digital architecture in a virtual development project procedure is presented in Chapter 5, followed by how the resulting virtual work from a project can be utilized for future attempts and installment in Chapter 6.

Chapter 7 finishing up Part I with concluding remarks and suggestions of future work, followed by a summary of the included papers in Chapter 8.

CHAPTER 2

Prerequisites for virtual development within industry

A request for a new production system or an upgrade of an existing one can be initiated from different company instances. For example, a greenfield project with a brand new system can be suggested if a new product is under development and, due to circumstances, might not be compatible with the old plant. Another reason can be if the current production rate is insufficient and the company needs to expand to increase the plant's output.

In contrast, a brownfield project is an alternative when the old system requires a technical upgrade or extensive maintenance due to deterioration or poor performance, implying that changes might be built on top of older systems and require semi-integration with the surrounding system.

Virtual Commissioning can be beneficial for both greenfield and brownfield projects but will require slightly different approaches due to the nature of the situations. For example, a greenfield project usually has a more longer time horizon but might need more work to be specified, from facility to construction and finally commissioning of new production equipment. In comparison, a brownfield project has a shorter installation and commissioning time frame due to the interference with the running production and requires more significant effort in integrating with the surrounding environment.

A general problem with adapting virtual preparation and commissioning to each type of scenario is the lack of technical standards and a common understanding of how to execute it and make the best use of the virtual work. On top of that, different production areas within a company may also have different groups and teams approaching this concept from a very distinct perspective based on in-house competence, prior knowledge, or other driving factors such as varying support from management.

The complexity of a VC project is rooted in technical cross-sectional disciplinary challenges. Furthermore, the complexity on an organizational level may consist of the number of stakeholders growing with the extent of the project.

This chapter will explain why stated parameters and key factors are crucial and relevant for a successful start and execution of a project using virtual development.

2.1 Understanding the purpose of a virtual approach

The first thing to grasp in deciding when to consider VC is to understand when and for which scenarios it can have great value. Some of the different cases that the conducted research have come across are listed below:

1. If the lead time of equipment is long VC can make use of the waiting time to be more prepared
2. If the on-site commissioning time is short VC can enable earlier testing and potentially remove errors ahead of time
3. If extensive testing is crucial to verify functional behavior due to either high complexity and system interconnection or when testing cannot be achieved after the on-site commissioning
4. If a future installation of multiple systems with a similar setup can be tested in advance using the same platform with lesser modifications

In paper A, three questions are presented as a guideline to understand the initial starting position. The first question is to ask what we need. A change request can come from multiple directions within the company, but all share the same objective: to ramp up or maintain the production rate without costing too much.

The second question is what we want or how we want the development to be carried out. This question refers to the preferable solution and supports the vision and goals for technical advancement.

The third question concerns what we already have in the current production plant, referring to what type of technology and equipment can be re-used, upgraded, exchanged, or combined with future greenfield and brownfield installments.

2.2 Industrial use cases and project setup

The industrial use case for this thesis focuses on the production systems within the automotive industry. The scope starts with the early construction of the car body at the body shop, following the process of applying color to it at the paint shop, before ending up at the final assembly shop where the additional equipment is attached to the soon-to-be-finished car model.

A shorter description of each different production area in regards to the distinctive features of each and how they correlate with the prerequisites for VC are listed below:

- **Body Shop:** High rate of automation; geometry stamping and spot welding; majority discrete and sequential operations; shorter production system life-cycle; high share of greenfield projects.

- **Paint Shop:** High rate of automation; chemical pre-treatment; sealing and color applications; ovens; high complexity of interconnected systems; process-oriented manufacturing; long production life-cycle; high share of brownfield projects.

- **Final Assembly Shop:** Mixed level of automation; assembly oriented manufacturing; high degree of human involvement; complexity with logistic and material flow.

The use case in paper B describes the complexity of a paint booth system, where four paint application robots operate on a moving car body. The complexity increases with each interconnected system operating in parallel such as air supply for control of humidity, temperature, and fall speed, water curtain system for color waste handling, and temperature interference from a subsequent oven for heat treatment.

In contrast, one case in paper D studies the preparation and execution of a significant control system upgrade for a conveyor and transportation system of car bodies, where 16 zones, each with a corresponding PLC, were exchanged over three weeks. Even though this project had a more straightforward and simplistic setup than a paint booth system, both project scenarios can benefit from the use of virtual testing in advance of on-site commissioning.

2.3 Digital transition and maturity

Technical development concepts, in general, can be hard to implement, mainly because most untested or unproven concepts can be seen as risky with an unknown outcome. Moreover, most companies do not have significant capital to invest in development that does not have a proven financial gain or can guarantee a quick payback [13].

Due to this, managemental support for investing in VC can be hard to justify from a financial standpoint [2]. Furthermore, similar technical development attempts and modern concepts such as Industry 4.0 and Digital Twins can also require significant changes to the technical infrastructure and business model of a company, leading to even more ground to consider when moving forward in future advancement [14]–[16].

It is safe to say that some changes do not happen overnight. Some technical areas will naturally adapt faster, while other areas will face more of a challenge to handle higher complexity or manage more stakeholders with a mixed variety of support from the organization itself [17]–[19]. Areas that, under circumstances, develop at a higher rate risk leaving less developed areas behind, creating a gap both technologically, organizationally, and mentally [18].

The challenge of adopting smart technologies is not a unique trait for the automotive industry [20]. A company's ability to adopt modern and nontraditional elements to their operational development can be denoted as level of digital maturity, describing the willingness and readiness to start to integrate said technology [1].

The digital maturity of the industrial use case for this thesis is further elaborated in paper D, where a second case is studied with a relatively successful VC project of spot welding and marriage stations in the body shop. One of the reasons for the project's successful outcome was good support from management who wanted to make the financial investment to try out the concept; another reason was the understanding of the prerequisite of the project resulting in a well-performed planning and preparation phase.

2.4 Multidisciplinary collaboration

Virtual Commissioning is a multidisciplinary concept that involves several parties and requires cross-functional teamwork and communication between technical disciplines. A general misconception about VC is that it only concerns the interaction between robotics or machinery connected to the corresponding automation system or PLC. However, depending on the area of production or project size and complexity, that misconception will very fast be far from reality.

A manufacturing company's different competencies and disciplines can vary from technicians operating or maintaining the production systems to people designing the products and management that supervise the whole supply chain. On top of that, a semi-large company might also have supporting roles with a more specific focus, like plant engineering, subject matter experts (SME), or technical specialists from a wide range of areas.

At Volvo Cars, an organization called Manufacturing Engineering (ME) aims to realize and develop the production systems and facilities required for manufacturing. The requirement for the developed production systems comes from the different types of car models that the Research and Development (R&D) organization has requested to be built within each plant.

The ME organization has several sub-divisions for each production area or manufacturing plant (body, paint, and assembly). Each sub-divisions has three more sets of sub-groups with different functions:

1. The Core unit will define the ideal plant and vision of the work.

2. The Facility, Tooling, and Equipment unit is responsible for carrying out the implementation project for all production systems.

3. The Commodity unit will support the plant organization with the running production.

Paper D focuses on the development process within the Facility, Tooling, and Equipment unit consisting of project leaders and equipment engineers, which is also responsible for gathering and communicating between the many different disciplines involved for the current projects.

Whether or not an implementation project involves VC, it is of the highest importance to specify who is doing what work [21]. For instance, who will design the technical specifications, verify the outcome, and how should the verification be carried out? The project also needs to consider if the work will be done in-house or by a line builder.

Usually, the manufacturing industry will hire a line builder, also referred to as a contractor in this setup, due to a lack of that particular set of skills and competence to build and install the equipment. Acquisition of a line builder could be possible but also costly if the request for new systems is not as frequent [22].

Regardless of any given scenario and its prerequisites, the challenge of aligning and communicating across a vast spectrum of disciplines, teams, competencies, and contractors can be very demanding and will need to be enriched with a standardized approach for a successful implementation of VC and is the topic for the upcoming chapters.

CHAPTER 3

Modeling of multidomain system

This chapter will elaborate on the different concepts and dimensions of modeling connected to the development of virtual production systems. This thesis has encountered a lot of different approaches where modeling has been used to acquire the desired functionality or to solve a particular problem.

Since modeling is helpful for a wide variety of technical areas and disciplines, it is necessary to put it into perspective to understand when a particular approach is required and what constraints are put on the model properties to meet the objectives of a virtual development project.

3.1 Background

Modeling within the field of engineering is an extensive topic on its own, stretching from representing a binary operation to large and complex physics models. The fundamental idea is to create or combine a set of relationships based on one or multiple dimensions of a real-world system.

Modeling from a narrow perspective can involve binary operation, creating logical statements, forming a sequence of multiple operations with discrete characteristics. On the other hand, modeling a continuous or nonlinear system, a formal mathematical approach is suitable by creating a differential equation of higher order.

Most real-world scenarios are represented by a combination of both continuous and discrete structures at the same time [23]. However, only applying discrete modeling can significantly increase a model's complexity, while in contrast, only using continuous approaches will fail to represent the individuality and operational behavior of a system [24].

Moreover, the properties of a system can be described by its characteristics whether or not a system contains static or dynamical elements, such as fixed parameters or simplified generalization over a more real-world accurate behavior. Furthermore, a representation of a system can have a deterministic nature over a more stochastic nature.

Different technical domains can be categorized by their disciplinary area, such as electrical, mechanical, hydraulic, thermodynamic, or fluid systems, all of which can be modeled according to said approaches. A model-based approach of the technical domain can be used to create larger systems or mechatronic construction towards machining and robotics.

Abstract and geometrical modeling for 3D visualization and kinematic operation of mechatronic construction, such as an industrial robot can be designed using CAD drawings, containing enriched information of the links and joints between movable objects in the context of a virtual environment.

Higher fidelity modeling of physical systems with complex physics engines is possible today due to improved software and computational power. However, the simulation of physical models is still far from an exact representation of reality. A vital aspect of the surrounding physical world is that 'nature does not know domains' as stated by [25], meaning, boundaries between technical domains and disciplines are artificial and is an interpretation of how humans interact with their environment.

Furthermore, modeling towards virtual environments also requires an understanding of how the system will interact on multiple dimensions related to the physical plane of existence. Some of the design parameters to consider to meet realistic accuracy involve coordinate frames, metric alignment, domain and system boundaries, and relevant time and space scales to enable a sense of reality.

3.2 Multidomain modeling

As stated in Chapter 2, Virtual Commissioning is a multidisciplinary concept and consequently consists of a subset of models from a wide arrange of technical domains. The execution and simulation of this set of models require a multidomain modeling approach to cover the characteristics of the considered system to be developed, whether the system is a production line, a small robot cell, or a complex interconnected process for paint application.

There exist a plethora of definitions and terms for the concept of multidomain modeling and simulation throughout published research, like hybrid simulation, multi-method simulation, cross-paradigm simulation, and mixed modeling, to name a few [23], [26]. This thesis will refer to multidomain modeling where a combination of two or multiple models with different objectives can co-exist, either within the same simulation environment or distributed across multiple simulation platforms, referred to as co-simulation.

Paper A and C elaborate on a developed framework categorizing the different domains of a production system similar to how the interconnection between each domain corresponds to the physical setup. The first level of the framework covers the automation control system, where the PLC logic modeling (or coding) is defined. The second level defines the signal and communication properties between the interconnected domains, followed by levels 3 and 4, where the behavior and kinematic aspects are defined.

What distinguish level 4 from 3 is the focus on the kinematic relationship of the resources within the virtual environment of the production area, usually what is "seen" or visualized when simulating. In contrast, the modeling of behavior models in level 3 focuses on the functionality of the equipment used to translate the control signals from level 1 into translating movement of physics acting on the resources.

In other words, level 3 emulates the electrical equipment such as relays, sensors, actuators, power supply, and surrounding dynamic essential for the system to operate according to system requirements, and level 4 consists of the mechanical resources like robots, conveyors, tools, and other equipment acting on the actual products.

A fifth level presents that defines the interconnection between multiple production systems and type-specific application areas of use, such as human elements, virtual reality, and flow simulation. However, it has not yet been applicable for any cases covered by this thesis.

3.3 Co-simulation

Any model type's actual construction requires a formal technical language for software to understand and compile the information in a running simulation. For instance, a PLC can be programmed in software-specific environments using ladder diagrams (LD) and structured text (ST) to create logical statements. Likewise, graphical interfaces like function block diagrams (FBD) and sequence flow charts (SFC) are used to create function blocks and sequences.

Modeling of behavior models can be constructed in type-specific software such as Simulink and OpenModelica, or in a language-specific domain such as C for embedded systems closer to the hardware or higher abstraction language such as Java and Python. However, an issue when developing inside a type-specific domain is the limitation and possibility of handling multidomain models.

As long as the language is compatible and can compile in a suitable simulation environment, usage of open standards for behavior models will gain performance and flexibility when developing models for Virtual Commissioning [27]. One way to achieve openness between technical domains and simulation platforms is to use the FMI standard (functional mock-up interface), which is compatible with commercial simulation platforms such as SIMIT and WinMod as used in the cases in paper D.

Software like Simulink and OpenModelica both supports the FMI standard. The sub-models can be defined by determining constitutive relations between, for instance, how the power and signal ports correspond to the model's internal functionality. An exported model using FMI standard is called FMU, or functional mock-up unit, and contains embedded knowledge of a system which now can be imported to the desired compatible simulation platform [28].

Paper C elaborates on the modeling and co-simulation of a mechatronic pick-and-place robot in a flexible and modular setup, where a corresponding software separates each technical domain. In contrast to applicable models such as FMU's, re-usable models are developed within each type-specific software and communicate and share information between each domain using a standardized communication protocol called OPC UA, which enables openness compatibility to the developed system.

A big problem with simulation is the real-time performance, especially true for more complex models. Digitalizing a real-world system inevitably means discretizing an otherwise continuous system that requires more computational processes. Simplifications around that issue can lead to a constant misinterpretation or error regarding sampling time, simulation speed, synchronous behavior, and alignment between systems and software.

However, technical advancements are constantly improving these factors, making it reasonably safe to say that it will improve over time. Therefore, it is not of the highest focus for this thesis.

3.4 Visualization

There can be a significant difference depending on who designs a virtual plant model. It may have to do with everything that may not be visible is not always intuitively included and translated into a virtual environment. [29].

A simulation engineer may not know what is essential for the whole production system to operate when developing the plant model. Likewise, the automation engineer creates a functional PLC program according to a given specification. However, the two domains can not be fully verified in simulation due to the lack of essential components inside the plant model, which may only consist of a robot.

The success of a VC project is only as accurate as the quality of its input. As little as one missing component can endanger the whole execution, and a complete simulation cannot be performed [27]. However, in contrast, not everything that can be seen does necessarily has to be visualized.

If possible, separating the animation or rendering of the simulated objects can improve the performance and highlight what is essential or not for a user to see when running a simulation. Furthermore, commonly used CAD and simulation software can turn off the rendering of specific (or all) objects created if desired.

Due to the modular setup used in paper C, the animation of the kinematic movement was not essential to run for all tested scenarios since it only represented the information given by the behavior models in Simulink (level 3).

3.5 Mixed fidelity of models

Paper D introduces the new concept of Multi Domain Mixed Fidelity (MDMF) modeling, combining a multidomain model but classifying each component's different requirement for fidelity from the different domains. The concept

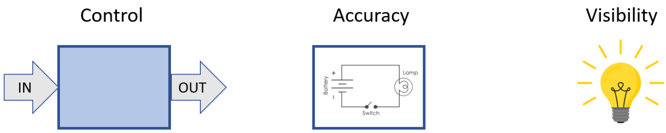

Figure 3.1: Example for the fidelity of a light bulb as categorized in aspects of control, accuracy, and visibility.

is used to describe a multidomain model from a sufficiency perspective. It concerns what is essential or relevant to model in a high or low level of details to carry out a complete verification with VC, depending on the requested objective to simulate in advance according to the boundaries of a project.

Given the industrial setup of a VC project with an OEM hiring a contractor to develop a system, it would be of the highest value to avoid over-engineering a solution. Hence, a contractor usually does what the specification says. Therefore, an OEM must be capable of describing in great details what should and should not be included in a digital model.

Fidelity for multidomain models is for this thesis defined by a combination of three different aspects; control, accuracy, and visibility. As an example, a request for a virtual light bulb to be created and defined using a fidelity scoring can be seen in Figure 3.1.

The light bulb itself does not acquire any control logic except on and off, or as seen from a circuit's point of view, positive and negative connection sides. The accuracy of a light-emitting circuit can be defined by the electrical properties of its threads, like resistance (Ω), emission of light, and heat. The visibility aspects define what can be seen in the simulation and how detailed or realistic it should be.

Imagine that the light bulb is put into a more extensive system, including a microcontroller with a daytime sensor, a manual light switch, a small interface to switch between operational modes, and a battery as a power source with connected cables.

By scoring each submodel from all required domains according to said aspects, it is possible to abstract and illustrates the summarized MDMF model as seen in Figure 3.2.

As depicted in the example, the automation system (microcontroller) is scored high in control and accuracy. However, the visualization of the operating mode and current state is represented in a separated interface (HMI).

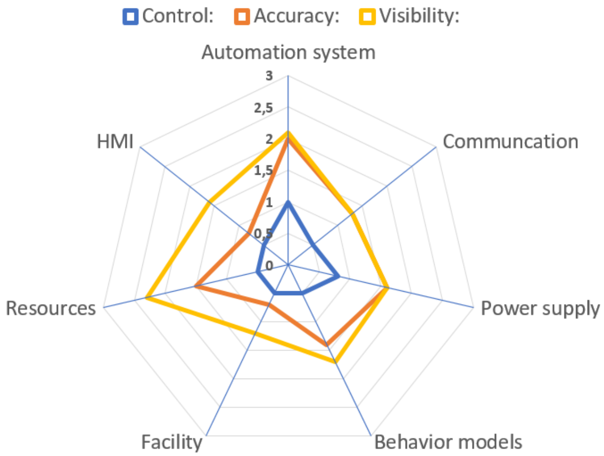

Figure 3.2: Abstraction of an MDMF model with scored aspects of control, accuracy, and visibility for all included domains (features), where control is the inner most area of the graph, followed by accuracy and visibility.

The same is true for the signal communication and power supply, which is not necessary to visualize. The facility is not specified for this small example; therefore, a random room is applied as the virtual environment.

The only visualized elements of the MDMF model are the light bulb itself, the user interface, and a small but simplistic light switch. For further examples, see paper D.

CHAPTER 4

Digital architecture

Throughout the conducted research, there are many noted misconceptions regarding differences between framework and architectures of virtual development and construction. Furthermore, due to lack of standards and experience, the concepts of Digital Twin architectures and its proper definitions are also widely debated.

This chapter will elaborate on the technical infrastructure, or digital architecture, required to test and simulate a digital model using the proposed framework presented in papers A and C and how it can be applied in virtual preparation and commissioning.

4.1 Digital models vs Digital Twins

Much published work has widely discussed the different approaches in different areas for a Digital Twin (DT) and how it can be utilized to enrich its physical counterpart with conceptual data for multiple purposes [30]–[33].

One definition of the DT concept describes the virtual representation of a production system as a model that can run on different simulation disciplines and be synchronized between the virtual and real system using smart sensors and connected devices sharing information through some network [34].

As proposed in paper C, the DT is defined by its intended purpose and setup as first depicted in [35], also illustrated in Figure 4.1.

By definition illustrated in Figure 4.1, the virtual representation is referred to as a *"Digital Model"* (DM) if the digital system only works as a stand-alone model mirroring the physical system. Hence, exchanging information between separate entities is only possible through a manual data flow.

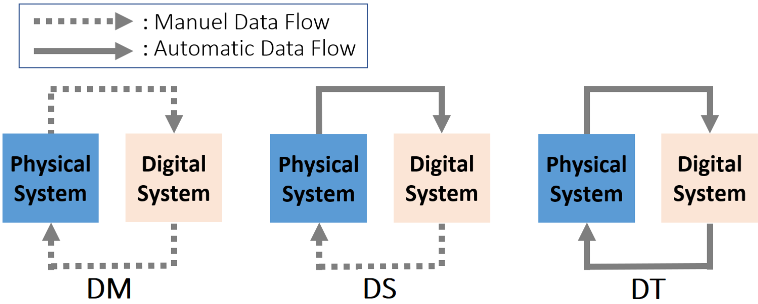

Figure 4.1: Different ways to describe the intended use of a Digital Twin and its data flow between the physical system and its digital counterpart, according to [35].

A *"Digital Shadow"* (DS) is defined by the way a digital system operates through mirroring the physical plant through the received data flow. The *"Digital Twin"* (DT) would consequently be the fully interconnected setup with a bidirectional data flow of exchanged information in real-time.

For the purpose of this thesis, an MDMF model can be seen as a digital model when treated as a stand-alone model in VC attempts. Furthermore, according to the request for implementation, an MDMF model can be seen as a digital twin if that is the purpose or end goal.

4.2 Software solution to a modular framework

Due to the lack of standardization of VC and no consensus definition of the essentials features of a DT, confusion arises within the industry. Both between cross-disciplinary areas and between the OEM and the contractor when specifying, requesting, and executing a project [32], [36].

Paper C expands the proposed Virtual Commissioning framework presented in paper A by specifying each technical domain in accordance to desired functionality and consequently adopting a corresponding tool or software for modeling, illustrated in Figure 4.2.

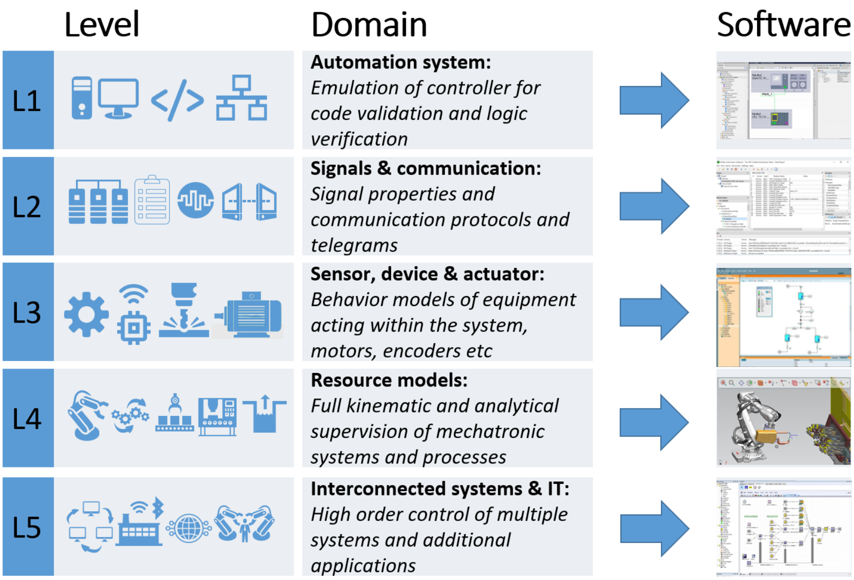

Figure 4.2: Illustration of the VC framework constructed in paper A with a corresponding software solution for each domain level.

The modular setup enables isolated development work across the different software, from the PLC programming to behavior models, down to the kinematic properties of the digital model, similar to how a distributed development of the physical system is executed to enable multidisciplinary and parallel work.

A modular and open standard approach also enables independent software development by focusing on the development methodology and standardized communication interfaces between the domain levels [37]. However, as reflected upon in paper D, the previous attempts determined the software solution in advance of the development; the boundaries of decided software also limit the feasibility of the technical solution.

4.3 Realization and integration of MDMF models

Paper A states that it is crucial to understand what prerequisites and purpose a company has when requesting a new production system using virtual preparation and commissioning. It is a distinct difference in approach to a project if the MDMF model will be used for a single occasion as a stand-alone digital model or to be integrated with the industrial infrastructure as a digital twin.

A significant factor in deciding on specific software is to evaluate what a company is currently using for a smoother adaptation. However, it is also essential to evaluate if the current software provides those features a company desires, implying that a trade-off can be necessary.

A generalization can be made of when it is most demanding and easiest to argue for an investment in a new digital architecture. For example, a brownfield project of a complex system with high interconnectivity and long life expectancy with a low digital maturity plant infrastructure and organization is probably the most demanding and challenging situation. In contrast, the easiest is when it is a greenfield project with a discrete system with few resources, shorter life expectancy, and a high level of digital maturity.

CHAPTER 5

The virtual development process

Virtual development refers to the complete value change of the virtual engineering work, from the very early preparational phase of defining the work to be done to the essential decisions to be made and the modeling before the final delivery of Virtual Commissioning.

This chapter covers the current state of development at Volvo Cars and how Virtual Preparation and Commissioning (VPC) can be integrated for an efficient execution with possible benefits beyond the project milestone.

5.1 Current procedure of development

Paper D evaluates the traditional process of developing a new production system for the different plants at Volvo Cars. The procedure is a company standard used by the Facility, Tooling, and Equipment department, specifying how a request for a change starts a consecutive order of different phases before reaching the final stage of delivery of the new production plant.

An overview of the consecutive phases can be seen in Figure 5.1, starting with a request followed by an initiated prestudy phase. This phase defines the required equipment, project scope, feasibility of the potential solution, estimated cost, and delivery milestones. Finally, guidelines for the project are given through the annually updated guidelines from the core management.

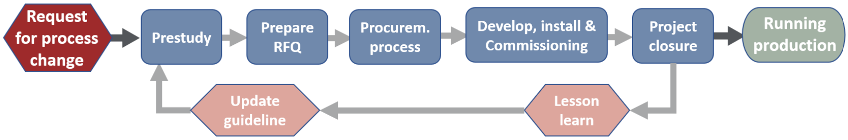

Figure 5.1: Illustration of the development and tooling process at Volvo Cars.

The outcome of the prestudy initiates the preparation of the RFQ (request for quotation), where the defined project scope and all essential documents are collected as a compendium to be sent out to a list of potential suppliers. The compendium covers the billing of equipment, technical specifications, check-lists, time plan, obligations, and the purchase order etc.

When the RFQ is finalized, it gets sent out to potential suppliers and starts the procurement process. First, an interested supplier will reply to the request by sending a quotation containing a description and offer on how they interpret the RFQ. Then, one or several design reviews can take place before a decision is made and a legal contract is signed between the purchaser (OEM) and contractor (supplier). From this moment, the development and construction of the physical system begin.

Depending on the situation, a contractor can either develop, construct, install, and test the new system in advance at their headquarter and later ship the system in batches to be installed and commissioned on-site, or built directly on-site for consequent commissioning. The latter is a more common practice for greenfield scenarios.

During installation and commissioning, the project leader or staff in charge of a particular task will ensure it is executed according to a given standard or verification protocol to guarantee qualitative work before the final machine and production try-out. If every milestone and delivery is met from the contractor side, the project reaches its closure and can be handed over to the running production.

The project execution and outcome are documented and evaluated by the lessons learned, providing experience to the existing guidelines for future projects.

5.2 Virtual Preparation

A lot of focus and emphasis has been put on the potential benefits of Virtual Commissioning and the savings it can bring. However, as accurate as it is for traditional projects, exceptional execution and delivery come from thorough planning and cannot be undermined [36].

The buzz word Virtual Commissioning may have grown outside of its preliminary scope and objective, which covers the actual development and testing of the virtual models, which occurs at the very end of an implementation project before the physical installation occurs. Therefore, the term Virtual Preparation (VP) is highlighted in this thesis and refers to all work that needs to be specified and carried out before VC can start.

By integrating virtual development with the current development procedure, Virtual Preparation starts from the first stage of prestudy. Then, the virtual strategy is planned based on the prerequisites mentioned in Chapter 2, following the specification of the MDMF and what requirement must be embedded into the RFQ compendium in phase 2.

The final planning of the virtual engineering work takes place in the procurement process with the assigned contractor that will interpret the given preparation work and create the detailed planning for execution of the virtual commissioning in the following phase.

Virtual Preparation has been elaborated on throughout all included papers in this thesis. Starting from paper A with standardization and understanding of the prerequisite to carry out virtual commissioning, followed by complex system identification and data openness for a digital model in paper B.

Paper C elaborates on the purpose and possible use case of a digital model with a modular architecture, followed by a more comprehensive look at the possible integration of VP in the current industry standard of development presented in paper D.

5.3 Virtual Commissioning

The execution of VC can use different setups. For example, either as a software-in-the-loop (SIL) setup where the hardware PLC is emulated and simulation is used for verification, or as a hardware-in-the-loop (HIL) setup, where the real hardware PLC is connected to an interface connected with the simulated plant model.

A SIL setup enables mobility where every instance can be handled within a computer but is also bounded to the processing power compared to a HIL setup when the scan cycle from the PLC can be utilized to guarantee the correct synchronous behavior. Other variants of setup exist and can be mixed depending on the situation [38].

Using a modular architecture like the one presented in paper C, testing and verification can be carried out between the different domains and software used to distribute the workload and enable flexibility during development.

Almost all studied cases for this thesis have had a situation where the Virtual Commissioning has been carried out by a contractor (line builder) and supervised by the respective project leader or representatives from the company.

Also, as shown in paper D, the implementation projects using VC did manage to save on-site commissioning time. Case 1 could see a two-week reduction in on-site time for construction, installation, and commissioning compared to a similar project from the year before. Case 2 managed to meet the delivery for installation and commissioning using a low-level simulation of behavior models in simulation when a reduction of one week for installation was required mid-way through the project due to a tight production schedule.

However, none of the studied projects have shown a wide variety of different technologies and types of production systems. Furthermore, even though the technical functionality can be verified in an earlier stage of development, it has not been utilized to the fullest extent for any observed case. The reasons for it are either by not requesting through the RFQ specifications or because the software used was not fully compatible or insufficient to develop a feasible solution.

It is also hard to fully predict the financial gain of using VC due to insufficient data on the cost factors. It is easier to estimate the profit of starting production earlier but harder to account for the extra hours required to plan, model, and execute VC compared to not using it.

The project managers in Case 2 tried to use a so-called "burndown chart" to measure the time of the on-site installation and commissioning activities. However, it was not initially within the agreement of the project and was therefore not considered by the contractor due to the extra amount of work required to document it.

Paper D evaluates the outcome of the cases using VC, and based on the insight, proposes how VPC can be integrated seamlessly. Furthermore, the idea elaborates on how to adapt and use the requirement for an MDMF model to create and schedule commissioning activities and how to measure them to gain more information from a project. However, the proposed idea will need to be implemented for further research and evaluation in a future project.

CHAPTER 6

Utilization of virtual engineering

After the final phase of an implementation project of a new production system where Virtual Preparation and Commissioning (VPC) has been applied, the remaining question is what to do with the work developed for the virtual testing. Unfortunately, in most of the studied cases in this thesis, this question has been left unsolved, maybe because the initial purpose of the created digital model never being specified.

The narrow focus of VPC evaluates the potential gain in the short term, for instance; did we save on-site commissioning time, or did we find errors earlier that could cause more harm to us in the later phase of development? However, if the digital models could provide further useful for the company, the actual profit and gain may lie beyond the first project closure.

This chapter will present ways to utilize further the virtual engineering work invested throughout the development process. By extending the digital life-cycle and creating more opportunities to apply the technologies and lessons learned, the invested initial cost may be more easily persuaded and financially justified to move forward with technical development such as VPC.

6.1 Towards the Digital Twin

As was elaborated on this thesis, one way to make more use of the invested digital model, created for VC purpose, is the transition towards the concept of a Digital Twin. In other words, instead of throwing away a good enough digital model that has only been used for a single purpose, it can be an excellent opportunity to take a step ahead and advance the current state of production with an integrated digital twin [39]. Furthermore, by taking advantage of the invested work done for VC, another investment can be avoided if a DT is requested in the near future [29].

Potential use areas of a DT have been explored in a lot of published research, in both a small and a big scale [30]. Not only can it be used in parallel with the running production to supervise and contribute with conceptual data or higher intelligence from analytical tools, but it can also be used with additional tools for educational purposes. For example, Virtual Reality (VR) or 3D simulation has been explored to train users and technicians in advance or parallel to the running production [40], [41].

A big challenge today is how to keep a DM or DT updated towards the physical counterpart, and more research would be needed to investigate the technical as well as the organizational challenges to handle it with efficiency [42].

Suppose a DT is the desired outcome of a VPC project. In that case, it would require even more detailed and carefully well-thought out strategic decisions in the preliminary stage of development and aligning it as a prerequisite requirement from the steering group within a company [42]. Especially emphasizing on the level of fidelity an MDMF model needs to have to match the desired functionality of a DT, but also on how to adapt and verify the digital architecture to be integrated during commissioning without further problems [32], [33].

6.2 Component library of MDMF models

The use of different libraries with standardized components or objects for modeling is common practice for most modeling software, like model-based elements for electrical or mechanical applications such as circuit diagrams or rigid body simulation [27]. A more extensive subset of system models is rarer, although still offered by some software providers at an extra cost [43]. In addition, some suppliers of specific equipment may offer behavior models to be bought, but in some cases it may not be freely distributed due to the protection of intellectual properties that apply to the creation (as for Case 2 in paper D).

The possibility to use open standards with flexible interfaces such as FMU's enables an easier way to integrate sub-components with the digital models and still keep it software-independent and modular [28], [44].

Standardization of mechatronic systems, in general, is beneficial for reducing additional expenses when modeling, also seen in Figure 6.1. For example, in [45], standardization of models used for a robotic cell in a body shop was proven very efficient in the long run for a repetitive setup with discrete event systems. A similar effects could be seen for Case 1 in paper D, where re-usable models generated efficiency for iterative implementation of the robotic cells.

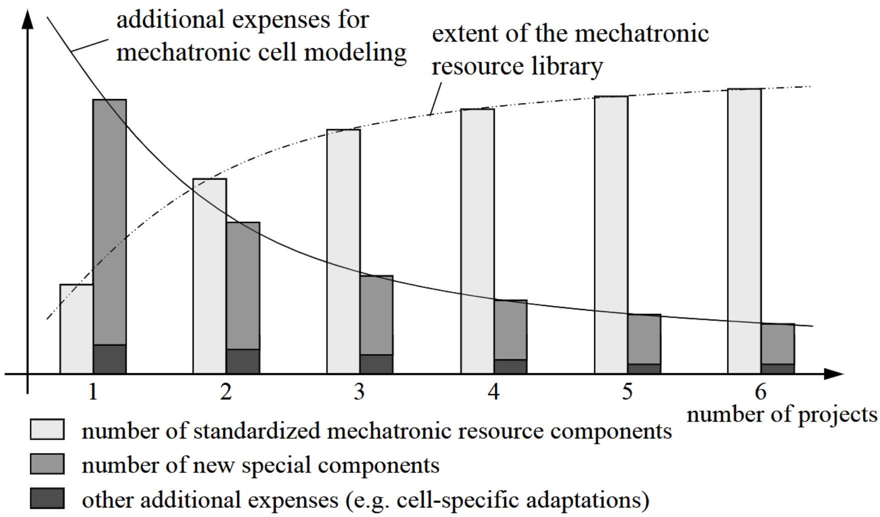

Figure 6.1: Reducing additional expenses for mechatronic cell modeling [45].

In comparison, modeling of continuous and nonlinear processes such as in the paint shop is still behind when it comes to framework for the integration of the process dynamical models with a logic control layer, making it more limited to type-specific software [46], [47]. In these cases, reverse engineering would still be acquired to develop non-standardized objects during a VPC project.

Regardless, the beneficial modular structure of an MDMF model makes it possible for an OEM to re-use sub-components from each domain and intentionally collect and distribute them throughout the company to be fundamental components in future development projects.

6.3 Cost efficiency of invested virtual development

The possibility of estimating the potential profit of using VPC is very sought after. Unfortunately, though some improvements can be clearly seen, it is still difficult to obtain hard numbers to compare different attempts.

It is doubtful that there will be a situation where two different projects with the same setup can be executed in parallel, one being approached with traditional means and the other using VPC.

Case 1 from paper D had the experience of a somewhat similar project scope from the year before without VC. Therefore, comparing and observing savings in on-site commissioning time was more straightforward. However, it is hard to say how repeatable the approach would be for another project with different prerequisites.

In addition to Case 1, because of virtual testing in advance, the number of required staff on-site during the installation phase was significantly reduced, leading to fewer people occupying the same area simultaneously. However, whether or not it implies that the same amount of work hours required for one technician was only moved to an earlier phase of development remains to be investigated.

It is easier to account for the cost of a project using VPC from start to finish. However, due to each case's different key factors, unique elements, and inconsistency, it is not easy to account for the cost for all different activities within a particular project. Furthermore, it is also important to highlight that the financial gain of VPC can be separated into two distinct groups. First are the hear-and-now savings, second is the long-term gain which might be harder to justify or guarantee.

The research conducted in this thesis has focused on investigating the essential key factors for cost, such as planning, model specifications, decision making, project management, execution, verification, and utilization. As proposed in paper D, having quantitative data for all project activities would enable comparisons between projects on a much more specific level.

Some activities and key factors, such as planning, model specifications, and verification, can provide efficiency throughout the development process and potentially show a more profitable result in the short term if done right. However, other key factors, such as project management and execution, require multiple iterations with feedback and experience to efficiently execute a VPC project.

Finally, increased utilization of the virtual engineering work and efficient use of MDMF models requires full support from management and a structured vision of the long-term goal for the concepts to increase the level of digital maturity within the company and adapt to future technological advancements.

CHAPTER 7

Concluding remarks and future work

The thesis has presented an explanatory insight with a holistic perspective of the different challenges a manufacturing company can face when introducing the concepts of virtual preparation and commissioning.

The scope of the research is rather ambitious and covers a lot of different scientific and technical disciplines. The aim has been to create a general approach of VPC to a plethora of different types of production systems and try to find the least common denominators that can be exploited to optimize and reduce the variety of unique solutions of a VC setup.

Due to practical reasons for the long-term planning of a VPC project, it has been challenging to find suitable projects to directly apply and test out the concepts and ideas presented in the thesis. Therefore, studies have been done for already decided projects where VC was carried out.

The most significant outcomes of the studied cases were the lack of understanding of the prerequisites for virtual engineering work and its contributions to the projects. Furthermore, the company's ability to analyze and measure progress and results gained with VC was incomprehensible.

To summarize the research carried out in the thesis, a resulting methodology have been presented, made for quantifying the wide arrange of different technological and operational activities to be integrated with future implementation project to provide enhanced data to be analyzed through continuous research.

This chapter concludes the thesis by providing answers to the research questions introduced in Chapter 1 before a final discussion regarding future work.

RQ1 *How can virtual preparation and commissioning be integrated into the current preparational work to optimize workflow and save physical commissioning time when requesting, developing, and implementing new production systems?*

Paper A explains the essential steps and decisions to be made after evaluating the prerequisites for a planned implementation project. Furthermore, adopting a standardized framework to describe and specify an MDMF model's properties and how to realize it is described in paper D. The specification of said MDMF model is added to the RFQ documents, providing additional guidelines for development and verification. Separating the requirements for each domain also enables parallel work, which has been proven beneficial in the observed cases.

RQ2 *How can modeling a complex production system be specified and simulated using different levels of details to reduce developing time by applying the right level of detail according to desired verification accuracy?*

The standardized framework for VC, presented on paper A, was adopted into the experimental setup developed for paper C by applying a corresponding and compatible software to each domain. The modular architecture enabled cross-sectional development and testing, which was evaluated in three cases, each with a different level of fidelity. Both the framework and the modular architecture were further integrated into the concept of an MDMF model, where it was put into the context of the virtual development process, presented in paper D.

RQ3 *How can the utilization of collected process data and virtual model libraries be increased to improve the developing procedure of future production systems?*

A contribution from paper B is the importance of openness when modeling multidomain systems and how information can be distributed between interconnected systems and for analytical purposes. The same approach is being used in paper C, where all subcomponents in each domain are modular, re-usable, and communicating through a standardized OPC UA interface. Re-usable models, compatible with an open and modular architecture, can be collected for an expanding component library. Furthermore, with prerequisite knowledge, the component library can provide enhanced support in the prestudy for future VPC projects, as elaborated in paper D.

RQ4 *How can virtual preparation be utilized to verify and test a large variety of interconnected and complex systems?*

System identification of a complex paint booth application was introduced in paper B, where multiple interconnected resources were modeled for simulation and verification. The complexity of a multidomain was also covered in paper A, where the standardized framework improved the complex structure. Furthermore, paper C addressed the possibility of verifying a multidomain model by creating a modular architecture and applying suitable software for each domain to solve a feasible solution. In addition, paper D further elaborates with a multidomain system by introducing the fidelity scoring of each domain to meet the complexity by excluding unwanted aspects of an MDMF model through a sufficiency approach to easier comprehend the virtual engineering work of a project

7.1 Future work

In regards to future research, it would be of the highest interest to integrate VPC as a holistic method into a near-future implementation project at Volvo Cars. The VPC enhanced development process presented in paper D could be executed with hands-on experience and provide valuable insight with quantitative data to be further evaluated in research.

However, due to the broad scope of the concepts, it may be necessary to involve more researchers and engineers who focus on different parts to cover all essential areas. Therefore, for future research, the concept of VPC can be grouped in three different tracks for deeper investigations.

Technical track

Research within the technical field of VPC would need to focus on MDMF model specifications and requirements by further investigating and evaluating how to translate them into the RFQ to be built by a contractor. It would also require focusing on the digital architecture and software setup to find a feasible solution that covers the desired need.

Based on the requirements specified for the MDMF model, it would also be valuable to schedule the execution of the listed activities to be verified during VC.

Utilization track

Another field of interest is the utilization of virtual engineering work. This track would focus on the purpose for modeling and consequently evaluate the outcome of a VPC project.

New use areas can be researched by exploring the possibilities when gathering virtual elements. Concepts such as Digital Twins or component libraries and how to keep them up-to-date can be further investigated and potentially test them towards other areas such as virtual and augmented reality, machine learning, education, or analytics.

Operational track

The final track focuses on the organizational structure of a VPC project and will need to explore the "soft" requirements of implementing and managing new technologies. It would imply how the cross-disciplinary collaboration needs to operate in a project structure, how different stakeholders affect the procedure, and how to defend and predict the financial gain of VPC.

Furthermore, required competencies, virtual ownership, and business relations between OEM, contractor, and software provider will also need to be investigated.

Regardless, all tracks have dependencies between each other which need consideration. Quantifying the process and generating efficiency through the projects is the central theme for all tracks.

CHAPTER 8

Summary of included papers

This chapter provides a summary of the included papers.

8.1 Paper A

Anton Albo and Petter Falkman
A standardization approach to Virtual Commissioning strategies in complex production environments
Published in Procedia Manufacturing, Volume 51, (pp. 1251-1258), 2020
30th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2021)

DOI: 10.1016/j.promfg.2020.10.175 .

This paper presents a standardization approach to defining the different technical domains levels that constitute the production system. The paper evaluates the prerequisites for applying Virtual Commissioning and how a framework can improve how a virtual model can be specified in a request for quotation situation between an OEM and contractor.

8.2 Paper B

Anton Albo, Kristofer Bengtsson, Martin Dahl and Petter Falkman
A framework concept for data visualization and structuring in a complex production process
Published in Procedia Manufacturing, Volume 38 (pp. 1642-1651), 2019
29th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2019)

DOI: 10.1016/j.promfg.2020.01.120 .

This paper presents a concept for visualizing production information and data towards a specific user. The paper further elaborates on the complexity of interconnected systems within a paint booth application, where a digital model has been developed using Sequence Planner (SP). The embedded tools inside SP show that relevant data from the simulated sequence is published on the virtual service bus and visualized using a human-machine interface.

8.3 Paper C

Anton Albo, Ludvig Svedlund and Petter Falkman
Modular Virtual Preparation method of production systems using a Digital Twin architecture
Published in conference proceedings of IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Volume 26, (pp. 1-8), 2021

DOI: 10.1109/ETFA45728.2021.9613654 .

This paper presents a modular digital architecture based on a Virtual Commissioning framework and further used to model a pick-and-place robot in different scenarios with different levels of detail. In addition, the paper investigates topics of Digital Twin specifications, verification, flexibility, openness, and software limitation and dependencies.

8.4 Paper D

Anton Albo and Petter Falkman
Integrating efficient Virtual Preparation and Commissioning into traditional production system development work flow
Submitted to CIRP Journal of Manufacturing Science and Technology .

This paper describes how Virtual Preparation and Commissioning can be integrated into the process to improve overall efficiency. A new development process is proposed together with concepts for specifying multidomain models with mixed fidelity and utilization of virtual engineering work, based on qualitative investigations of two practical use cases.

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