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Digital Plant for Final Assembly

A Project Plan with Simulation Deliveries Aimed at Achieving a 3D Model of the Final Assembly Plant within the Automotive Industry

Master's thesis in MSc. Production Engineering

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Abstract

This paper presents a case study conducted at a leading car manufacturer, where the objective was to design a project plan with simulation deliveries interwoven into the ordinary development plan. Car manufacturers must streamline operations since the industry currently demands a short time to market due to rapid changes in market trends. A realisation of the project plan aims at aligning organizational strategy to transition towards a digital plant environment, supported by a common product lifecycle management system. The study followed design research methodology, encompassing interviews with engineers specializing in various instalments of the original development plan. The project plan outlines key steps and integration points necessary for successful implementation, addressing challenges and leveraging opportunities inherent in the digital transformation process. If implemented successfully, the project plan serves as a strategic point of departure for the study object, promoting transparency and reduced time to market.

Keywords: Product Lifecycle Management, Digital plant, Virtual Commissioning, Teamcenter, Digitalization, Final Assembly.

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Henrik Bratt & Gustav Hagström
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List of Acronyms

BAX	Rear Axle (Swedish: Bakaxel)
BOE	Bill of Equipment
BOP	Bill of Process
EBOM	Equipment Bill of Material
FA	Final Assembly
FAT	Final Acceptance Test
FDJ	Final Data Judgement
MBOM	Manufacturing Bill of Material
ME	Manufacturing Engineering
MTO	Machine Try Out
PII	Process Inspection Instruction
PLM	Product Lifecycle Management
PP	Pre Production
RFQ	Request for Quotation
SD	Simulation Delivery
SOP	Start of Production
TT	Tooling Tryout
VC	Virtual Commissioning
VP	Verification Prototype
VR	Virtual Reality

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1
Introduction

The thesis project is conducted at the Manufacturing Engineering (ME) division of a car manufacturer and presented at the Chalmers University of Technology. This chapter outlines the project proposal's overview, outlining its background and origins. It details the project's main objectives, defines the scope, and presents the research questions.

1.1 Background

The automotive industry stands as one of the largest globally, boasting a turnover of approximately 2.9 trillion dollars in 2022 [1]. Historically, Europe and the United States have held dominance, but in recent decades, Asia, particularly China, has made significant strides [2]. Market dynamics are in constant flux, and fierce competition propels ongoing evolution within the industry. Major car manufacturers have sparked a price war, leading to decreased retail prices and narrower profit margins [3]. Given the rapid shifts in market trends, manufacturers must streamline lead times and optimize design processes to remain competitive [4].

Amidst intensifying competition, the automotive industry faces its most significant challenge: transitioning to electric drivetrains while phasing out combustion engines. Electric cars are expected to make up almost 50% of passenger cars worldwide by 2035, making them the majority type of car sold in the coming decade [5]. This transition also aligns with the UN's sustainability goals [6]. By embracing electric drivetrains, car manufacturers contribute to *Goal 7: Affordable and Clean Energy* by promoting clean energy solutions and reducing greenhouse gas emissions. Car manufacturers need to rebuild their plants and change their way of working to keep up with this change. Streamlining their organization and optimizing operations thoroughly, including everything from software to work structures, can contribute to sustainable industry practices, thus aligning with *Goal 12: Responsible Consumption and Production*. These efforts drive the transition to electric vehicles, foster economic growth, and promote environmental sustainability, contributing to *Goal 13: Climate Action*.

This transition is not expected to be without obstruction since there is a shortage of pertinent workers such as engineers and software developers. To overcome this problem, the automotive industry must become more attractive but also ensure that all workers can adapt appropriately [7]. Digitalization can optimize and help the work of engineers and help to improve competitiveness by reducing costs and lead times [8]. However, the technological advancements applicable in this area are changing the dynamics of the value chain collaboration, especially regarding how both products and processes will emerge in the future. A common platform shared between departments and where different user interface needs are integrated would optimize the work. The full comprehension of this concept has proven to be a great engineering challenge, having to rationalize and fit the newly developed approaches into already established industry development processes [9].

Bridging the gap between recognizing the need for a collaborative work platform and implementing essential methods and strategies for enhanced effectiveness through digitization is complex. It requires meticulous synchronization with existing processes, a significant portion of which have progressed to an unprecedented level of complexity [10]. The manufacturer participating in this study employs more than ten thousand personnel and utilizes tens of thousands of components throughout its production, clearly cannot address this concern without effective information management [11]. In light of these engineering challenges, the study object is struggling in its ambition to effectively manage the structural organization of design resources within this domain. The endeavour involves crafting an approach that considers the legacy production system while maintaining a clear vision of the industry's future production landscape.

Within the Final Assembly (FA) department of the study object, efforts are being initiated to transfer from obsolete legacy systems to a comprehensive Product Lifecycle Management (PLM) system. Siemens Teamcenter as a web-based client has emerged as the preferred platform for this transition. There are also ambitions of utilizing the PLM system to visualize a potential digital factory, which has been identified to enable interconnectivity between factory products, resources and processes while aligning them with engineering capabilities [12]. However, the endeavour is being opposed, mainly due to insufficient funding and a lack of working hours being subsidized towards the effort. In the manufacturer's current operations, progress toward enhanced transparency also faces impediments stemming from administrative challenges in cyber-security and data access related to integration with suppliers and other involved departments. As the commitment to working towards a digital plant is at best fragmentary, employees in software and electrical development have resorted to seeking help from middle management to perform pilot projects.

With the situation having reached a stagnation point, FA intends to explore the potential applications of digitalization within its operations and pinpoint shared motivations among stakeholders to foster a more dedicated journey towards a digital plant. Given that this transition is a rather multifaceted challenge, there is a need for guidelines to show the different steps that must be taken to identify the best integration solution [12]. FA anticipates enhanced daily operational efficiency and optimized data flow throughout the development stages by establishing an approach incorporating the requirements of a digital plant.

1.2 Purpose & Aim

The purpose of the thesis is to contribute to the study object's digital strategy and increase competitiveness by adopting the principles of a digital plant. The project will be one of several initiatives aiming to improve transparency and accessibility throughout the organization.

The project aims to investigate the current state and future way of working to reach the required level of 2D/3D models in Teamcenter with Bill of Equipment (BOE). Additionally, the project aims to expedite the assessment of maturity levels during quality reviews, surpassing the current pace facilitated by virtual verification. Looking ahead, the project also seeks to lay the framework for a new project plan during future developmental phases.

The investigation will assess the procedures and timing for reviewing the quality status throughout the development phase. The findings are required to be valid for all types of bound and standard tools & equipment and their levels of design maturity will be reviewed during the development phase. The required format of the 3D model for FA will be investigated to see if it can differ from CATIA V5 Units. The valid model (consisting of product, process and tool connected in Teamcenter) used to assemble the product must be available as information in a Process Inspection Instruction (PII) to ensure the updated model is visible to all stakeholders.

1.3 Delimitations

The car manufacturer subject to the study is a multinational corporation and to achieve a digital plant numerous departments have to be involved, resulting in an overwhelming amount of stakeholders. To achieve progress in the project considering the short timeline, the stakeholders regarding PIIs will be limited to the Rear Axle (BAX) department of the study object.

This project will not designate roles for the specific tasks in the new framework for project plans at the study object, mainly due to the study object regularly making organisational changes. Also considering that the project scope is limited to one single generic project plan, timelines and gates are approximated due to the varying magnitudes of each project.

Supposing that the project will produce a project plan that is permanently applied to the daily operations of the manufacturer in question, several success parameters can not be analyzed due to the limited duration of the project. Long-term effects of results derived from research may exhibit a break-in phase for an indefinite time, making the possibility to fully examine if the project has contributed to information of significance very limited.

Implementing a new project plan requires a substantial organisational change, possibly resulting in resistance and problems. Therefore, change management stands as a pivotal factor in achieving success in this project. However, given the project's current focus and limited time it has been excluded from consideration.

1.4 Research Questions

- **RQ1:** *What is the current status of the company's efforts in achieving a digital plant?*

  A central ambition of the project is to understand the current situation, ways of working and obstacles regarding a digital plant.

- **RQ2:** *How can a project plan be designed to facilitate the integration of virtual tools within final assembly?*

  This question refers to the exposition of a project plan developed to advocate using virtual tools in future endeavours. The proposed plan is also expected to highlight which steps of the original development plan can be changed or removed due to the introduction of simulation deliveries.

- **RQ3:** *How can the implementation of the proposed project plan affect involved stakeholders?*

  This reflective question is formulated to consider the possible outcomes when the proposed project plan is implemented. Specifically, an evaluation of how the project plan affects the various stakeholders involved and to some degree investigate the possible improvements associated with the plan.

2
Theory

This chapter provides the theoretical background that this study is based on. A literature study has been conducted to lay a foundation for the theoretical framework and enhance the findings' credibility.

2.1 PLM Systems

PLM systems are crucial tools for modern enterprises, enabling effective management of a product's entire life cycle from conception to disposal [11]. This section aims to establish a theoretical foundation for understanding PLM systems' core concepts, principles, and frameworks.

The term PLM does not refer to any specific software or method itself, but instead to a holistic approach that provides a comprehensive overview of the product information [11]. The idea is to control and steer the process of creating, handling, distributing and recording product-related information during its entire life cycle. In simpler terms, completed work should remain visible and exploitable, within prescribed limits, in tailored formats for various user interfaces. In practice, this is fundamentally achieved through incorporating a general plan containing business rules, practices and methods on how to sustain synergies between product and business areas.

Practically speaking, the concept PLM is nowadays synonymous with some type of information processing system used to aid in storing and visualising product/process data [11]. In an ideal setting, the PLM software is supposed to serve as the company's backbone, integrating processes and functions on a common platform [11]. As previously mentioned, PLM software is first and foremost a connecting technology that ties together several specialized IT systems, enabling cross-functional data flow between core processes within the enterprise. It also gives way to new operation models and processes such as simulations and virtual verifications required for Virtual Commissioning (VC).

2.1.1 PLM Systems & The Automotive Industry

The engineering environment in the automotive industry has widely adopted PLM systems due to the need to be deeply interconnected with all facets concerning the operations, especially as the trend of mass customization has led to an increased demand for a shorter time to market [11]. Seamless exchange of information spanning intra-company departments and external partners is essential to address the demands of process activities running largely in parallel to reap the benefits from concurrent engineering [13].

The call for shortened development times also makes it imperative that tasks are structured efficiently and that workflow is coordinated appropriately. Supporting this engineering environment calls for equally interlinked information management support [13]. These systems establish links to all relevant data during engineering change orders, enabling cross-referenced updates, standardization of items and immediate visualization of part and assembly relationships in a networked operational environment [11]. As commonly found during development processes, difficulties arise from employing disjointed IT systems, leading to redundant efforts in recreating existing product information due to inconsistent documentation [13].

2.1.2 System Architecture

Acknowledging the industry's development into producing more complex products has led to current IT systems becoming successively more inadequate, and inconsistencies and variations between the document types have grown larger [14]. Since PLM systems serve as the integrative platform and manage product-related information, domain-specific tools such as product data management and supply chain management systems are arranged in different constellations depending on the requirements of the network model. To have the requirements broken down is problematic from an information modelling perspective, but necessary if a digital plant is supposed to be relied upon in total network integration. Four major approaches are identified and simplified to fit the needs of this specific case [14].

Best-in-Class

The first approach, see Figure 2.1, can be described as a best-in-class system, which promotes a structure that allows each development discipline to keep its tools in a preferred user interface. This adaptability allows for preserving each discipline's traditions, reducing product designers' resistance as their interfaces towards the enterprise PLM remain unchanged [14].

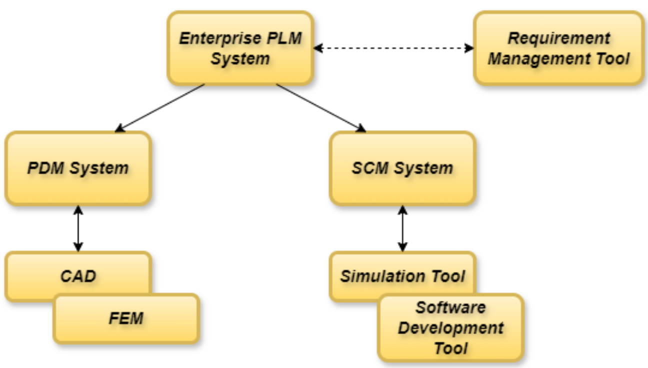

Figure 2.1: Best-in-Class, inspired by Dag Bergsjö.

One System as Integrator

The second approach, see Figure 2.2, is migrating legacy data into a PLM system that takes the role of enterprise integration system [14]. This system would then serve as the backbone of the enterprise, making relevant information accessible for all development disciplines. This method is similar to the best-in-class, where the communication interface needs to be available to ensure successful integration. However, with the difference of the PLM supplier having greater abilities to facilitate requirements engineering solutions [14].

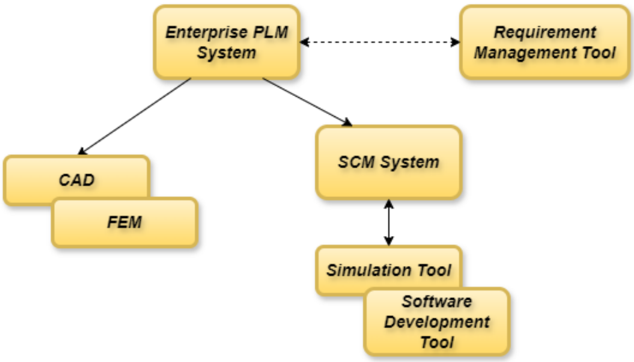

Figure 2.2: One system as Integrator, inspired by Dag Bergsjö.

All-in-One Integration

A third approach, see Figure 2.3, is to remove all current management systems and replace them with a supreme system. While this approach may be viable for smaller companies, implementing such a solution within a larger organization would most likely result in inefficiency or, in some cases, an incomplete implementation [14]. This approach aligns with claims made by other experts on the subject [11], where adapting the business processes to the software's capabilities and constraints can be a reasonable approach to facilitate solution validation.

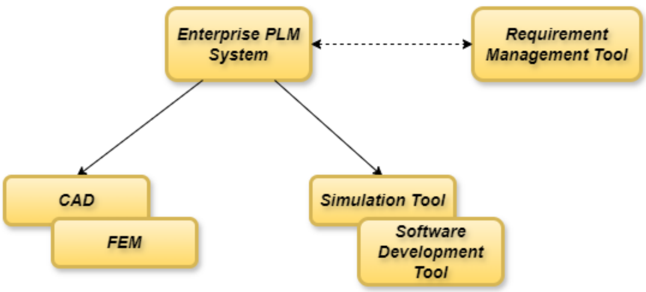

Figure 2.3: All-in-One Integration, inspired by Dag Bergsjö.

Peer-to-Peer Integration

The final approach, see Figure 2.4, advocates for an environment where the software systems are adapted to the business processes to facilitate data-sharing and communication [14]. This approach is bold and extremely robust considering it implies using standalone software exclusively, possibly providing better conditions for the organisation to create support for its business instead of depending on vendors [15].

On the other hand, this approach makes the organisation vulnerable to changes in external factors such as industry standards [14] and escalated costs for solution design, deployment and maintenance [11].

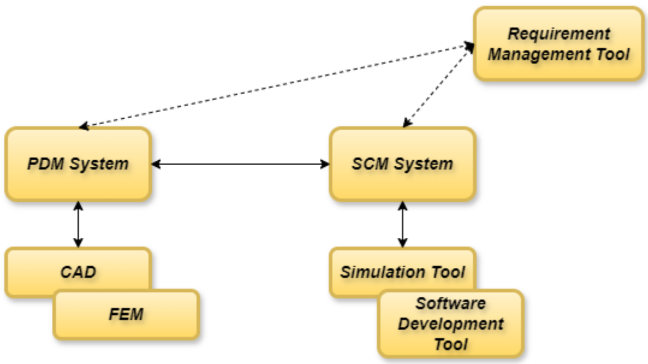

Figure 2.4: Peer-to-Peer Integration, inspired by Dag Bergsjö.

2.1.3 The Potential Value of PLM

The value of PLM can be assessed through return on investment, which encompasses all positive and negative changes to income parameters relative to the PLM investment. It has the potential to impact several of these factors positively. For example, streamlined product information availability could shorten product development timelines, reducing the time it takes to bring new products to market. This enables companies to capitalize on market opportunities more quickly, leading to increased sales and revenue [11]. Conversely, costs may decrease through reductions in material or labour expenses [15]. Specifically, labour costs may diminish through decreased requirement of engineering hours [13].

Furthermore, an optimized PLM solution could mitigate environmental impacts during development, such as reducing CO2 emissions from travel and minimizing material consumption for physical prototypes. Nevertheless, translating these enhancements or reductions in value-adding activities resulting from a PLM implementation into measurable success criteria poses a challenge, rendering the concretization of the endeavour often less tangible than desired [16].

However, the advantages of implementing operational PLM extend well beyond mere incremental savings. They result in significant bottom-line savings and top-line revenue growth, not only through the adoption of tools and technologies but also through the implementation of necessary, albeit challenging, changes in processes, practices, and methods. Additionally, operational PLM grants control over product lifecycles and lifecycle processes. The return on investment for PLM is rooted in a broader corporate business value [11], particularly in achieving greater market share and higher margins. This is achieved by streamlining business processes to deliver innovative, successful products with a strong brand image to market rapidly. Furthermore, PLM enables informed lifecycle decisions across the entire product portfolio throughout each product's lifecycle.

Implementing a PLM system for managing product data throughout the organization has previously proved beneficial. For example, the average time to finalise an engineering change proposal decreased by 40% for an aerospace and defence company [17]. The time for their document data management decreased by 62%, creating more time for value-adding activities. The company also managed to perform different kinds of processes faster saving 36% of time compared to before the implementation of a PLM system [17].

2.2 Web-based Siemens Teamcenter

The software, developed by Siemens, provides compatibility with the CAD software CATIA V5, integrating aspects such as visualization technology and 3D design capabilities. It is a web-based application accessible via the internet, contrasting with a rich application that typically requires local installation. This offers a solution for engineering process management, particularly in handling diverse CAD environments, enabling design teams to work on multiple products efficiently. The frame structure mainly consists of the user interface layer, the application system layer and the system support layer. Several tools can be used to tailor the user interface when interacting with the software. Java is employed for client development, while the server-side utilizes C++ to enable integration with office packages [18].

Efficient and organized management is essential for successful collaborative design processes [18]. Consequently, the system is equipped with tools tailored for dynamic collaboration among project supervisors, facilitating the automatic selection of suitable team members using application algorithms. Furthermore, a mission planning tool assists in coordinating and monitoring activities throughout the collaborative development phase. Additionally, a conflict management tool is implemented to preempt and mitigate conflicts during the design process, where publishing material helps keep track of the trail of iterations and data ownership, ultimately enhancing the productivity of multidisciplinary personnel [18].

2.3 Virtual Commissioning

Designing new lines or completely new factories for manufacturing a new product requires numerous experiments and testing to reach the desired outcome. The new facilities must be test-run to ensure high quality and everything working as intended. This delays the product release and costs the company large amounts of money. Virtual verification is a method for verifying that the requirements are met through simulation with digital models, resulting in big cost savings and a quicker development phase [19]. However, it is important to understand that VC is only a method to speed up the physical implementation and will not eliminate the whole implementation period of the physical system [20].

The long-term goal of VC is to eliminate the need to use the physical product or object for tests and validation. This includes the training based on numerical data and simulations for robots, systems and AI as well [19]. Achieving this would enable analysis, line balancing and decision-making before the physical machines have been manufactured. However, confidence in VC requires trust in the simulations and sufficiently detailed digital models which require a high level of expertise and a major effort [21]. Virtual confidence is a term describing the level of trust in VC and the utilization of it. The maturity of VC can be divided into five different levels [19].

- **Level 0:** No CAE technology is available.

- **Level 1:** Only immature CAE technology is available and not used for the development processes.

- **Level 2:** CAE is available and recognized. It is also used as a complement to physical testing and support decisions as well.

- **Level 3:** The CAE technology is available and well-established. It is used for product-, process- and resource development. The results from it are used as a base for a majority of decisions. Physical prototypes are only used as a complement to virtual verification.

- **Level 4:** CAE technology is commonly used throughout the organization, including suppliers. It is used for analytical sign-off and the results are used to close project gates. No soft tools are required since there are no physical prototypes used for tests or verification. The serial tools are ordered based only on the simulation results.

2.3.1 Previous Outcomes of Virtual Commissioning

A study conducted in the automobile industry regarding VC at a plant focusing on PLC-governed robots showed great benefits compared to ordinary commissioning [22]. The VC helped find numerous bugs and errors in the PLC codes before the robots had been installed in the plant, enabling troubleshooting and solutions to be found early. Overall, the VC resulted in fewer bottlenecks, reduced ramp-up times and less downtime throughout the development of the new manufacturing system [22].

Furthermore, studies have shown that VC can help with a ramp-up time reduction of 20% in the context of installation of an automotive production line [23]. The need for physical verification has shown to be significantly reduced due to the possibility of validating the project's technical feasibility through VC. The VC cost has proven insignificant compared to the savings made from not requiring extensive physical validation. This mainly refers to large-scale assembly environments such as the automotive. VC has also proven to improve the ability to maximize the equipment's flexibility, enabling carefully planned control strategies to be validated earlier than before [23].

Everything around the process must be tested and validated for a complete VC of a whole production line. The material handling system is a crucial part of the production line that easily can be forgotten during VC [24]. However, it can be simulated and verified to shorten the total installation and ramp-up time of a new production line. In an industry environment, testing was performed with the help of a material flow controller together with PLC simulation reducing the on-site installation time by 25% [24].

2.4 Digital Plant

A digital plant can be represented in various levels of intricacy, such as in the form of a digital model, a digital shadow or a digital twin, see Figure 2.5. Significant distinctions among them result in distinct purposes and application areas. The level of digital representation should therefore align with its suitability for the intended purpose. This is particularly crucial because adopting a level of digital representation with excessive functions, which may remain unused, can be financially irresponsible. The intricacy of the digital plant should therefore be vital in the decision of which digital representation to consider in the project [25]. It is important to understand that all three digital representations can be categorized as digital models. However, a digital model does not necessarily have to be a digital shadow or a digital twin even though both a digital shadow and a digital twin are always considered digital models [26].

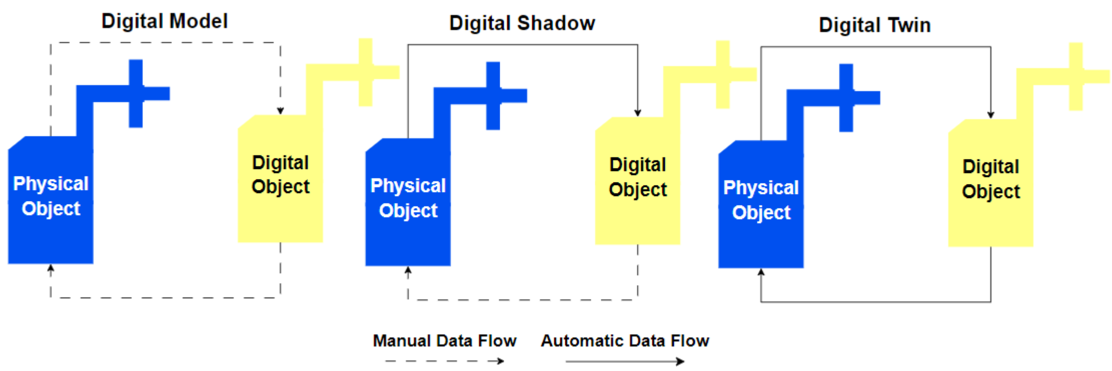

Figure 2.5: Various levels of digital representation.

2.4.1 Digital Model

A digital model is a digital representation of a physical object, without automatic data flow in any direction to [26]. This digital model is represented as a 3D model, often designed in some CAD software. It is important to recognize that a digital model is only connected to the physical object through manual data flow, thus no automatic synchronization between the two.

2.4.2 Digital Shadow

A digital shadow is a digital model of a physical object that is constantly updated in a data-driven way [27]. One example of this could be a digital tool representing a physical tool whose status can be monitored by sensors. These sensors give data used in physics-based modelling to update the wear on the digital model. A digital shadow is updated based on data-driven processes to mirror the physical object throughout its lifespan [27]. However, the data flow from the digital shadow to the physical object is still manual, see Figure 2.5.

2.4.3 Digital Twin

The digital twin is an improved digital shadow that can use AI to make real-time changes in the processes or similar where the physical object is used. The digital twin is constantly updated through an automatic data flow like the digital shadow [25]. The difference is that the digital twin is also used to automatically make decisions regarding the physical object, see Figure 2.5. AI is often used in this process to improve decision-making and ensure faster and better processes. A digital twin is most useful for objects that change over time making the initial digital model outdated. One major use of digital twins is predictive maintenance since they can alarm before critical failures occur [25].

2.4.4 Results of Implemented Digital Representations

There is always a lot of discussion about digital models, especially the digital twin and its benefits and applications. Some state it can help reduce lead time, ease engineering and optimize solutions [26]. Others claim the challenges with digital twins are great and due to its hype and vagueness, people can reject it as a useless buzzword resulting in limited potential [25].

According to one study [28], a digital model was used for redesigning an existing automotive factory, a so-called brownfield operation. The material flow increased by 12.5% with the help of the digital model. Also, a digital shadow of the factory was established to further increase capacity with the help of real-time data.

Another study [29] found that a digital twin could be used for predicting abnormalities in industrial processes with high accuracy, up to 98%. Utilizing a digital twin this way can help with planning and ease the possibility of synchronizing production for large automotive manufacturers.

3

Methodology

This chapter covers the methodology used in the project and describes the reasons behind the chosen methods. The theoretical methodology is described as well as the derived practical application.

3.1 Design Research Methodology

Design Research Methodology (DRM) is the chosen methodology for this project. It is a well-known method suited for design projects, making it a logical choice for a project aiming to develop a new framework for a project plan. This project is performed using an adaptation of the comprehensive type for all stages except the descriptive study II where only an initial evaluation is performed [30], see Figure 3.1.

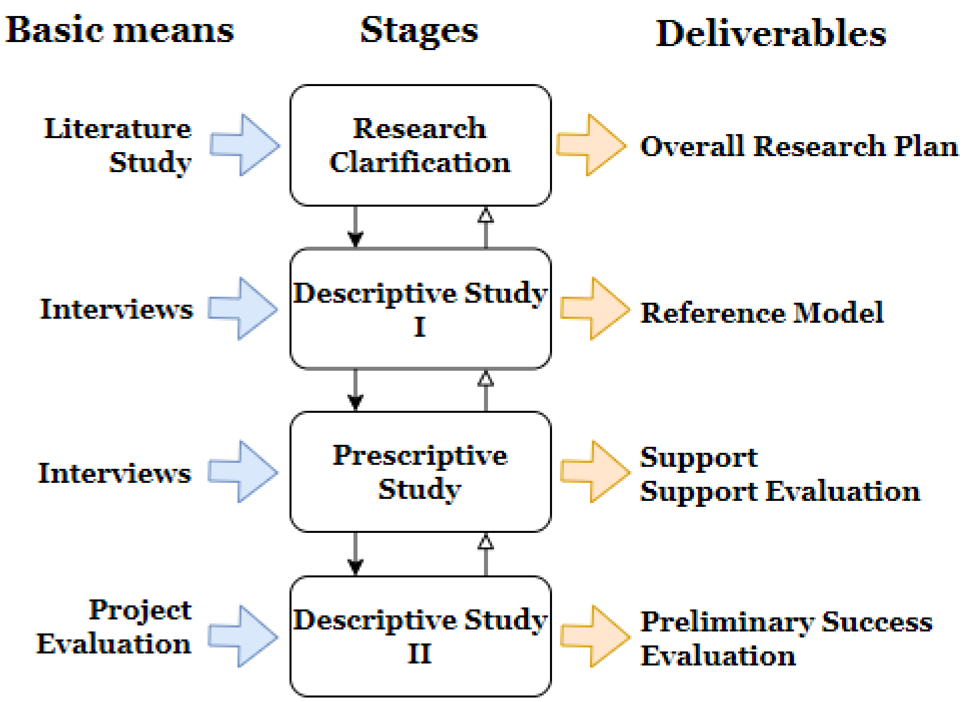

Figure 3.1: Design Research Methodology: basic means and deliverables, inspired by Lucienne Blessing & Amaresh Chakrabarti

3.1.1 Research Clarification

The first stage of DRM is to conduct a research clarification including four deliverables. It aims to bridge the gap between studied factors and project goals, ensuring accurate measurement [30]. The research clarification is a foundational step in the DRM, laying the groundwork for effective research and decision-making throughout the project.

An overall research plan should be included in the research clarification. The overall research plan is made up to focus the project towards its aim and purpose while scoping it to ensure sufficient quality is achieved. The overall research plan includes six different topics [30]:

- Research focus and goals
- Research problems, main research questions and hypotheses
- Relevant areas to be consulted
- Approach (type of research, main stages and methods)
- Expected (area of) contribution and deliverables
- Time schedule

3.1.2 Descriptive Study I

The next stage of the study methodology aims to investigate the current state of the undertaking and its success criteria through empirical data analysis and reasoning. Since the undertaking is a multifaceted one, an important aspect becomes to establish a model of links between success and the influencing factors investigated that can serve as a base for the development of effective design support [30]. With the help of empirical data, a reference model which describes the current state can be created. The reference model functions as a starting point for the support developed throughout the project.

3.1.3 Prescriptive Study

The third stage is conducting a prescriptive study, which entails the delivery of support, support evaluation and an outline evaluation plan. The support can be regarded as a proposed solution to address the research questions. It can be delivered in different forms such as a project plan or a physical object. The prescriptive study also covers the evaluation of the support functionality [30].

The support is the first deliverable and consists of what the project is trying to develop. It can be established based on the knowledge gained from the previous stages and the reference model. The second deliverable is the support evaluation. It is important to note that the support evaluation is done to evaluate the function of the support rather than the effects that the support can achieve. The functionality, consistency and complexity of the support are evaluated during this process.

3.1.4 Descriptive Study II

As part of descriptive study II, efforts are dedicated toward identifying whether the support can be used for the task for which it is intended. As it has been found that detailed evaluation of the developed support is often neglected [30], methods of validating the results in a useful format shall constitute the majority of this stage of the methodology.

- **Application Evaluation**
  An application evaluation is used to verify that the support accommodates its intended purpose. Target users of the project plan will be consulted closely and factors such as *usability* and *applicability* are addressed.

- **Success Evaluation**
  Identifying if the project plan has the expected impact as originally intended is also of utmost importance. In a parallel approach to the application evaluation process, the emphasis will shift towards assessing the *usefulness* and *impact* aligned with the project's overarching purpose and objectives.

3.2 Applied Methodology

This part of the methodology chapter describes the execution of the project in more detail. The method theory outlined earlier works as the foundation to build on for the practical applications described here.

3.2.1 Literature Analysis

The research clarification of the DRM methodology was performed through a literature analysis by finding gaps in existing research. A gap regarding digital deliveries in project plans and their purpose was found, laying the foundation for the research questions formulated in the project.

A literature analysis is an essential part of academic research since it gives a comprehensive understanding of the existing literature regarding the topic. It also lays the foundation for the knowledge required for the project and helps to find gaps in the existing research [31]. A summarized step-by-step guide to a literature review is described below:

1. **Define research scope**
It is important to define the research scope to focus the search. The research scope should be based on the project's aim, which in this case concerns prerequisites for a digital plant and virtual commissioning that can be used as milestones in a project plan.

2. **Identify keywords**
Based on the research topic identify keywords that can be used to find relevant articles. Using a keyword helps the search engine find what you are looking for to a greater extent compared to searching for a complete sentence [31]. The relevant keywords established for this project were as follows:
    - Product Lifecycle Management
    - Teamcenter
    - Digital Plant
    - Project Planning
    - Virtual Commissioning

3. **Search relevant databases using filters**
Only academic search engines and databases should be used to ensure reliable and relevant information. Filters can be used to limit the search to the most relevant information. Filters regarding publishing date and the number of citations were used to ensure the information was up-to-date and relevant.

4. **Read abstracts and evaluate scientific papers**
A general understanding of academic papers can be achieved by only reading the abstract and is therefore a time-effective way of reading academic papers. Evaluating the sources regarding credibility, relevance, and reliability is important. This was done by controlling the project's methodology, and publication venue and checking if the author could be biased in some way [31].

5. **Synthesise literature**
After collecting and reading a sufficient number of academic papers a comprehensive understanding was achieved. Conflicting results were interpreted and overarching trends were highlighted and analyzed.

6. **Write literature review**
With all information gathered the final step was to write the literature review in an academic way with correct citations. It is important to try to be as objective as possible and state your interests in the research to obtain high credibility.

3.2.2 Interviews

For the descriptive study I, an automotive company was chosen as the case study to ease the findings of the research questions. Within the study object, it was essential to understand the needs and requirements of different stakeholders to ensure a successful project. Qualitative research is the most appropriate to obtain the research data which consists of opinions and expectations from a small group of people [32]. The stakeholders must be able to present their opinions, experiences and behaviours in a structured and academic way to increase the chances of a successful project, both from the study object's perspective and an academic point of view. Qualitative research is useful for obtaining detailed information in comparison to quantitative research which relies on numerical data and statistical analysis [33]. One of the benefits of qualitative research is the possibility to achieve a complete understanding of the subject including answers to how and why questions.

There are three different forms of interviews, unstructured, semi-structured and structured [34]. This project used semi-structured interviews, a mixture of unstructured and structured interviews. It ensures the interviewee stays on topic by having a set of planned questions but still has the chance to elaborate and explain certain things [34]. A mix of closed and open-ended questions was used and extra follow-up questions such as why or how were used for further depth, see Appendix A. The maximum length of the interview was confined to one hour, as per recommendations from literature [35].

Recognizing that qualitative data collection through interviews may give way to subjective assessments [36], the most important aspect for the interviewer is being involved in the project and having knowledge about the subject [37]. This is required to ensure the interviewer has enough knowledge to know when it is essential to ask follow-up questions to gain deeper insight into specific areas. The interviewer also requires knowledge about the project to understand which topics are less relevant for the research and should not be dug into too deep [37]. In line with the requirements of qualitative data collection, the questions were formulated objectively to ensure that the interviewees could provide honest answers without predefined notions [38].

In Table 3.1, a detailed overview of the participants in the study is given. The table includes the participant's position, years of experience, team name and its associated department. The selection of participants for the study was based on recommendations from the project supervisor. Furthermore, the participants had to fulfil some requirements related to the project's scope. The requirements were:

- All interviewees must at some point be involved in the original development plan when conducting duties associated with their position.
- All interviewees must repeatedly employ Teamcenter in their everyday tasks.
- All interviewees must possess basic knowledge about 3D model formats and their areas of application.

Table 3.1: Interviewees and corresponding positions, departments and interview groups.

Interviewees			
Position	**Experience**	**Department**	**Interview group**
Solution Lead	20+ years	Manufacturing Engineering	Digital Solution Groups
Solution Lead	25+ years	Manufacturing Engineering	Digital Solution Groups
Business Analyst Manufacturing PLM	10+ years	Vehicle & Manufacturing Engineering	Digital Solution Groups
Commodity Manufacturing Engineer	20+ years	Manufacturing Engineering	Manufacturing Engineering
Manufacturing Product Leader	40+ years	Manufacturing Engineering	Manufacturing Engineering
Business Development ME FA	30+ years	Manufacturing Engineering	Manufacturing Engineering
Core Engineer	20+ years	Manufacturing Engineering	Manufacturing Engineering
Added Value Time Specialist	35+ years	Manufacturing Engineering	Manufacturing Engineering
Commodity Manufacturing Engineer	20+ years	Manufacturing Engineering	Manufacturing Engineering
Project Manager FA	25+ years	Manufacturing Engineering	Manufacturing Engineering
Simulation Engineer	40+ years	Manufacturing Engineering	Manufacturing Engineering
Plant Layout and Visualization	30+ years	Manufacturing	Plant Engineering

3.2.3 Framework of Project Plan

Regarding the prescriptive study, a framework for future project plans was established by synthesizing information from the literature study and the interviews. It was an iterative process of creating the project plan, where stakeholders got to evaluate and give feedback during different development phases.

The foundation of the project plan was achieved from the existing project plan. Information gathered from the interviews helped highlight which new deliveries should be included in the new project plan and where in the timeline they belonged.

3.2.4 Preliminary Evaluation

Descriptive study II was impossible to perform as a whole since the project finished before the project plan could be implemented and tested. However, a preliminary evaluation was conducted by letting different stakeholders evaluate the project plan and possible outcomes of it. Also, the project was compared to similar projects and their outcomes to better understand the possible impacts of it.

4
Results

This chapter covers the current way of working throughout the automotive company. It investigates the current development plan and the procedure for ordering tools and equipment. All conducted interviews are summarized to encompass the current operational methods and the future vision, including the necessary prerequisites to achieve it.

4.1 Manufacturing Engineering

The ME department is working as a link between research and development and the production facility. They are responsible for ensuring that the designs developed by research and development are possible to manufacture. They are constantly working to make the new designs required production operations as compatible as possible with the existing equipment to reduce the number of new tools and equipment needed. If new equipment is necessary, ME is responsible for writing an equipment card specifying the equipment specifications and requirements. To make this possible ME is involved throughout the whole development phase and the entire production lifetime since the processes and operations are constantly improved even after the start of production.

Also, the ME department is responsible for creating and updating all PIIs. A PII is an instruction describing an operation, how it is performed, what equipment and tools and which components are used. The PII is a formal document and includes exact identification numbers for the components and equipment making it possible to link 3D models to the PII for further visualization. The PIIs are then rewritten by the local process engineers responsible for each workstation at the plant to make the instructions easier for the line workers to understand. The rewritten edition is less formal and has the purpose of informing the line worker how the operations should be performed without extensive detail.

4.2 Use of Teamcenter Today

Teamcenter (rich client) is the current PLM system used throughout the organization. All development work for new projects is made and filed in the system, where information is sorted based on applicability for various activities. As seen in Figure 4.1, the Equipment Bill of Material (EBOM) represents the product structure from an engineering and design perspective. It includes all the components, sub-assemblies, and materials required to build a product as defined by engineers during the design phase. The EBOM serves as the foundation for the manufacturing process, providing detailed information about the product's composition and specifications.

The Manufacturing Bill of Material (MBOM) refers to the product structure from a manufacturing perspective. While the information regarding the product structure is essentially the same as in the EBOM, the structure is rearranged to facilitate efficient and error-mitigating manufacturing. Factors such as manufacturing constraints and assembly sequences directly influence the assembly structure in the MBOM, which further clarifies that there is a lack of interconnection between development practices and manufacturing practices.

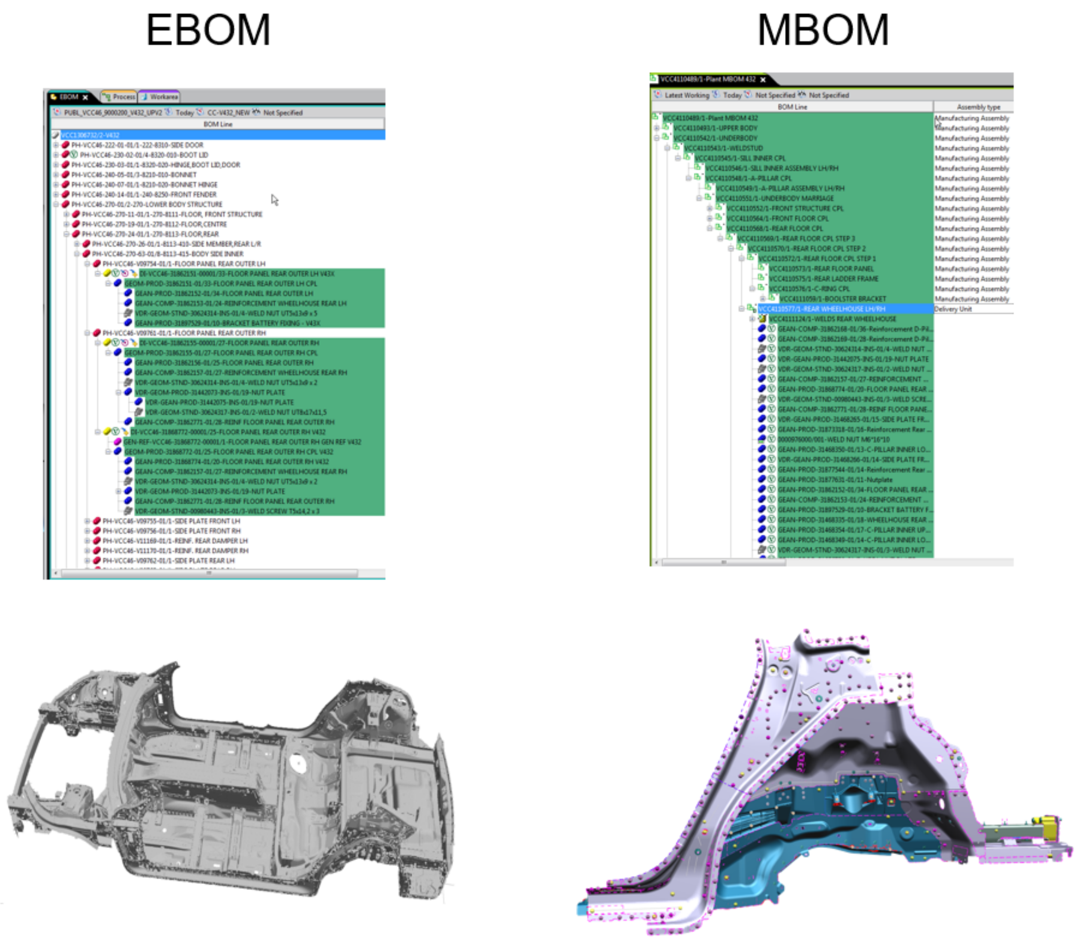

Figure 4.1: EBOM and MBOM visualised in Teamcenter (rich client).

The Bill of Process (BOP) outlines the manufacturing processes and operations required to manufacture the product. It consists of PIIs and describes procedures and specifications for each step of the production process. As illustrated in Figure 4.2, the BOP, much like the MBOM, is organized to align with the sequence of operations in the factory rather than the product structure.

The BOE lists the equipment, tools and resources needed to execute the manufacturing processes outlined in the BOP. It includes information about equipment specifications, capacities and maintenance requirements. The BOE is supposed to ensure that the necessary resources are available and optimized to support manufacturing operations effectively.

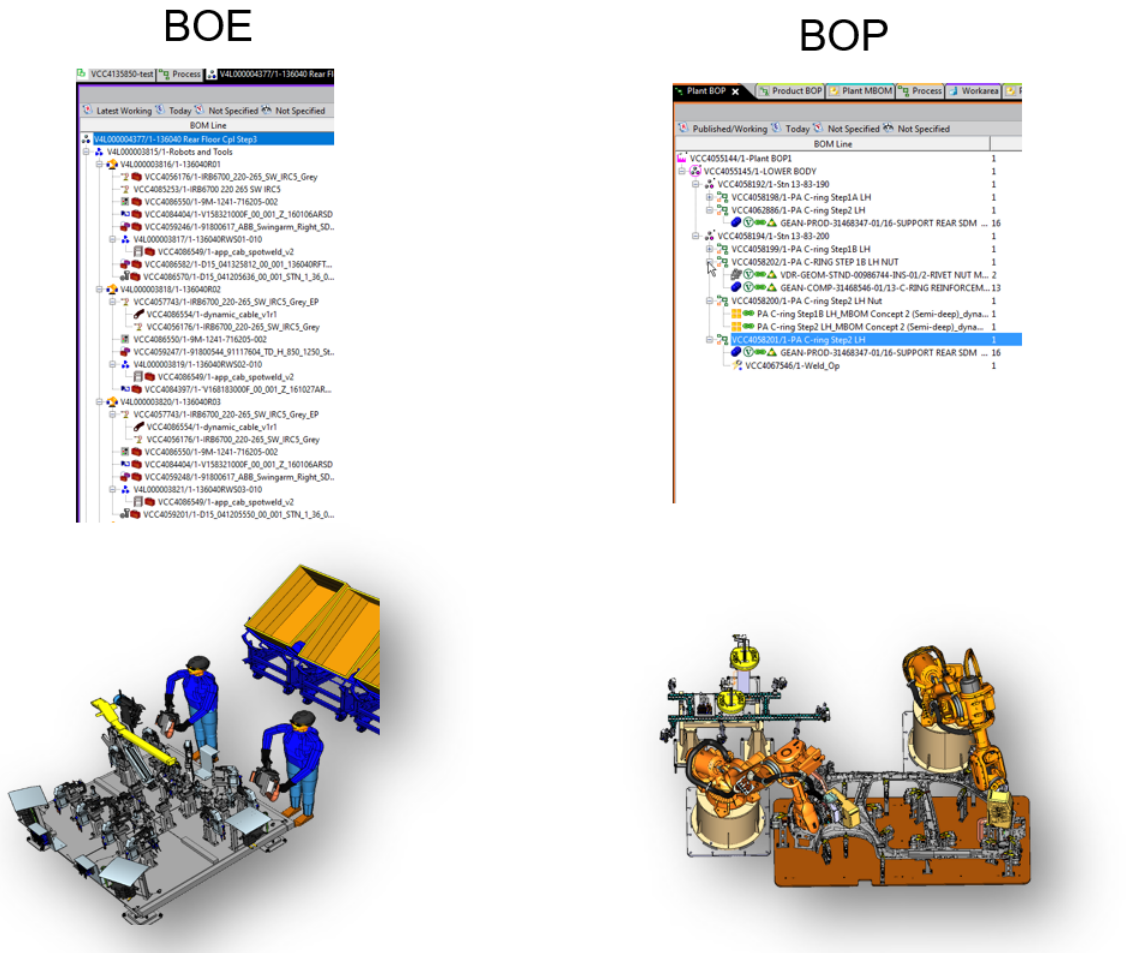

Figure 4.2: BOE and BOP visualised in Teamcenter (rich client).

4.3 Original Development Plan

A planned delivery schedule is devised to manage the activities during project initiation. Given the complex interconnections between departments, progress relies on cohesive collaboration within this intricate constellation. Comprising numerous milestones, each with specific deadlines and functions, the interdependence of these milestones necessitates the achievement of all deliverables to prevent any ripple effects or delays throughout the project. Figure 4.3 depicts a typical development plan during a project, including milestones, from the perspective of ME.

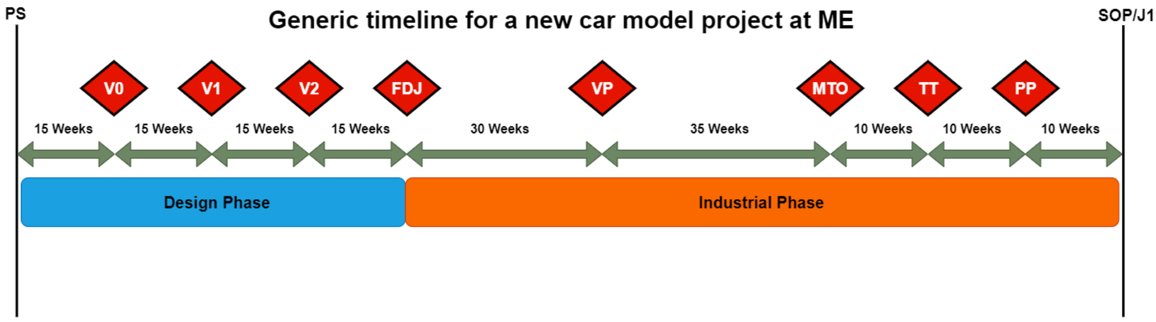

Figure 4.3: Project timeline with milestones for ME.

V0 & V1 & V2

The first milestone is VO, which is the first of four major milestones during the development phase before the design is locked in. During V0, the car is mostly finished and ME starts establishing processes to manufacture the car according to the design. The car's design is almost complete but some details are still uncertain and can change throughout the four iterations.

The V0, V1, and V2 represent various stages of maturity in the design process, with incremental changes typically occurring between them. However, more substantial design modifications may also occur intermittently. As the design is successively iterated, ME can start establishing the processes required to manufacture the car. With the processes established, a Request for Quotation (RFQ) regarding equipment and tools can be placed and mediated to suppliers, initiating the procurement phase.

The changes made during the iterations of maturity degrees primarily stem from process adjustments, legal mandates, and environmental considerations. Additionally, design alterations are frequently necessary to adhere to weight and noise specifications. It is crucial to recognize that these modifications typically do not impact the fundamental structure of the vehicle and are often imperceptible to the customer. Each milestone is finished in an event where all PIIs are presented and it is ensured that the car can be manufactured according to the planned sequence.

Final Data Judgement

The Final Data Judgment (FDJ) is the milestone marking the end of the last iteration of design changes, meaning the design is now definite. When FDJ is completed, suppliers can finalize the design of tools and equipment and receive design approval to start manufacturing.

Verification Prototype

A Verification Prototype (VP) is built in a special workshop when all the design and process choices have been finalized. It is used to verify that the car functions as intended and that problems occurring can be fixed as soon as possible to prevent delays in the start of production. This is the first physical build of the new car model. Several VPs are built to ensure the car functions as intended and that all requirements are met. Another purpose of building the VP is to physically validate the interactions work as intended between the process and the product.

Machine Try Out
A Machine Try Out (MTO) is performed when all tools and equipment have been installed in the plant, verifying compatibility between product and process. A limited quantity of cars are manufactured during the MTO to ensure all workstations, tools and equipment function as intended. The MTO is a lengthy and costly procedure since it is the first extensive physical testing of the production line and virtual commissioning is not applied. Given that MTO only encompasses a limited number of cars, its purpose is only to validate the functionality of isolated stations, rather than the entire system's functionality in full-scale production.

Tooling Trial
The next milestone is to test the production flow throughout the plant in the Tooling Trial (TT). Products are manufactured as intended to validate and verify the complete production. During TT, between 100 to 200 vehicles are manufactured, making it possible to identify bottlenecks not detectable in current simulations. This is a major enabler for fine line balancing considering it is the first time it is possible to physically see the flow of materials and products throughout the production lines. The cars produced during TT are used for testing and evaluation.

Pre Production
Pre Production (PP) is the last milestone before production is expected to start. Everything should be up and running as intended for this milestone, but minor problems frequently occur and must be corrected. Line builders should have undergone pre-training and now do their final training to ensure they can perform all operations within the predetermined time. More than a thousand cars are produced during pre-production but never sold to external customers. Instead, the cars are used for further testing and to entertain other intra-organizational interests.

Start of Production
Lastly, the Start of Production (SOP) is the final milestone in the project plan. By this stage, every aspect of production functionality must work as intended, initiating full-scale manufacturing.

4.4 Ordering of Tools and Equipment

The study object manufactures some tools and equipment in-house, but the majority is outsourced to suppliers. Purchasing new tools and equipment is highly expensive and in attempts to save money, a lot of work is put into refurbishing old tools and equipment to function for new processes. However, a great portion of tools and equipment are tailor-made, necessitating the procurement of new tools.

Purchasing new tools and equipment can be a long process extending over several years. To ensure this does not delay projects, work with ordering new tools and equipment is begun at different stages throughout the project depending on the lead time of the tool or equipment in the matter. There is a standardized sequence of events for all ordering of tools and equipment, see Figure 4.4. However, the starting time is initiated in advance for orders with longer lead time orders.

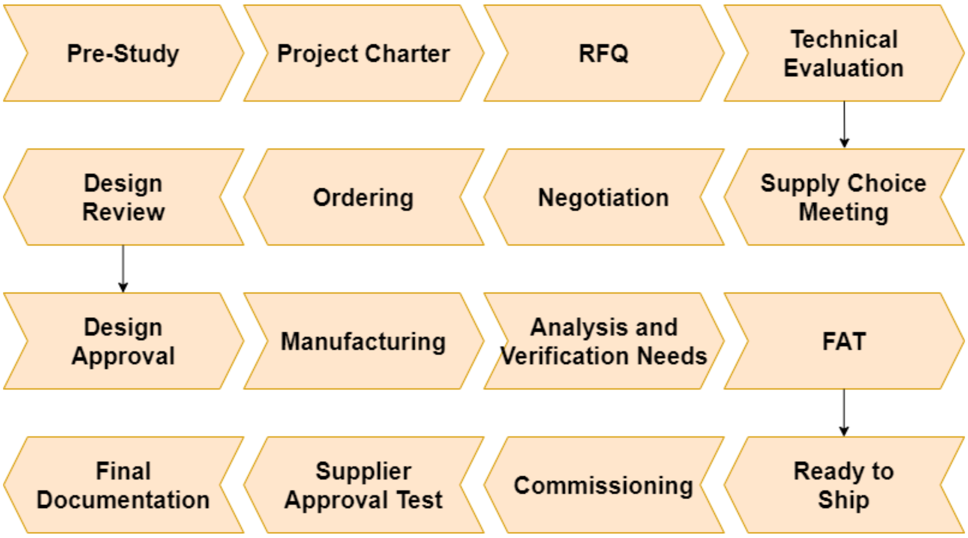

Figure 4.4: Sequence of tasks when ordering tools and equipment.

Firstly, during the pre-study of the project, processes are matched with existing tools and equipment. A purchase of new equipment must be made for processes that can not be matched with existing tools or equipment. A project charter is created and signed by the plant, which declares that the plant has accepted the proposal and it is accepted to send RFQ to suppliers. Suppliers have approximately 20 days to respond to the RFQ before a quotation must be submitted. Technical evaluation of the different quotations is performed for about three weeks before a supply choice meeting with the purchasing department takes place. One or a few suppliers are selected and negotiation takes place for another three weeks.

After selecting a supplier, a final discussion is held to discuss the order in detail, including specific requirements and deadlines. The supplier is usually given around two months to design the tool or equipment and, several design review meetings between the supplier and automotive company are held to ensure all requirements are met. When the final design is approved, the supplier is given an *ok to manufacture* and can start manufacturing. Manufacturing the equipment takes a few months up to a few years, depending on the type of equipment. When the supplier has manufactured the equipment, analysis and verification needs are conducted during a few weeks. When eventual issues are remedied, the automotive company sends an engineer to the supplier location to perform a Final Acceptance Test (FAT) to ensure it fulfils the requirements. A FAT takes one or two weeks to perform and if the equipment is approved it can be delivered to the production plant. The supplier installs the equipment in the plant and makes the initial verification in a commissioning phase for approximately four weeks. Then engineers from the supplier and the automotive company perform supplier approval tests together before ownership of the equipment is transferred to the production plant. These tests are the final step before it is possible to perform the MTO.

4.5 Interviews with Digital Solution Groups

The ME Digital department oversees digital deliveries and associated documentation at ME. They lead and manage the development of digital tools striving for a digital plant. This includes coordinating activities supporting the development of virtual methods and data-driven decisions. ME Digital is also responsible for leading activities enabling the next generation of engineering tools to help improve ME. Being a part of the digital department, however not constrained to only manufacturing, the PLM specialist is in charge of implementations regarding new features and connectivity with the PLM provider.

Current way of working
According to the PLM specialist, when 3D models of tools and equipment are delivered it is possible to place them according to the process sequence of the virtual plant. Since ME is in charge of defining the layout while the BOP is being established, placing the 3D models of tools and equipment in the correct position in the virtual plant is not difficult as long as ME provides the positioning. However, defining the correct position of tools and equipment relative to product coordinates is strenuous. Especially since ME works in Teamcenter (rich client) while the plant works in another software resulting in low transparency and a lack of collaboration regarding the subject. Also worth noting is that the level of detail in the BOP is too complex for the plant personnel to interpret, resulting in the engineers having to search for relevant information. The high level of detail requires more computational power than is currently supported by Teamcenter (rich client), meaning that its environment would not support a digital plant as it currently stands. The PIIs created by ME include tools and equipment and these are rarely directly linked within the PLM system.

Scanned data
Ideally, during the initiation phase of a project, the plant is scanned and the project is planned and executed based on the scanning data. However, this is rarely the case and the procedure is rather that a project plan is established before the scanned data is used. When the equipment has been installed, a new scan should be made to update the virtual model. However, since moving the virtual equipment is easier than moving the physical equipment, the physical model serves as the master in practice. The scan data is often used with other virtual tools in the company, such as CATIA and Process Simulate. However, this is only done on an individual level since there are no standardized procedures in place regarding working towards achieving a digital plant.

Usability of PLM system in the context of a digital plant
Regarding the support of a digital plant in Teamcenter, a move to the web-based

client would enable a leaner data-sharing process within the organization. For instance, plant engineers could filter information relevant to their assignments. Suppliers could also provide more insight regarding the development process, providing access to virtual model updates while they still possess ownership. The goal is to have all suppliers working with the same software and allow the study object access to all the material at all times. Almost every supplier is conducting virtual tests on the equipment they are responsible for and the tests could be developed further by increasing the level of detail and adding kinematics. In a digital plant setting, all movable parts of tools and equipment must also be movable in the 3D environment. The 3D models are then supposed to be published in Teamcenter and the study object can start designing the digital plant.

Necessary prerequisites for a digital plant

The future strategy must streamline operations by implementing increasingly more digital solutions, in which a digital plant could be used to reduce the lead time for new projects. This aligns with the study object's ambition of immediately being able to install equipment and start production at full scale, a process that currently is experiencing a considerable ramp-up time. The digital models of tools and equipment should be used for virtual commissioning/verification, where each section of the production line is verified and validated before production starts. To make this possible, sensors must be defined, the material added and various scenarios tested. With more details in the VC and more scenarios tested, the risk of errors decreases for the physical commissioning, wherein a great portion of the potential value of the digital plant lies.

The suppliers must deliver 3D models with the required level of quality with defined kinematics and motions to enable virtual commissioning and verification. Virtual verification should be made on tools and equipment without PLC systems, which are computerized control systems designed for industrial automation. VC can be performed on larger tools and equipment by adding material flow, sensors and other things necessary. These types of validation should be performed by the supplier and approved by the study object before the physical installation. The study object can also perform its own VC on a complete subsystem if the various suppliers responsible for the equipment within the subsystem provide PLC code, process logic in WinMod and a simulation in Process Simulate. WinMod is a software managing process logic for VC and Process Simulate is a software tool with multiple functions such as simulation, validation and VC. Also, if the subsystems involve a robot, its code should be delivered in the software RobotStudio. It is important to note that a VC can not ensure that tools and equipment are physically installed correctly, for instance, if an electrician makes an incorrect installation on the production line.

Future possibilities of a digital plant

Provided that a digital plant can be achieved, having 3D models for the equipment linked in the PII would enable the shop engineers to balance the lines earlier, possibly resulting in reduced waste and shorter TT and MTO. Also, having the 3D models linked would increase quality and improve preventive maintenance. In the instance of malfunctioning equipment, the digital thread in the digital plant may enable a cross-functional search option to display if the same type of equipment is used in other processes. A digital plant presented in a VR environment would enable operators to train their tasks and procedures virtually, reducing the time required to train during TT and PP. This would also improve their competence since there often is a shortage of material during TT and PP resulting in inadequate possibilities for training. If operators and maintenance received access to virtual reality training on the digital plant, it would enable improvements and reduce the risks of errors. One example could be that a tool could be positioned too high, resulting in bad ergonomics which was missed in the ergonomic simulations. The operators could then deliver feedback and the tool position remedied before it even being physically installed.

4.6 Interviews with Manufacturing Engineering

BAX is the department within ME responsible for the back axle part of the car and functions as a link between the plant and R&D. Their tasks include optimizing existing designs and implementing new designs into the plant. Business Development FA functions within ME and develops digital strategies to capitalise on market opportunities and enhance the company's competitive position. The undertakings of Business Development entail accessing new technologies, assessing infrastructure requirements and expanding production capabilities to align manufacturing strategies with broader business objectives. The ME project manager oversees the development of project plans for new car development. The duration of the project plan varies depending on whether it involves creating a completely new car or updating an existing model.

Current ways of working
While gathering information from the interviews, the consensus among the interviewees was that there are currently no standardized requirements for suppliers to deliver 3D models of the equipment to support a digital plant. Documentation regarding equipment arrives late during a project, sometimes after the MTO has been finalized, which creates a knowledge gap between development and manufacturing processes. Business Development has observed, that leveraging virtual verification can help bridge the knowledge gap between development and manufacturing processes. This approach can reduce the confidence gap between product and process. The problem lies within structuring the development plan with appropriate support for such an initiative.

Business Development emphasized the need to concretize virtual deliveries during the development project plan when describing the constellation in which such a commitment would materialise. As of now, there are no clear requirements formulated in regards to support the needs for a digital plant. Such requirements could be demands of interactive 3D models and simulations being introduced to the collaborative process with suppliers, where the progress in maturity levels of such deliveries should be made able to be closely followed as the project goes on. In line with the proposition of integrating operations through a common platform, a possible discipline suggested by the ME project manager would be for the supplier to release the newest edition of 3D models in Teamcenter or at the very least deliver the 3D models during the design review meetings in the early stages of the project.

Currently, the local ME teams are responsible for design review meetings, but since they are not responsible for the equipment before the VP, strategic alignment within ME regarding the matter is in disarray. BAX has actively tried to set a standard for itself when ordering new equipment, including demands of 3D models that can be interacted with in Teamcenter. The recurring problem is that after equipment has been installed according to specification, changes done to the equipment and processes by factory personnel reduce the confidence ordinarily obtained through having virtual models. Physical changes in equipment must be updated in their respective 3D models and reported in Teamcenter, preferably by a governing body that has both competence and the knowledge of why maintaining digital confidence is important. BAX expressed that if a governing body dedicated to this can not be assigned, which in all likelihood would not be a realistic expectation, routines of updating models in conjunction with changes must be uniformly prioritized. Recognizing that factory personnel may have other incentives for conducting changes to the equipment without updating the corresponding model, a conceptual digital plant must be kept up to date to be justified in a broader business setting according to both Business Development and the project manager.

Requirements of a digital plant

Looking into the future, the study object aims to shorten or even remove the MTO with the ambition to reduce lead times and time to market. Replacing the MTO, by replacing physical verification with VC requires a high level of detail and competence. BAX expressed that the difficulties with achieving a digital plant may relate to the availability of 3D models in Teamcenter and to them not being connected to corresponding processes. A VC must consider all scenarios covered by the current MTO, which entails ensuring geometrical compatibility and process logic between product and equipment but also a comprehensive overview of system behaviour during special occurrences such as power outages, fire alarms, emergency stops etc. The 3D models must include cabling, kinematics and sensors to make the simulations reach a viable virtual confidence level.

Presupposing that shortening or replacing the MTO with VC will result in an increased competitive advantage for the study object, a disposition supported by all interviewees, virtual verification would also possibly result in a considerable amount of material cost and engineering hours saved. Engineering hours required for simulations would increase but seem insignificant compared to the total amount saved. Having process logic available in a 3D environment would also enable plant engineers to start line balancing earlier, a disposition also vocalized by ME Digital.

The vehicle's upperbody is always developed trailing the underbody in the project plan since design choices for the upper body are decided based upon the iterations of design changes done to the underbody. Therefore it is important to recognize that the checkpoints of virtual deliveries would follow the same sequence. Accordingly, payment releases would be attributed to corresponding checkpoints when met. One milestone could be when 3D models are delivered, putting pressure on the supplier to complete the 3D model on time to ensure the payment is received.

4.7 Interview with Plant Engineering

The plant engineers are responsible for the layout of the production lines and other practical matters that concern the factory. Tasks involve optimizing line balancing and space utilization. Additionally, during the development of new car models, plant engineers plan the layout of all workstations based on process order and available space.

3D models of tools and equipment
If 3D models of equipment are delivered, it happens approximately one year before the installation of the equipment. However, only tools and equipment associated with a specific process are provided. All equipment related to transportation, logistics and other background activities are never delivered together with 3D models and standard tools such as hammers and handheld drills also lack corresponding 3D models.

Scanning of plant
The scanning of the production facilities is well-covered and made available already. The use of reference points in the facilities has made it possible to establish positions with a tolerance of 0.1 mm, a level of accuracy typically used to provide suppliers with clear guidelines regarding the acceptable dimensions for the tools and equipment. However, the scanning data is quickly rendered outdated since the production layouts constantly change, resulting in additional scans having to be performed to achieve up-to-date information.

Maintenance of a digital plant
Concerning the maintenance of a potential 3D plant, various departments may make physical altercations to the tools and equipment once they are installed and operational. This presents significant challenges as these alterations are not reflected in the digital 3D models, and the departments lack the expertise and authorization to update them since it is outside their designated responsibilities. Having outdated 3D models in Teamcenter can present significant problems when assessing the feasibility of manufacturing a new car model. When the tools and equipment are verified during the conceptual virtual MTO, the project may be delayed drastically because of outdated 3D models. One example of this could be that the dimensions of fixtures have been physically updated without updating the 3D models, resulting in the fixtures not matching the new product.

Corresponding with the disposition of ME Digital and ME project manager, the maintenance of a conceptual digital plant must be supported by a common PLM platform. The tools and equipment must be placed according to process logic and associated with corresponding processes, which include transportation devices and rudimentary tools. A new system for updating the 3D models needs to be implemented. Involved parties must be educated on the significance of maintaining the digital plant. In cases where competence is lacking, training should be provided on how to update the models. This would instil confidence in the accuracy of the 3D models, preventing unexpected issues during the MTO process as the products will consistently align with the dimensions of the tools and equipment

5
Synthesis

This chapter covers the future framework for project plans resulting in a digital plant of the final assembly factory and the expected outcomes it brings. The surrounding support system facilitating continued utilization of the digital plant even after project completion is also incorporated.

5.1 Future Framework for Project Plans

The new framework for future projects follows the same structure as the original development plan with the addition of mandatory Simulation Deliveries (SD), see Figure 5.1. All deliveries are listed based on whether it is internal deliveries or deliveries a supplier is responsible for. Note that this is a generic description of a future project plan and that differences may occur on specific projects based on their demands. Also, there is no distinction made between the under and upper body since the deliveries are identical. However, the development of the upper body must be adapted to that of the underbody resulting in postponed times for the upper body in practice.

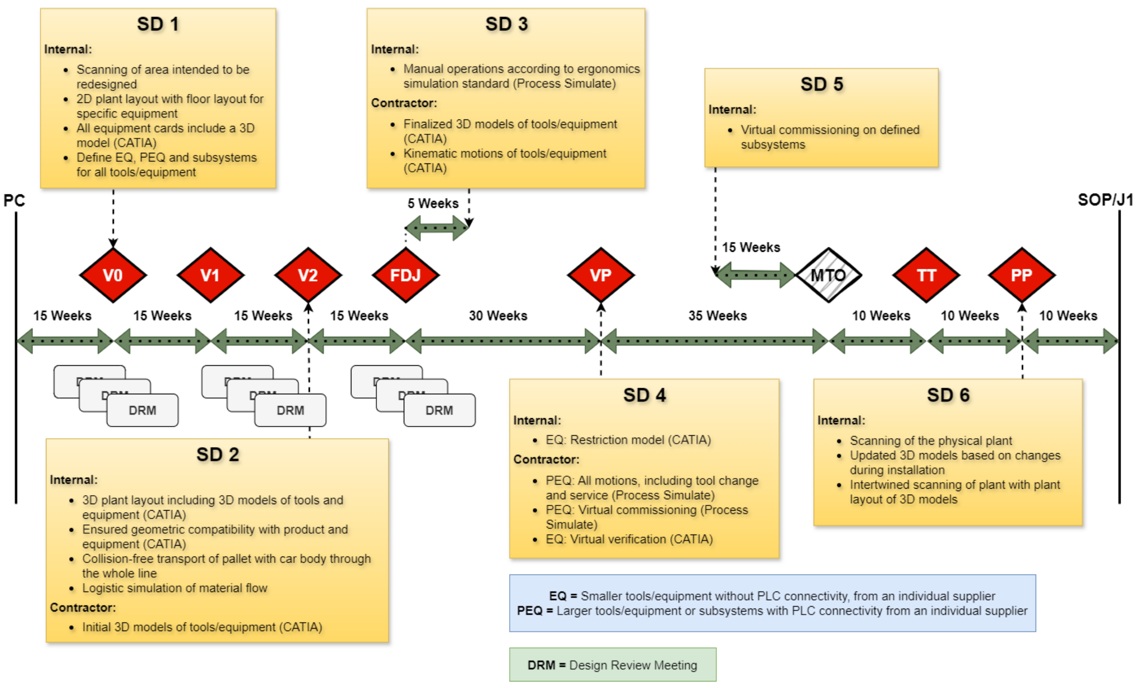

Figure 5.1: Project timeline with simulation deliveries.

The contractor must continuously update their work in Teamcenter to increase transparency and enable the study object to monitor progress and design changes. This allows the study object to adapt and optimize project plans leading to a more efficient and streamlined way of working on projects. Having the most updated versions of different materials open for everyone in Teamcenter also improves accessibility.

Digital applications operate using various file formats, therefore, the formats provided by suppliers must be compatible with the formats used by the study object. For the simulation in Process Simulate, JT is the supported file format. Regarding 3D model deliveries, models must be compatible with CATIA V5, with CATProduct and CATPart being the native file formats. The study object requires three deliveries regarding virtual commissioning, PLC code, logic in WinMod and simulations in Process Simulate, with the addition of RobotStudio if robotics is included. The preferred way of delivery is a folder per component, containing a CATIA assembly structure, corresponding JT files and connected documentation.

SD1

By the V0 milestone, the first SD must be finalized. If the project concerns changes to an existing line or building a new manufacturing line in an existing plant, the area intended to be redesigned must be scanned. The scanning data is used to help with the new production line's design. ME are responsible for creating a plant's layout in 2D with all tools and equipment included in the correct sequence according to the BOP. The layout is based on the BOP and will work as a foundation for the 3D layout that will be designed with 3D models later in the project. Also, all equipment cards must include a request for a 3D model in CATIA to ensure it is included in both the RFQ and the order to suppliers. All tools and equipment in the production line are defined as EQ if they lack PLC connectivity and PEQ if they are PLC-connected. Vital subsystems of the production line are defined during SD1. These subsystems are crucial for the production and a VC is intended to be performed on them for a later simulation delivery. All deliveries for SD1 are stated in Table 5.1.

Table 5.1: All deliveries included in SD1.

Simulation Delivery 1	
Internal deliveries:	
1:	Scanning of area intended to be redesigned
2:	2D plant layout with floor layout for specific equipment
3:	All equipment cards include a 3D model (CATIA)
4:	Define EQ, PEQ and subsystems for all tools and equipment

SD2

SD2 should be completed to the V2 milestone. This delivery is supposed to contain the initial 3D models of tools and equipment made available in Teamcenter to ensure accessibility for all stakeholders involved. A new stage in the equipment cards needs to be added, which ensures that by V2 the initial 3D model is delivered as planned. The 2D plant layout outlined in SD1 is supposed to be updated with the corresponding 3D models. SD2 encompasses a level of digital study in such detail that geometrical constraints and collision-free paths for equipment can be ensured. The production feasibility of the car must be verified according to demands from the fixture and tool design. This delivery aims to validate the overall process logic by performing digital pre-assembly operations. Process sequence must be updated based on 3D model geometry and attributes.

A logistic simulation of the material flow to all workstations and throughout the plant is performed. This simulation ensures enough room to transport parts and material to all respective workstations without hindering the process flow. It is important to note that the logistic simulation only simulates the transportation of materials and is thereby not process-adjacent but product-adjacent. The deliverables for SD2 are listed in Table 5.2.

Table 5.2: All deliveries included in SD2.

Simulation Delivery 2	
Internal deliveries:	
1:	3D plant layout including 3D models of tools and equipment
2:	Ensured geometric compatibility with product and equipment
3:	Collision-free transport of pallet with car body through the whole line
4:	Logistic simulation of material flow
Contractor deliveries:	
1:	Initial 3D models of tools and equipment (CATIA)

SD3

SD3 must be finished five weeks after FDJ when the suppliers have gotten design approval. The 3D models of tools and equipment should be finalized. SD3 also contains kinematic motions of the tools and equipment used to verify adequate process logic. A simulation including kinematic motions is performed to ensure the process scheduling of tools and equipment is functioning without colliding. Handling parts from material feed and mounting details to the product is also included.

All manual operations must be simulated in an ergonomic aspect to ensure acceptable working positions for operators. The supplier can perform the ergonomic simulation by themselves and show the results to the study object. But if the supplier lacks the competence to perform a sufficient ergonomic simulation the study object handles it. All deliveries for SD3 are stated in Table 5.3.

Table 5.3: All deliveries included in SD3.

Simulation Delivery 3	
Internal deliveries:	
1:	Manual operations according to ergonomics simulation standard
Contractor deliveries:	
1:	Kinematic motions of tools and equipment
2:	Handling of parts from material feed to product

SD4

The next deliverable, SD4, is supposed to be delivered at the start of VP. The purpose of this delivery is for the supplier to have performed virtual verification or commissioning on the tools and equipment they are responsible for. VC is performed on tools and equipment with PLC connectivity while tools and equipment without PLC connectivity only are virtually verified. The virtual verification ensures that the virtual model of the tool or equipment fulfils its purpose and works as intended based on the inputs and outputs defined by the study object. A VC is performed to ensure the tool or equipment works as intended by simulating and testing various scenarios that might occur in a manufacturing setting. Cabling, tool changes and other specific scenarios are included to achieve a highly qualitative virtual commissioning. The virtual commissioning must be delivered with PLC code, logic in WinMod and simulations in Process Simulate to enable seamless transfer into Teamcenter and further virtual commissioning performed by the study object.

The study object is required to define restriction models in the 3D layout of the plant. These restriction models showcase how certain pieces of equipment can move and prevent clashes with equipment that is not PLC-connected. The deliverables for SD4 are listed in Table 5.4.

Table 5.4: All deliveries included in SD4.

Simulation Delivery 4	
Internal deliveries:	
1:	EQ: Restriction model (CATIA)
Contractor deliveries:	
1:	PEQ: All motions, including tool change and service (Process Simulate)
2:	PEQ: Virtual commissioning (Process Simulate)
3:	EQ Virtual verification (CATIA)

SD5
SD5 consists of one delivery which virtual commissioning on defined subsystems. The study object uses the 3D models and files regarding VC delivered from suppliers for tools and equipment within the subsystem. These are combined into one cohesive system that the study object controls by a VC. In an ideal world, the whole production line would be combined and validated by a VC, but since a lot of the equipment lacks PLC connectivity and it requires an immense amount of engineering hours it is not reasonable. Therefore, vital subsystems have been chosen instead to ensure the most crucial parts of the production line have been tested before the physical commissioning starts.
SD5 is required to be 100% completed and reviewed 15 weeks before the MTO. Communication must be conducted with robot developers and PLC programmers to ensure that identified syntax errors are eradicated through the verification loop in Process Simulate. The deliveries of SD5 are listed in Table 5.5.

Table 5.5: All deliveries included in SD5.

Simulation Delivery 5	
Internal deliveries:	
1:	Virtual commissioning on defined subsystems

SD6
One of the main deliveries of SD6 is scanning the newly installed physical plant. The scanning is performed at the end of TT to capture eventual changes in process logic regarding the equipment's location due to balancing changes. The scanning of the plant utilizes fixed points installed throughout the plant to achieve high accuracy in all three dimensions. Any physical changes to the equipment or tools during MTO and TT must be updated in the digital 3D models.

The scanning of the plant should be intertwined with the 3D layout of the plant, which includes the models of tools and equipment, to achieve a comprehensive digital plant. This digital plant will consist of highly detailed 3D models that are up-to-date and equal to their physical replicas. The digital plant would correspond to the level of a digital model since there is no automatic data exchange. Also, the environment in which the 3D models are displayed should be an exact mirroring of the physical plant, made possible by combining the scanned data with the geometry defined in the 3D models. SD6 should be finalized by the start of PP and all content required for it is listed in Table 5.6.

Table 5.6: All deliveries included in SD6.

Simulation Delivery 6	
Internal deliveries:	
1:	Scanning of the physical plant
2:	Updated 3D models based on changes during installation
3:	Intertwined scanning of plant with plant layout of 3D models

5.2 Future Required Support for a Successful Digital Plant in Teamcenter

The value and purpose of updated 3D models must be understood throughout the organization. Currently, many project managers lack the understanding of the value of 3D models and can skip them in orders to suppliers to reduce costs. This has to be stopped under all circumstances since it will be impossible to establish a digital plant if not even the new equipment is provided with 3D models.

Workers from four groups make physical changes to the plant's tools and equipment to ensure they function as intended. These changes must be updated in the 3D models to ensure that ME can do their work effectively and trust the 3D models stored in Teamcenter. The employee making the change to the equipment often lacks the competence to update 3D models but is still responsible for communicating the change to local tooling. Local tooling then has to update the 3D model of the object changed. To ensure this is always done with no exceptions, a new procedure including documenting the change in Teamcenter and assigning it to local tooling for an update of the 3D model is implemented.

Also, a strategic payout plan has been developed to ensure the contractor delivers what is expected at the right time. The new strategic payout plan involves various payouts after certain milestones are achieved, see Table 5.7. Also, if a delivery is not received within the agreed time frame, a reduction of 10% is applied to the sum associated with that delivery. This is done to motivate suppliers to meet the agreed deadlines ensuring the study object can continue working on their project according to schedule.

Table 5.7: Strategic payout plan showing the percentage of total payment at each project milestone.

Digital plant payout plan		
1:	Design approval	20%
2:	FAT approval	10%
3:	MTO approval	40%
4:	Full completion	30%

As the future project plan for a digital plant necessitates more sophisticated simulation deliveries, the intended payout plan is being adjusted accordingly. Considering the relatively short time contractors are instructed to deliver virtual assets, 20% of the project budget is paid out once the study object approves the equipment's design.

The next checkpoint is the approval of FATs, where the contractor confirms that rudimentary requirements are met. The major checkpoint is when the equipment has been confirmed to work compatibly with the product during the MTO, freeing up 40% of the project budget assigned to the contractor.

The remaining 30% of the agreed cost is transferred when the project is finalized to create an incentive for the contractor to fulfil its deliveries within the agreed time frame. This includes documentation regarding updated 3D models and confirmed functionality of the processes. The project can never be finalized before the SOP has been completed, ensuring that the equipment fulfils its requirements even during production.

5.3 Expected Outcomes

Successfully implementing the proposed new project plan for simulation deliveries within the original project plan is expected to bring multiple benefits to the organization. As mentioned previously, VC can reduce or even mitigate the need for having the MTO and reduce the time for TT. Removing the MTO and reducing the TT by half, 15 weeks of work is removed and the project would be completed earlier. The 15 weeks of work removed saves the company a lot of money since all the engineers and other employees working full-time during those weeks can put their time into something else. It would also enable SOP earlier, ensuring the revenue from the new car model faster. This is a key aspect to match the current market trends demanding a faster time to market.

The virtual commissioning would enable the shop engineers to start line balancing earlier and during a longer period to achieve more balanced lines before the SOP. The downtime when the production is up and rolling is also expected to be reduced by simulating various scenarios during the virtual commissioning. Also, by constantly updating the 3D models when physical adjustments are made to the tools and equipment, ME can trust the 3D models resulting in more accurate planning during new development projects.

With the 3D models used for the virtual commissioning, operators could practice their work in Virtual Reality (VR). The operators would get sufficient time to practice their operations and procedures long before SOP even with the MTO removed and the TT reduced. This would improve quality and increase competence compared to the current state. Having the operators train virtually enables them to get more training in less time. It would also save the company money on expensive materials during testing.

6
Discussion

In this chapter, the methodology used for the project is discussed. Additionally, the project plan's established results and potential outcomes are analyzed, along with an assessment of its ethical and sustainable impacts. In the end, future possibilities for further development of the digital plant are discussed.

6.1 Evaluation of applied methodology

The project follows a variant of the DRM where a literature study was the initial step. The literature study showed a gap in research regarding digital deliveries in project plans and their purpose. The research questions were collaboratively formulated with the study subject to address the identified gap in scientific knowledge while exploring the potential impacts of simulation deliveries within their existing project plans. Also during the literature review, particular emphasis was placed on PLM systems, virtual commissioning, and digital models, as these topics are interconnected and relevant to the study.

Interviews were conducted using a semi-constructed methodology to ensure the interviewee stayed on the topic but was still able to elaborate and provide new insights [37]. Interviews were conducted with interviewees of various engineering departments related to manufacturing, pursuing higher credibility and reduced susceptibility to individual bias. It would have been advantageous to expand the interview pool to include more plant engineers as they are also stakeholders in the project.

Combining the information gathered through the literature study and the interviews, a project plan for simulation deliveries in synergy with the existing project plan was established. The project plan was discussed with various stakeholders in an iterative process to ensure feasibility and potential to achieve the expected outcomes. The iterative process was performed to enhance stakeholder engagement and enable continuous improvement of the initial project plan. It also enabled an acceptable compromise between various stakeholders' requirements to reach a final project plan.

The final stage of the DRM is descriptive study II, which is supposed to evaluate the support. However, this stage is only possible if the support has been implemented and tried in the organization for a considerable time [30]. Given that the project plan established in this project is only a suggestion to the study object, conducting a comprehensive evaluation of it is unfeasible. Therefore, evaluating the project plan is limited to comparing it with similar projects and the feedback from stakeholders. In an ideal scenario, the project plan would be implemented and evaluated after a long period to understand its effects fully.

6.2 Possible Impacts of Findings

This project plan can help the study object achieve its digital strategy and increase transparency throughout the organization and suppliers. Efficiency is expected to increase, resulting in a shorter time to market for new car models [26]. The project plan also facilitates the seamless integration of future innovations, such as digital twins and VR.

Delays can be prevented in the project plan when having the possibility to detect errors and bugs in PLC programming early. Also, ensuring a higher system quality can result in shorter ramp-up times and reduced downtime [22]. It also enables strategic planning of material handling and optimization of the production to enhance flexibility [23]. This can help the study object to stay competitive in a toughening industry and help ensure future profitability.

If this project plan is not implemented the study object risks falling behind competitors by having a protracted development methodology not adapted to modern technology and requirements. The MTO would then still be kept resulting in high costs for engineers and materials limiting the profit margins. The speed to market would also not improve making the company adapt to new market trends slower, inevitably leading to a smaller market share [4].

6.3 Arising Challenges

There are challenges associated with the presented project, especially considering that it has been designed based on certain prerequisites that are not currently in place. One critical requirement for the project plan to prove effective is the ability of suppliers to operate within the Teamcenter software. As it stands, suppliers' capabilities in performing virtual verification and VC can vary significantly resulting in lower virtual confidence and a lower maturity of the VC [19]. The subject of the study may remedy this by imposing higher demands and even by providing training subsidies to encourage extended capabilities among suppliers. However, some suppliers will likely be unable to meet these requirements, necessitating negotiating agreements with new suppliers who can. This could result in suppliers taking on a larger portion of the assembly line, which promotes the feasibility of conducting VC but likely also reduces the total number of suppliers [16]. There are also issues of data security and ownership associated with a digital plant supported by a common PLM system that demands more attention. This refers particularly to the peripheral data exchange occurring during the development phase.

It is also imperative to recognize the need for domain-specific tools to be integrated into Teamcenter to provide adequate support for the digital plant. A structure supporting these requirements could resemble that of the *One System As Integrator* approach depicted in Figure 2.2 where the PLM software provides the prerequisites for integrating dedicated tools while facilitating some standalone requirements engineering solutions. Worth noting is that over the last few decades, IT systems have generally been built to carry out certain functions or business processes that companies traditionally have considered independent [11]. It is unrealistic to expect the PLM system to integrate all necessary systems seamlessly given that FA involves numerous interconnected value streams within the enterprise and with suppliers [11]. Instead, it will likely require support from configurator applications to facilitate data transfer between these systems [11].

6.4 Ethical and Sustainable Considerations

All interviewees remain anonymous and details such as the exact years of experience are not given. Instead, the years of experience are rounded to the closest five years to ensure a specific employee can not be pinpointed. The interviewees also read the summarized text before approving and accepting its use in the final report. This ensures all stakeholder who accept an interview is treated with respect and dignity.

The project plan developed can positively impact sustainability in various aspects. Regarding economic sustainability, the study object has a lot to gain from adopting the project plan, encompassing faster time to market and reduced expenditures. Less material will be used during the MTO and TT since more can be done virtually, benefiting ecological sustainability. Having a digital layout of the plant enables more extensive ergonomic simulations, contributing to a better working environment for operators making the project have a positive social impact.

6.5 Future Scope

Although the proposed project plan demands a high level of interconnected systems to support the digital plant, the level of complexity expected of the digital plant would resemble that of a digital model since the proposed model does not entail the two-way exchange of data commonly associated with a digital twin [26]. As previously mentioned, the model is intended to be applied when conducting geometric and physical modelling, with the addition of behaviour modelling. Acknowledging that conducting behaviour modelling in a virtual space is of a digital twin nature, the objective thus far is restricted to emulating and verifying the physical system.

However, with technical capabilities growing within the automotive industry, an elevated model resembling a digital twin can support the back-and-forth interactions between a physical entity and its virtual model, connecting the physical and virtual spaces without the need for a human to initiate the exchange. In this way, not only can the physical entity be better controlled, but progressively optimized and upgraded based on big data obtained through the digital representation of the system. Further promoting the ambition of reaching a digital plant, a digital twin combined with the other technologies, such as training of plant personnel in a VR environment can help deliver a holistic view using increasingly maturing technologies [39].

7
Conclusion

This project has proposed a new project plan for simulation deliveries compatible with the generic project plan for the study object. The new project plan aims to achieve a 3D model of the FA plant with detailed 3D models of all tools and equipment. The current trend within the automotive industry is leaning towards faster changes in customer demands requiring car manufacturers to adapt and reduce time to market for new car models.

The project plan's findings were deducted following an established procedure, having adopted design research methodology as the basis of data collection and analysis. Currently, the study object follows a project plan that specifies each step from concept design to the start of production when developing new car models. However, the commissioning of production lines is conducted physically and unexpected errors often delay the start of production.

With a web-based PLM system functioning as the backbone of the study object organization, it is possible to have one platform with all the necessary information. The new project plan requires the study object and suppliers to constantly update their work in the PLM system to obtain transparency and cross-functionality among stakeholders. The project plan, supported by a PLM system, specifies what needs to be delivered and at what time to optimize the possibilities enabled by simulation deliveries. Starting with a 2D process layout, in which 3D models of the specific tools and equipment are added and subsequently fused with scanning data of the built plant has been identified as the approach to achieve a digital plant. The 3D models of tools and equipment are also used to perform virtual commissioning of the production line, enabling the removal of critical and time-consuming physical commissioning that is a part of the current development phases.

The proposed project plan in the study aims to enhance transparency, efficiency, and integration of innovations in the automotive industry. Enhancing competitiveness in a challenging industry is crucial for sustaining growth and optimizing profitability. In the future, the digital model of the plant can be developed further by incorporating sensors for real-time updates of the system's status, enabling adaptive decision-making by artificial intelligence, possibly leading to a comprehensive digital twin of the plant.

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A

Interview Template

General questions

- Could you describe your role and responsibilities?
- How long have you been working at the company?
- How do you work within Teamcenter today?
- What benefits do you see with a Digital Plant?
- What obstacles are there for reaching a Digital Plant?

Questions for Digital Solution Groups

- Which milestones in the current development plan have long lead times?
  - Is there a way to shorten these?
- How are current 3D models of tools and equipment delivered?
  - What happens with these after they are delivered?
  - Are they updated if any changes occur to the equipment?
- How is virtual commissioning on tools and equipment performed?
  - Should it be performed by the study object or the supplier?
  - Do you have the competence required at the study object to perform it?
  - What would the supplier have to deliver to ease the work for you?
  - Can it be performed on the whole production line?
- How is virtual verification on tools and equipment performed?
- How is scanning data used?
  - Is it easy to combine it with 3D models?
- How are suppliers working with the PLM system now?
  - Why are they not working with it more?
  - What would happen if everyone worked within the PLM systems?
- How can a digital plant be achieved?
  - Does it require 3D models everywhere?
  - How do you create the plant's layout with 3D models of the tools and equipment at the correct positions?
  - What would be the expected outcomes of it?

Questions for Manufacturing Engineering Department

- How are current 3D models of tools and equipment delivered?
- What kind of demands are in place in regards to 3D model availability and formats?

- How established is the connection between equipment and appurtenant process?
- How would a digital plant look like from your perspective
  - How would a digital plant affect the way you conduct your work?
  - How would the relationship with suppliers be affected if a digital plant was implemented?
- What steps of the development process do you regard as possibly being facilitated by a digital plant and virtual verifications?
  - Does ME currently possess the competence to conduct these virtual verifications?
- What benefits do you associate with a digital plant?
- What are some difficulties you foresee in the process of trying to reach a digital plant?
  - What procedures have to be in place to align the various departments within the organization to work towards a digital plant?
  - What procedures have to be in place to maintain a digital plant?

Questions for Plant Engineering

- If 3D models are included as a demand when ordering equipment, at what point does the study object get access to these models?
- Are there specific types of equipment where the demand for 3D models is more prioritized?
- In the case a digital plant was implemented, who should bear the responsibility to maintain it?
- Which departments are authorized to make physical changes to the equipment once it has been installed?
  - Do these departments have the expertise/authorization to update the digital model according to the physical changes?
  - If certain changes are not updated in the digital model, what could be the consequences?
- To what extent is the physical plant scanned?
  - To what extent can this scanning data be interacted with, for example in Teamcenter?
- From the factory's perspective, what prerequisites must be in place for the implementation of a digital plant to be feasible?

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