Digital technologies for design and performance optimization of manufacturing lines in industry 4.0

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INDUSTRY 4.0 Ph.D. Program
SSD: ING-INF/04–AUTOMATICA

Final Dissertation

Digital Technologies for Design and Performance Optimization of Manufacturing Lines in Industry 4.0

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Digital Technologies for Design and Performance Optimization of Manufacturing Lines in Industry 4.0

Thesis submitted for the degree of Philosophiae Doctor

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Abstract

The paradigm of Industry 4.0 (I4.0) is propelling the development of smart factories, wherein physical and digital systems are seamlessly integrated to achieve fast production and flexible mass personalization. The core of such an industrial revolution is the promise of extraordinarily high operational productivity and efficiency through the establishment of a high degree of connectivity between the real and virtual worlds. In this regard, industrial tasks have long been a strong suit for digital technologies such as *Virtual Reality* (VR) and *Digital Twin* (DT). Numerous benefits and major obstacles to the adoption of digital tools have been identified by a thorough review of the literature; these issues are currently being addressed through research projects and user surveys. For instance, VR is demonstrating significant potential as a robust tool for cost reduction in both production and design by identifying and anticipating eventual assembly issues in the engineering stage. Simultaneously, DT tools are changing industrial procedures by building digital representations of actual systems that provide real-time information, and opportunities for predictive maintenance, and optimization. Industrial businesses are redefining traditional design and the integration of parts, equipment, and services, leveraging both VR and DT to facilitate communication between operators and machinery to stay competitive in the market. The possibilities for individual and group collaboration, machine-to-machine and even machine-to-industrial object interactions are being opened up by digital technologies. The ultimate goal is to incorporate VR applications and DT functionalities into detailed simulation models as part of the endeavour to incorporate these research objectives and various digitalization tools into the analysis.

The first focus of this thesis's research is to examine the current state of VR technology and how it can be used in the manufacturing industry. VR technologies have generally been employed in the training of industrial operators for tasks related to maintenance and assembly, as well as in the VR-assisted design reviews for ergonomic assessments. As a first phase, this study investigates the integration of VR into manufacturing processes, specifically focusing on the intricate design systems of an electric axle production line, and how VR could improve business and product development. During this phase, a detailed process for moving from computer-aided design (CAD) to VR is also outlined. Subsequently, the research examines two distinct case studies within the organization Masmec SpA, an automotive company leader of the Italian and European market. To improve the ergonomics of complicated production lines, first, the research defines the "Virtual Golden Zone Methodology" and proposes VR tools to implement such a methodology in a real-world setting. Second, with an emphasis on decision-making and control strategies for maximizing material flow, operator flow, and logistics across multiple stations, the focus is shifted to modelling production and logistics processes.

Similarly, digital models like DT greatly aid the planning process by enabling experiments and "what if" scenario testing without interfering with production systems' continuous operations. These tools played a key role in the case study simulation, digital production models, and operational optimization of production lines, plants, and individual logistics processes—with a focus on automated guided vehicle paths—all of which were optimized. The research then moved forward to clarify how different digital technologies interact with one another and to designate specific functions for each tool throughout the project. To assess various production scenarios and facilitate informed decision-making from the outset to ongoing production monitoring, this phase involved the use of sophisticated analytical tools like statistics, charts, and bottleneck

analysis. Interestingly, the definition of a hierarchical DT, which outlined the important roles that each digital tool plays across various process levels in manufacturing systems, was the stage's culmination.

In conclusion, encouraging the integration between VR tools and DT simulation techniques has the potential to offer users a productive and enjoyable experience that promotes inspiration, cooperation, and creativity. To promote creativity, productivity, and efficiency in manufacturing processes, this research project contributes to the advancement of knowledge across the complex intersections of digital technologies.

A chi c'è sempre stato
A chi se n'è andato
A chi ha creduto in me sin dall'inizio
E fino alla fine
A te che più di chiunque altro avresti voluto esserci
A te Commà Rosin

A mia nonna Rosa

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Part 1: Enhancing the Design of Manufacturing Lines through Digital Technologies

Part 2: Optimizing the Operations of Manufacturing Lines through Digital Technologies

Preface

This thesis is submitted in partial fulfilment of the requirements for the degree of *Philosophiae Doctor* in Industry 4.0 at the *Politecnico di Bari*. This work was supported by the company *Masmec S.p.A.*.

The research presented in this dissertation was conducted at the *Decision and Control Laboratory* of Politecnico di Bari –under the supervision of Professors **Mariagrazia Dotoli** and **Raffaele Carli**– in collaboration with the *Virtual Reality and Reality Reconstruction Lab* of Politecnico di Bari –under the supervision of Professor **Michele Fiorentino**– and the *Digitalization Office* of Masmec S.p.A. –under the supervision of Engineer **Vito Lazazzera**– between November 2020 and October 2023.

This work is to the best of my knowledge original, except where acknowledgements and references are made to previous work. Most part of this thesis has been published during these three years in different scientific publications where I am one of the authors. The papers are preceded by an introductory chapter (Chapter 1), that relates them to each other and provides background information and motivation for the work. A version of Chapter 3 has been presented in International Journals [1] while Chapters 4, and 5 have been published in the proceedings of International Conferences [3], [4]. Chapter 2 was presented at an International Conference and is under publication [5], while Chapter 6 is one of the last works conducted in the last year that is under submission to an International Journal [2]. A concluding chapter (Chapter 7) summarizes the main outcomes and findings for future developments.

Furthermore, in addition to the works presented in this thesis, I am one of the authors who contributed to research involving a survey of potential technical writers to discern their design preferences within the realm of industrial augmented reality [6] in collaboration with Prof. Engr **Antonio Emmanuele Uva**, Prof. Engr. **Jan Schmitt**, Prof. Engr **Michele Fiorentino**, Dr. Engr. **Michele Gattullo**, Dr. Engr. **Alessandro Evangelista**, and Engr. **Francesca Ruospo**.

The full list of papers written by the author is reported hereafter.

List of Papers Written by the Author

International Journal Articles

[1] Dammacco, L., Carli, R., Lazazzera, V., Fiorentino, M., and Dotoli, M., “Designing complex manufacturing systems by virtual reality: A novel approach and its application to the virtual commissioning of a production line,” *Computers in Industry*, vol. 143, p. 103 761, 2022.

[2] Dammacco, L., Carli, R., Lazazzera, V., Fiorentino, M., and Dotoli, M., “Hierarchical digital twin for smart manufacturing: Methodology and application,” *IEEE/CAA Journal of Automatica Sinica* ***(submitted)***, 2023.

International Conference Proceedings

[3] Dammacco, L., Carli, R., Gattullo, M., Lazazzera, V., Fiorentino, M., and Dotoli, M., “Virtual golden zone for enhancing the ergonomics of complex production lines,”

in *International Joint Conference on Mechanics, Design Engineering & Advanced Manufacturing*, Springer, 2022, pp. 1436–1447.

[4] Dammacco, L., Carli, R., Lazazzera, V., Fiorentino, M., and Dotoli, M., “Simulation-based design for the layout and operation of agvs in sustainable and efficient manufacturing systems,” in *2022 International Conference on Cyber-Physical Social Intelligence (ICCSI)*, IEEE, 2022, pp. 309–314.

[5] Dammacco, L., Carli, R., Lazazzera, V., Fiorentino, M., and Dotoli, M., “Virtual design of complex manufacturing systems by digital technologies: The case of an italian automotive company,” in *International Conference on Design, Simulation, Manufacturing: The Innovation Exchange* ***(under publication)***, Springer, 2023.

[6] Gattullo, M., Dammacco, L., Ruospo, F., *et al.*, “Design preferences on industrial augmented reality: A survey with potential technical writers,” in *2020 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, IEEE, 2020, pp. 172–177.

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Chapter 1

Introduction

In the landscape of Industry 4.0, the automotive sector is in the midst of a revolutionary shift. This evolution is driven by the seamless integration of digital technologies into traditional manufacturing processes, promising heightened productivity and efficiency [1]. The motivations behind this profound transformation are rooted in several key factors. First and foremost, there is a growing emphasis on sustainability and environmental responsibility, particularly with the shift from internal combustion engines to electric propulsion. This transition necessitates cleaner, more efficient manufacturing practices. Moreover, the changing dynamics of the global economy and consumer preferences are compelling the industry to adapt. Consumers now demand customized, high-quality products with shorter time-to-market cycles, pushing automotive companies to innovate their manufacturing practices [2]. The rise of Industry 4.0 offers a response to these challenges and opportunities. It involves converging digital technologies like the Digital Twin (DT) and Virtual Reality (VR), and automation to create a connected, intelligent, and efficient production ecosystem.

In this chapter, we will explore the motivations behind this transformation, particularly in the automotive sector. We emphasize the crucial role of digitalization in reshaping the landscape of manufacturing processes. By scrutinizing the integration of these advanced technologies, we highlight the profound impact of Industry 4.0 on how the automotive industry operates [3]. We progressively uncover the motivations fuelling this transformation as we look at how digitalization is fundamentally reshaping the landscape of automotive manufacturing. Ultimately, our investigation will lead us to a detailed discussion of the research objectives and thesis structure, with a special emphasis on the dynamic world of digitalization in the automotive industry focusing on real case studies.

1.1 Motivation of the Thesis

The term 'eco-friendly revolution' is used to describe the significant and extensive change that is recently affecting the global manufacturing sector. This transformation has profoundly impacted the planning and execution of manufacturing operations [4]. A new manufacturing paradigm has emerged characterized by shorter product life cycles, a greater emphasis on customizing products, and an increase in close-quarters interactions between humans and robots. This realignment in the manufacturing domain is inextricably linked to the emergence of Industry 4.0, a concept that is causing a revolution in manufacturing companies globally. Moreover, the motivations behind this profound transformation are linked to a growing emphasis on sustainability and environmental responsibility, particularly with the shift from internal combustion engines to electric propulsion. As a consequence, innovation is becoming more necessary in areas such as battery production, electric drive trains, and charging infrastructure.

The implementation of smart logistics and the digitization of products are the core principles of Industry 4.0, which departs from traditional automation concepts [5]. The seamless integration of the physical and virtual worlds is a crucial aspect of this paradigm shift, and in this context, digital technologies have become a crucial tool for designing complex manufacturing systems. In particular, the main supporting technologies of virtual design studied in this research are identified and categorized into areas related to product and process development and product management. These technologies include the DT and VR.

VR is a technology that can assist in the design of complex production systems and is one of the fascinating aspects of the revolution [6]. VR provides a unique way to interact with virtual environments, allowing for a profound and immersive understanding of intricate systems. Despite its enormous potential, VR is still not widely used in industrial practices for designing intricate manufacturing systems. The limited amount of scientific literature that is currently available on this topic is mainly concerned with design review processes, streamlined manufacturing systems, or consumer goods. Due to a lack of established and standardized practices, creating and deploying a VR application in an industrial setting is difficult. By providing a novel and thorough procedure for the design of complex manufacturing systems supported by VR, this thesis helps to close this gap [7]. An actual case study involving the creation of a production line for electric axles is used to implement and validate the suggested approach.

Furthermore, the DT, which is essentially an intelligent simulation of a physical system, is another tool that can help with the design and production. Its main objective is to increase the system's reactivity, allowing for real-time adjustments and improvements. DTs have become more sophisticated with the rapid development of computational and communication technologies [8]. The incorporation of domains like IoT, Big Data analytics, Cyber-Physical Systems, and Industry 4.0 is now widespread. Today's manufacturing environment is plagued by constant data inundation on production lines. The increasing demand for data collection and processing has led to the importance of DTs in all stages of production [9]. Process evaluation and improvement, as well as design, development, testing, and actual production, are dependent on their essential role. These intelligent digital representations make it easier to understand the behaviour, traits, and operational modalities of physical assets in a more precise and effective manner. The enormous amounts of data produced in manufacturing lines are nothing new to the automotive industry. DTs have become essential tools in response to this growing need for data collection and processing. By methodically gathering and examining data from various sources, they make it possible to create a highly precise virtual model. A virtual model that closely resembles the behaviour and attributes of physical assets and their operating procedures is built using this information [10]. The thorough analysis and optimization of manufacturing systems is made possible by the capacity to create simulations with such fine detail.

Another important tool for evaluating and improving production systems is simulation technology. It is crucial for building simulations of the processes occurring in a manufacturing system [11]. These models offer a thorough representation of the system's constituent parts, allowing for a thorough understanding of their properties and interactions. System dynamics, agent-based modelling, and discrete-event modelling are some of the methodologies that can be used to simulate data. The scalable level of detail in these models enables businesses to select the level of complexity that best suits their goals. A simulation model can produce useful statistics and performance indicators that help with decision-making when it is run for a long period. The efficient design and operation of material handling systems is one of the crucial aspects of this transformation, which are crucial for the movement of raw materials and finished products in production facilities [12]. To improve the operations of manufacturing plants and warehouses, it is crucial to move materials effectively and cost-efficiently. The vast majority of material handling operations use automated guided vehicles (AGVs), which are computer-controlled and frequently battery-powered robots [13]. Order pickers, forklift trucks, and tugger trains are a few examples of the various types of AGVs. The adoption of AGVs represents a significant investment for companies, making it imperative to perform a thorough analysis of the cost-effectiveness and performance enhancement they bring to the production line. Scheduling, routing, and self-adaptive configuration features are usually included in these robots' management and control units.

Although AGVs can be a great asset, their layout and operation need to be meticulously designed to optimize material handling. In this context, simulation-based approaches play a crucial role in the design process. Companies must perform a thorough analysis of the cost-effectiveness and performance improvement that AGV adoption brings to the production line because doing so will require a sizable investment. These robots frequently have scheduling, routing, and self-adaptive configuration features provided by management and control units. AGVs can be a great asset, but to maximize material handling, their operation and layout must be carefully planned. In this situation, simulation-based methods are essential to the design process. This work focuses on several real case studies involving the assembly of electric axles for heavy-duty vehicles to illustrate the practical applications of these technological advancements. One study investigates the use of DTs and simulation technology to enhance the production process. It demonstrates the interaction between variables such as energy use and output throughput and the significant impact of AGV charging strategies on both energy use and output. The case study shows how digitalization can increase the effectiveness and productivity of manufacturing systems.

The transformation that is currently taking place in the automotive industry within the framework of Industry 4.0 is motivated by a variety of factors, as this chapter's conclusion illuminates. This transformation is being driven in large part by the incorporation of digital technologies, the necessity of environmental sustainability and electrification, and the unrelenting pursuit of efficiency. The chapter also introduces the fundamental technological tools that are crucial in reshaping the design and operation of intricate manufacturing systems in the automotive industry, such as DTs, simulation technology, and VR.

1.2 Positioning with respect to the Related Literature

The automotive industry is being transformed by the manufacturing transformation caused by Industry 4.0. The seamless integration of digital technologies has been embraced, successfully fusing the real and virtual worlds to increase automation. This transformation has been brought about by the emphasis on environmental sustainability and the electrification of vehicles. These elements have fundamentally altered the environment, influencing how businesses function, influencing consumer demand, and changing consumer behaviour.

The use of VR, which offers a way to lower production and design costs by addressing issues early in the process, is one significant aspect of this change. As this study demonstrates, VR applications are very useful in the manufacturing industry, especially when it comes to intricate design systems like the ones used to make electric axles. Moreover, VR has played a pivotal role in automotive design, enabling detailed assessments and optimization of production systems. VR technologies have completely changed how humans interact with digital environments in recent years. VR, which is based on computer graphics, lets users interact with a virtual environment through input devices and immerse themselves in it, producing a very immersive experience [14], [15]. It has flourished in industrial contexts specifically in applications such as maintenance, design simulations, and training [16]–[18]. The literature shows how VR has been most prominently used to simulate real-world environments, providing invaluable tools for maintenance, training, and design. The use of VR for design modifications during the conceptual development phase is noteworthy because it is far less expensive than making changes later in a project, making it an essential component of the design review process [19], [20]. Numerous investigations have examined how VR can augment the design process, thereby promoting greater collaboration and effectiveness in design reviews. Accordingly, VR provides a medium for engaging with virtual product prototypes via mixed-reality design, thereby enhancing design dialogues [21] . Similar to this, VR facilitates realistic walkthroughs in digital factory models, improving the workflow integration of factory planning [22]. While VR has proven useful in customer-focused design reviews, internal company procedures have not yet fully incorporated VR. This hesitation may be caused by unfavourable past experiences with previous VR tools, a lack of engineering-focused VR standards, and a lack of VR expertise in companies [23]. Nowadays the relationship between design reviews and general business procedures is not yet fully established [24]. Despite their potential, practical applications are still fragmented and isolated, frequently restricted to lone machines or highly simplified systems. In addition to demonstrating the advantages of VR sessions for stakeholders over more conventional approaches, this thesis contributes by offering a comprehensive process for incorporating VR into the manufacturing systems design process. Using a real-world manufacturing systems design scenario as its case study, the study highlights the potential of VR in virtual commissioning—a process that defines design elements, competencies, requirements, equipment, and services.

An additional important instrument for assessing and analyzing the operation of production systems is simulation technology also identified such as process DT. There are several ways to build simulation models, such as system dynamics, discrete-event modelling, and agent-based modelling.

According to Chang [25], simulation is a potent tool for digitally simulating real-world systems through experimentation. It provides a behavioural analysis of complex processes prior and after to their physical implementation, providing insights into the processes themselves. This applies especially to a variety of industries where increasing Overall Equipment Effectiveness (OEE), forecasting results, and streamlining processes are critical [26]. According to Mouratzis [27], simulation plays a crucial role in decision-making related to system operations and resource utilization, as well as in optimizing control mechanisms and facilitating real-time communication. Numerous studies that highlight productivity and sustainability and concentrate on present and upcoming trends [28] demonstrates the growing importance of simulation in manufacturing. These models represent the actions of the production system as a series of commands carried out by computer programs. They aid in decision-making by offering thorough explanations of the traits and connections of the parts. However, previous research has primarily focused on laboratory case studies, single components, processes, and their operational parameters, often overlooking the critical situation in the system functionality from a sustainability perspective or the optimization at a real company production plant. To address this research gap, this thesis presents a real-world case study on AGV number, paths, battery capacity, and speed, often overlooking the crucial connection between AGV operation and energy consumption from a sustainable manufacturing perspective [29], [30]. In order to close this gap, the paper provides a real-world case study that uses a simulation-based model to assist in the best possible AGV layout and operation design that takes into account energy and production performance in intricate manufacturing systems. The study offers a thorough method for designing AGV systems by combining hierarchical decision-making with sustainability concepts.

As practitioners and researchers explore the potential of various industrial applications, extensive research has been done in the field of DTs. The idea of the "DT" has become a game-changer that represents a dynamic digital replica of a physical system, and it is an effective tool for comprehending and continuously improving intricate processes [31]. Literature shows that DTs are now essential for every stage of the production process, including design and development, testing, production, evaluation, and process optimization. A more precise understanding of physical assets, their operational characteristics, and behaviour is made possible by these intelligent digital replicas. They contribute to increased productivity and efficiency in manufacturing processes by providing a basis for critical decision-making and system optimization [32]. The use of DTs to emulate products has become essential to the modern manufacturing environment. For instance, precise 3D CAD modelling, physical assets analysis, and performance optimization of a product's features and capabilities are made possible by the application of DTs in product design and development.

Early in the design phase, these digital replicas are essential for assessing various product scenarios and helping to make well-informed decisions [26]. Moreover, the use of DTs in product design helps in responding to changing consumer demands and world economic conditions. Innovation in manufacturing practices has been driven by consumer demands for customized, high-quality products with shorter time-to-market cycles, which DTs effectively support [25], [33]. Throughout the design and monitoring phases, these intelligent digital representations are used for a variety of tasks. Simulating, analyzing, and optimizing various equipment, procedures, and production lines as a whole is made possible by them. This novel strategy increases design quality, shortens the time needed for development, and makes sure that production lines run as efficiently as possible. In this thesis, we explore the deep influence that DTs have on the manufacturing environment, highlighting how they influence the processes involved in product design and development. We investigate the forces driving this shift, which are based on sustainability, shifting global economic dynamics, and the need for customized products. We hope to highlight the DT's role in today's automotive environment by closely examining how they are used in product design and the production phase through real case studies.

The continuous task is to determine whether digital technologies—previously employed in trial projects—can be brought on board to facilitate increasingly intricate and inventive orders in the context of the car manufacturing industry. This work attempts to identify instruments that can support various professional positions in response to these objectives by analyzing the particular requirements of the sector. The requirements can be divided into two primary categories: the process layer and the product layer. Following a thorough examination of the digital technologies that are now accessible, the goal of this study is to identify the precise business activities where these technologies may be used most efficiently.

1.3 Research Objectives and Thesis Structure

Digitalization has become the prevailing paradigm in innovative industrial sectors such as the automotive, studies due to its capacity to capture interactions among interdependent decision-making challenges. The thesis is organized into two extensive sections, each of which discusses various aspects of integrating digital technology into complex manufacturing systems.

Part 1 focuses on using digital technologies to improve manufacturing line designs. Based on related research, **Chapter** 2 ("Virtual Design for the Process Digitalization of Complex Manufacturing Lines") offers a basic understanding of the topic and shows a first image of the digital technologies implementation in a manufacturing process. This chapter helps the reader to have an overview of the technologies studied and helps to understand how each of them could be used in a project timeline. It then explores the role that virtual design plays in the digitalization process and uses the virtual design of a Screwing Station as an example to illustrate these ideas in a practical setting showing the advantage obtained.

While it focuses only on ergonomics enhancement, **Chapter** 3 ("Virtual Golden Zone for the Ergonomics Enhancement of Complex Manufacturing Lines") introduces the idea of the Virtual Golden Zone methodology and provides an example of it through a case study involving the ergonomics evaluation of an operator manufacturing station.

Chapter 4 ("Virtual Reality for the Virtual Commissioning of Complex Manufacturing Lines") examines the use of VR technologies through a VR approach to support the design phase and presents a case study that shows how an E-axle assembly line was virtually commissioned.

Part 2 of the thesis is devoted to using digital technologies to improve and optimize manufacturing line operations. **Chapter** 5 ("Process Simulation for the Sustainability and Efficiency Optimization of Complex Manufacturing Lines") deals with the efficiency and sustainability optimization at AGVs: in particular, a suggested simulation analysis designed to maximize AGV performance on production lines is presented, showing an analysis regarding the number of AGVs and the charging area number defined for the design of an E-axle assembly line.

Subsequently, **Chapter 6** ("Hierarchical DT for the Performance Optimization of Complex Manufacturing Lines") shows forth a hierarchical DT strategy and demonstrates how to use it to improve the efficiency of assembly lines including the logistics part.

Finally, **Chapter 7** presents findings and conclusions, highlighting the research's major discoveries and contributions to the field.

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Part 1: Enhancing the Design of Manufacturing Lines through Digital Technologies

Chapter 2

Virtual Design for the Process Digitalization of Complex Manufacturing Lines

Abstract

Many industrial businesses have adopted new technologies in anticipation of Industry 4.0, or the fourth industrial revolution, in recent years. This global revolution in manufacturing practices connects the virtual and physical worlds, and it is driven by a set of powerful digitalization tools. Digitalization tools play a crucial role in allowing companies to decrease design and production costs, as well as accelerate the product development process. Focusing on a compelling real-world case study involving an Italian automotive company, this chapter focuses on the use of digital technologies in designing complex manufacturing systems. It highlights the myriad of benefits that can be obtained by outshining traditional methods. Digitalization tools have aided in the design of intricate manufacturing systems that demand advanced automation to optimize the arrangement, workflow, and equipment configuration within a manufacturing facility or production line. After examining the features of the virtual approach employed by the considered company, the virtual commissioning of a screwing station for an electric axle assembly line is analyzed in detail to show the efficiency and effectiveness of digitalization.

Contents

2.1 Introduction

In 2011, the German government introduced Industry 4.0, aiming to connect physical and virtual worlds for improved productivity and efficiency [1]. In industry, the main technology challenge consists in leading to a faster, better, and cheaper new product development process than traditional approaches. Moreover, in the automotive sector, the importance of environmental sustainability and the consequent electrification are radically transforming the way of working due to technology, consumer demand, and business opportunities [2]. Hence, traditional design and development processes must be redefined to meet these new challenges and requirements [3]. However, current design and development processes do not yet respond to these challenges and need [4].

In this context, Industry 4.0 is reshaping manufacturing with digitalized products and smart logistics [5]. Engineering procedures have undergone a transformation through the utilization of Digital Twins (DT), Discrete-event Simulations, Virtual Reality (VR), and Augmented Reality

(AR). These virtual tools facilitate the design and integration of collaborative systems, merging the physical and virtual worlds. They enable interactive co-working environments and enhance efficiency throughout the development process [6].

Concerning a real industrial case study of an Italian automotive company, this chapter is focused on highlighting the benefits of using digital technologies with respect to traditional methods in the design of complex manufacturing systems. First, this work describes the digital technologies used for the design of an electric axle manufacturing line, to explain the peculiarities of a virtual approach: virtual tools such as DT, VR, and AR indeed allow designers to detect potential issues in the early phase of the design process and reduce the testing and integration time during the developmental phase. Moreover, these innovative tools enable designers to easily share project details with customers, suppliers, and partners, thus facilitating project reviews. As a further outcome, this work shows the Virtual Commissioning (VC) of a screwing station as a real industrial application, analyzing in detail the advantages of digital technologies: benefits in terms of time and costs are evaluated to show the efficiency and effectiveness of digitalization. Virtual tools are instrumental in identifying design issues early on in the process, including during VC. This helps minimize testing and integration time, resulting in streamlined development processes. By leveraging these tools, companies can enhance efficiency and optimize the overall productivity of manufacturing systems.

It is crucial to emphasize that the primary motivation behind these studies is to shorten project development timelines. This is accomplished by reducing the need for actual machine modifications, which often appear only after the machines have been assembled. Proactive digital technologies are pivotal in this revolutionary path towards increased manufacturing productivity and cost-efficiency because of their ability to identify and address problems at an early stage of design and development. Incorporating VR, AR, digital twins, and simulations into engineering not only expedites advancement but also promotes a paradigm change in how industries handle design and development in the context of Industry 4.0.

The remainder of this chapter is structured as follows. Section 2.2 illustrates the state of the art on the use of digital technologies in the industrial setting, positioning the work in the related literature on Digital Tools used in manufacturing systems. Section 2.3 presents the virtual design technologies and processes adopted by an Italian automotive company with reference to the development of a complex production line. The application of the proposed approach to the VC of a specific station is presented and discussed in Section 2.4. Finally, concluding remarks are reported in Section 2.5.

2.2 Related Works

In today's manufacturing landscape, the rise of digitalization is nothing short of a revolution. It ushers in a new era where traditional design and development processes are being reshaped and redefined [7]. These changes are driven by a combination of factors, including advances in technology, shifting consumer demands, and emerging business opportunities.

At the heart of this transformation is Industry 4.0, a visionary concept that originated in Germany in 2011 [8]. Its core objective is to bridge the gap between the physical and virtual worlds to enhance productivity and efficiency in industrial processes. Industry 4.0 comprises a set of key pillars, such as the Industrial Internet of Things (IIoT), Cloud Computing, Big Data, Simulation, Augmented Reality, Additive Manufacturing, Integration of Horizontal and Vertical Systems, Autonomous Robots, and Cybersecurity [9]. This collaborative framework represents the foundation of the digital revolution.

One of the critical outcomes of this digital transformation is the concept of the Digital Twin (DT). The DT is essentially a digital replica of real manufacturing systems, capable of representing complex physical assets and intricate system interconnections [10]. It's a versatile tool for professionals across various industrial sectors, supporting activities throughout the product lifecycle.

Different application domains have used DT technology in manufacturing with different purposes [11], [12]. For instance, DT has been employed to manage the flexibility of modern manufacturing systems [13]. On the one hand, researchers have focused on defining DT architectures without taking into account the business benefit and added value of using DT technology during the process life-cycle. For instance, Kuts et al. [14] developed an immersive robotics environment that integrates DT and Virtual Reality (VR). Kousi et al. [15] proposed a DT architecture based on the Robot Operating Environment (ROS) simulation software. On the other hand, different use cases have been developed, showing the benefits of DT in robotics. Such as Pairet et al. [16] which utilized DT simulators for training and testing human-robot collaboration scenarios in offshore platforms.

Another notable aspect of Industry 4.0 is the ability to utilize digital Virtual Reality (VR) tools to detect issues early in the design phase [17]. The role of VR in simulating real-world environments is revealed by recent studies in the scientific literature, making it crucial for design reviews during the conceptual development phase [4]. VR provides a cost-effective method for making design modifications early in a project, which enhances design reviews and collaboration [18]. Improving workflow integration for factory planning requires the delivery of realistic walkthroughs in digital factory models. Moreover, several methods and tools have been created to evaluate the ergonomics-related activities of workers in industrial settings and their exposure to risk factors [19]. Additionally, the design phase is one of the crucial phases of the manufacturing system development process analyzed in literature [20], and VR is used extensively in the literature to enhance design for this reason. Bordegoni and Caruso underscore the importance of verifying design issues before assembly and during customer reviews, [21].

Discrete-event simulation, also known as process DT, is another tool that defines digitalization [22]. Simulation can be defined as an experimental process that uses a digital representation to replicate the dynamics of a real-world system or process over time. By analyzing the behaviour of the modelled systems or processes, simulation aids in the estimation and understanding of the system or process under study [23]. It is essential for making decisions about how to operate systems, use resources, optimize control mechanisms, and communicate in real-time. The scientific literature emphasizes how Process Digital Twins can help predict outcomes, streamline procedures, and increase overall equipment effectiveness. In industries where improving Overall Equipment Effectiveness (OEE) and optimizing workflows are crucial, this technology is especially important [24]. Additionally, simulation tools can help with real-time decision-making about optimal system operation and effective resource exploitation, as well as optimize control mechanisms [25].

However, the literature lacks studies on the use of digital technologies for supporting the supervision activity of the operator in the context of flexible manufacturing and does not consider applications used in real industrial projects for everyday life.

This chapter describes how and when to implement digital technologies in a business process in order to obtain important advantages. Moreover, shows that digital technologies are able to reduce issues during the assembly phase and facilitate the sharing of complex three-dimensional (3D) information with stakeholders, including customers and suppliers. This innovative approach is particularly valuable in industries like automotive manufacturing.

2.3 The Role of Virtual Design in the Digitalization Process

The case study analyzed in this chapter was developed in collaboration with a leading Italian automotive company in the European market. It focuses on the design of an assembly line for an electric axle of electric trucks. Electrification is indeed a new challenge for the automotive industry since the development of electric vehicle components involves various factors, such as different weights and sizes, vision-guided robots, automated part-feeding systems, and flexible machines. Electrification also requires a redefinition of design expertise, software, hardware, equipment, and services [26].

2.3.1 The Proposed Digital Technologies

The first step of an analysis conducted to define the design of an assembly line cannot disregard the requirements demanded by the customer. Meeting performance and cycle time targets, and effectively utilizing production resources, requires accurate management of logistics and production flows. In this regard, digital tools are often used to respond quickly and efficiently to the demands of the market. They provide a comprehensive overview of processes, enable testing of different scenarios, and identify errors early in the design process [27]. The implementation of these digital solutions is crucial to guaranteeing that the assembly line smoothly conforms to the market dynamics and customer expectations. In an ever-changing industrial landscape, it enables organizations to optimize production processes, improve resource utilization, and fine-tune their design approach—all of which lead to the eventual development of a manufacturing environment that is more responsive and agile [28].

In this chapter, the main supporting technologies of virtual design adopted by the company are identified and categorized into areas related to product and process development and product management. These technologies include the *Process DT*, *Product DT*, *VR for concept design and design review*, and *AR*.

- *Process Digital Twin* - It is a sophisticated digital replica of a physical manufacturing process or system. It serves as a dynamic model, capable of emulating the behaviour, operation, and performance of the real-world process. By harnessing data and simulation, it can identify bottlenecks, inefficiencies, and areas for improvement within the production process, and optimize Key Performance Indicators (KPIs) such as Overall Equipment Effectiveness (OEE). [29], [30].
- *Product Digital Twin* - It is a virtual replica of a physical product created that mirrors its characteristics and behaviour, allowing real-time monitoring and analysis [31]. It helps optimize operations, improve efficiency, and identify potential problems before they occur by providing real-time insights into the behaviour and performance of the digital model.
- *Virtual Reality* - VR immerses users in a virtual environment, enabling interaction with digital models. It aids concept design by allowing 3D sketching and facilitates design review by visualizing the final product before construction. VR strengthens teamwork, encourages innovative design discussions, and advances the design process as a whole [18].
- *Augmented Reality* - AR tools enable an interactive experience that combines the real world with virtual information. They allow starting from a 3D model, to create experiences capable of providing assistance and training during the assembly phase of the line, thanks to immediate access to information [32]. Through the smooth integration of digital data with the actual workspace, AR enhances task execution, minimizes errors, and boosts operational efficiency.

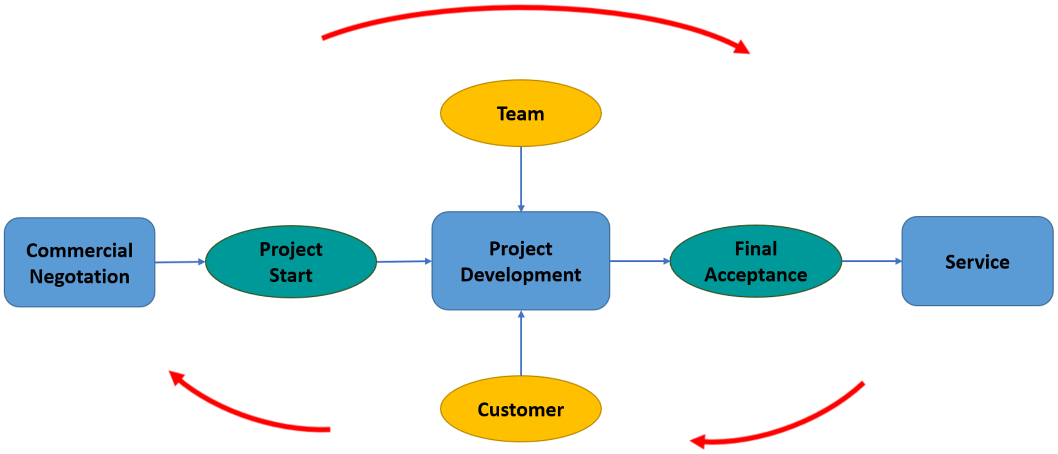

Figure 2.1: Project development process schema.

2.3.2 The Proposed Digital Process and the Comparison with the Traditional Approach

This section is focused on the comparison between the traditional commissioning process traditionally used by the company and the new VC process that incorporates digital technologies.

The manufacturing system development process begins with the commercial proposal and ends at the customer site (Fig. 2.1). The core component of this process is the product development phase, which involves multiple steps such as initial design and line assembly. Once assembly and testing are completed, the line is delivered to the customer, and the after-sales phase begins. A Gantt chart is an essential project management tool, visually representing the project schedule and indicating task start and end dates. Task definition, duration estimation, resource allocation, and material procurement are just a few of the many factors that are carefully taken into account in order to guarantee project success while also striking a sensible balance between the right amount of detail and expert knowledge. The transformative potential of venture capital and digital technologies in streamlining the manufacturing system development process and making it more effective, flexible, and customer-focused is highlighted by this comparative evaluation.

Fig. 2.2a illustrates the product development phases within the *traditional approach*. The design process begins with a preliminary study to identify the system architecture, followed by developing a preliminary 3D CAD model known as the 3D sketch phase. The "concept review" milestone marks the approval of the design draft by the team. Then, a detailed mechanical and electrical design phase begins, leading to the second milestone called “design release". Designers then finalize their tasks and generate mechanical and electrical bills of materials, signalling the "procurement start" milestone. Software developers start their work between the procurement phase and the delivery of materials needed for the assembly, known as the "offline coding" phase. Once assembly is completed, the "online debug" phase can begin, allowing for timely testing of the coded software and finalizing the assembly. However, It should be noted that problems that arise during assembly and review—including design modifications—often cause delays in the online debugging phase. New technologies are useful tools that can improve the effectiveness

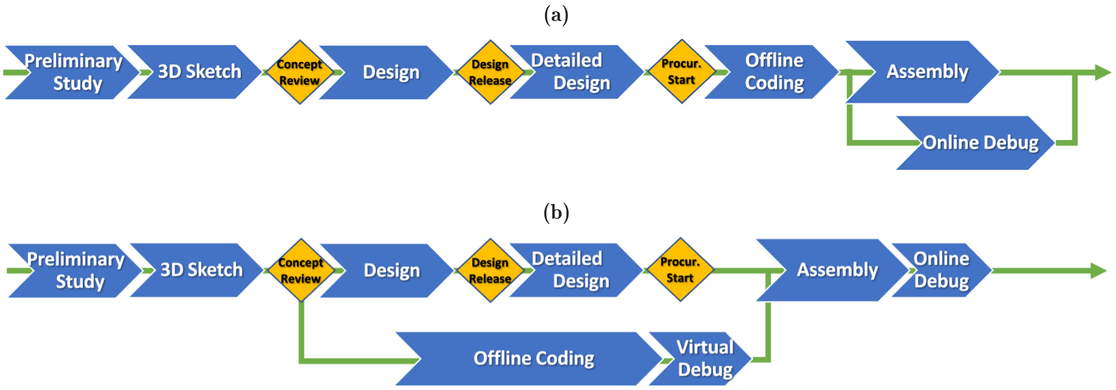

Figure 2.2: Scheme of product development phases using the traditional (a) and the digital (b) approach.

of online debugging and offline coding tasks. By simplifying the product development process and reducing the impact of typical obstacles and bottlenecks found in the conventional approach, these technologies act as transformative tools.

Fig. 2.2b illustrates the product development phases in the *digital approach*, where activities are scheduled in advance using digital technologies. Design and offline coding can occur simultaneously, leading to a mechatronics design phase for each machine. In our case study, mechatronics design is conducted on the NX-MCD Siemens platform [33], enabling the creation of a dynamic 3D model that encompasses physical and kinematic features. Integrated simulation facilitates direct testing of these properties, enabling the identification of design weaknesses before actual production.

To develop an accurate Digital Twin (DT), it is necessary to integrate the functional model of the electric system, equipment, Programmable Logic Controller (PLC), and Human-Machine Interface (HMI) into the mechatronic design using NX-MCD. This integration ensures a comprehensive representation of the system, enabling the creation of a reliable and authentic DT. Validation and testing of the DT's performance, control logic, and integration with physical components can be done in two ways: using an emulated PLC (Software in the Loop) or a real PLC (Hardware in the Loop). Therefore, by establishing connections between the appropriate hardware and software interfaces, this approach facilitates advanced virtual debugging. Consequently, the offline coding phase is expedited, resulting in reduced online debugging time. Virtualization enables early testing and understanding of system behaviour (Fig. 2.2b), detecting changes that would typically arise only after the assembly stage in the traditional approach (Fig. 2.2a). Moreover, modelling the virtual machine is a crucial phase in the digital process because the virtual debugging process requires a model that is detailed at a high level for it to be effective and a real DT. However, this level of detail can have a significant impact on the overall development time, Gantt chart, and process complexity. The first step of an analysis conducted to define the design of an assembly line cannot disregard the requirements demanded by the customer. Meeting performance and cycle time targets, and effectively utilizing production resources, requires accurate management of logistics and production flows. In this regard, simulations are often used to respond quickly and efficiently to the demands of the market. They provide a comprehensive overview of processes, enable testing of different scenarios, and identify errors early in the design process [34]. In this regard, the case study employed Tecnomatix Plant Simulation [35], [36], a discrete event simulation software, to simulate and analyze the performance of the complete production line. This enabled comprehensive evaluation and optimization by assessing cycle times and the quantity of produced parts. The design phase utilized VR tools, such as Unreal Engine [37], to conduct ergonomic analyses and identify critical issues regarding object and work tool

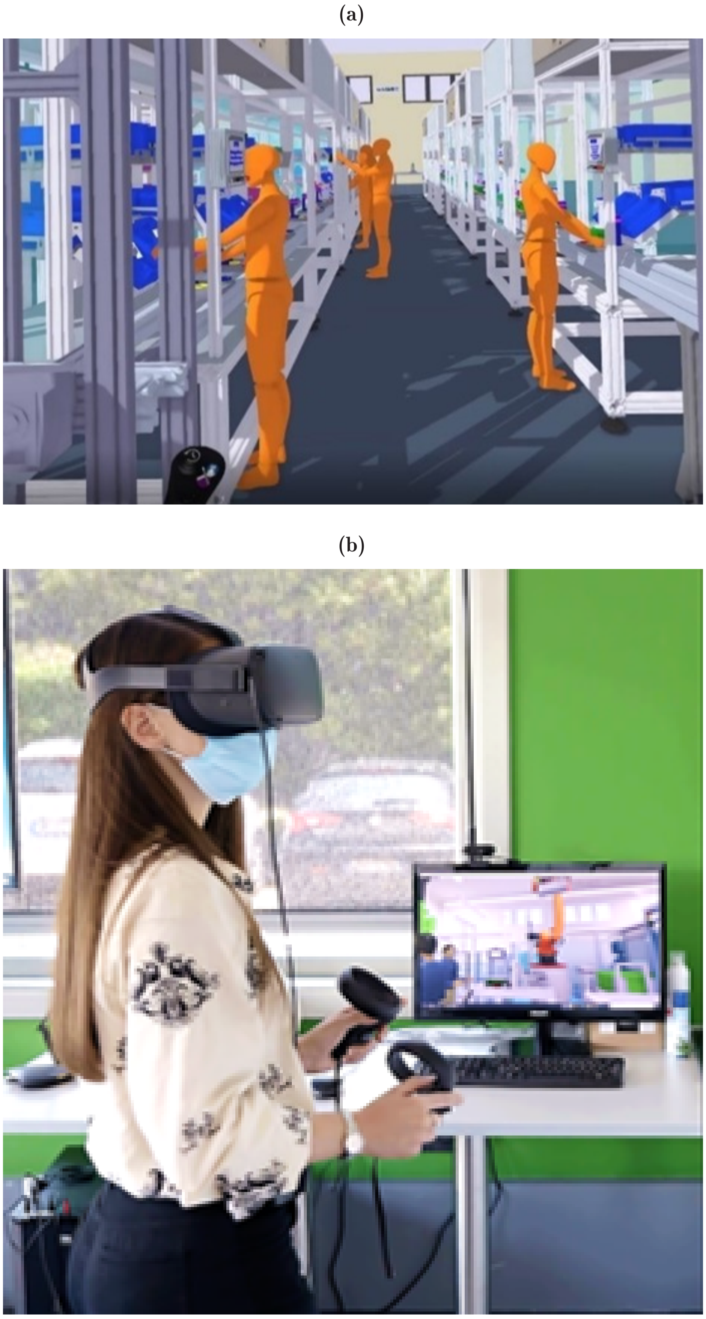

Figure 2.3: Example of VR navigable virtualization of the project developed for the ergonomic assessment during the design phase in a real manufacturing line (a) Example of navigating through virtual representations of machines using the VR device (b).

placement. These studies offer designers a realistic view of the model, reducing costs associated with resolving ergonomic issues typically encountered after machine installation (Fig. 2.3). During the assembly phase, AR comes into play with special customized applications, serving as a valuable

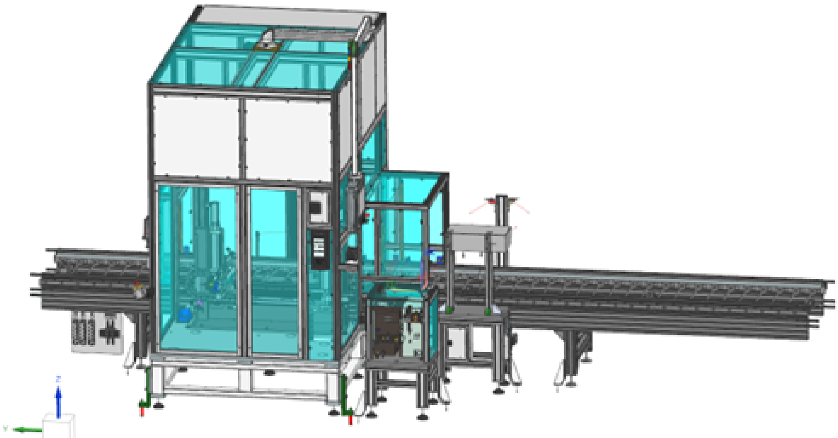

Figure 2.4: Product Digital Twin of a screwing station included in the case study e-axle assembly: excerpt from the NX-MCD platform [33].

support tool for assembly, training, and immediate access to interactive documents created using the Vuforia PTC (Parametric Technology Corporation) platform [38].

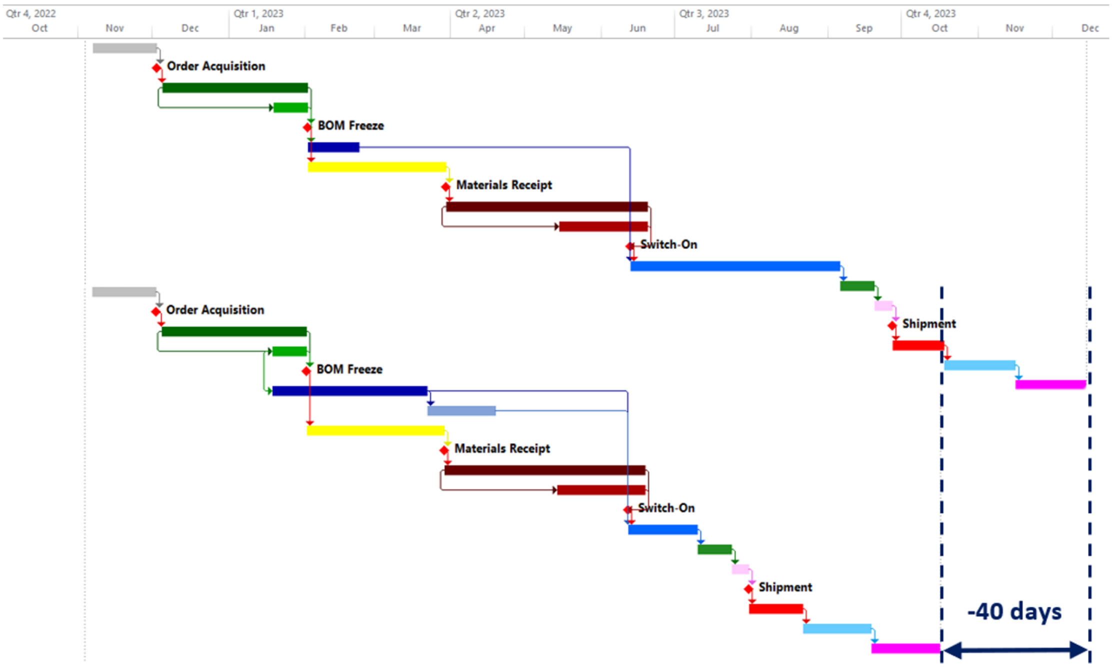

Figure 2.5: Gantt diagram of the analyzed station using the traditional (top) and the digital (down) design approach.

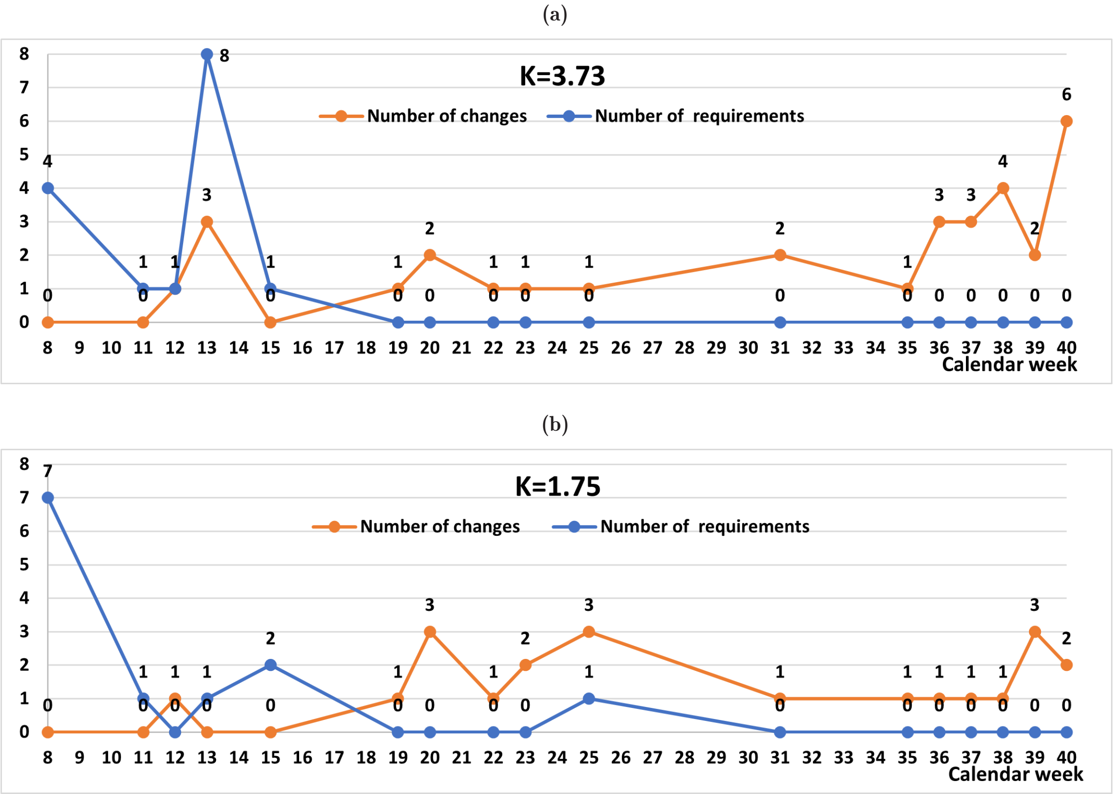

Figure 2.6: K-factor chart obtained on the QlikSense platform [39] using the traditional (a) and the digital (b) approach.

2.4 Case study: the Virtual Design of a Screwing Station

As an application of the proposed virtual design adopted for the electric axle assembly line, this section is focused on the VC of a screwing station. To highlight the benefits of the digital approach, two comparable machines with identical subfunctions have been developed, one based on the traditional method and the other using the digital system (shown in Fig. 2.4). Both machines under consideration feature an automated screwing station with a pallet lifting and clamping unit, an XYZ handling gantry comprising three electric axes, and an electric screwdriver mounted on the gantry. The final goal is to minimize time and costs without compromising quality. A detailed analysis reveals that the implementation of digital technologies is decisive in meeting the customer's requirements and successfully executing the project.

The entire lifecycle of the job order is analyzed by comparing the Gantt charts of the traditional and digital approaches, as established through the project schedule. As shown in Fig. 2.5, there is a significant reduction in the completion time, due to the early start and parallelization of the debugging and final tuning activities in the digital approach. The software and hardware designed are tested in a virtual environment, allowing for the identification of errors before purchasing materials and bringing forward the modification process. Vice versa, in the traditional process, modifications can only be made after the assembly is complete by verifying the integration and overall operation of multiple pieces of equipment together. In contrast, the digital approach allows for the immediate verification of integration as a whole before the assembly phase, enabling the early start of a possible modification process in the design stages. This results in a gain of approximately 40 days compared to the expected final testing date at the customer's site.

By comparing the changes applied to the two machines during the assembly phase, it turns out that the number of changes made in the digital approach is significantly lower than those made in the traditional approach. To track the number of changes, the QlikSense enterprise portal [39] was used, which registers the number of changes and the time they were made. The K-factor represents the ratio between the number of changes made on the post-assembly machine and the number of requirements initially issued at the procurement. The number of requirements differs between the stations due to variations in the detailed functions of the machines, although they share the identical principal function, which is the inside screwing station. Each modification incurs an additional cost and thus a deviation from the initial idea in terms of material cost, labour hours spent on the project, process quality, and delivery time. As shown in Fig. 2.6, the K-factors obtained using the traditional and the digital approach are respectively 3.73 and 1.75, indicating that VC allows saving about one change with respect to the traditional approach, while achieving higher project accuracy.

2.5 Conclusion

The case study presented in this chapter –as an application of digitization to the design and development phases of complex manufacturing systems– highlights the significant advantages of using Virtual Commissioning (VC) technologies with respect to traditional approaches. First, the results show that using digital technologies such as VC during the project development process leads to a substantial reduction in overall job order time by about 12%. Second, the use of digital tools allows about a 30% reduction in the number of changes made during assembly compared to the traditional approach.

While the findings are positive, this study has limitations: detailed model development requires expertise, time, and expert resources. Integrating digital tools with plant systems and ensuring data flow and interoperability is challenging. Future work will be devoted to integrating additional digital tools to enhance further product lifecycle phases, e.g., maintenance. For instance, the integration of Internet of Things technologies with Augmented Reality tools is expected to play a crucial role in predictive maintenance, by helping to identify in advance equipment failures and hence preventing costly downtime.

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Chapter 3

Virtual Golden Zone for the Ergonomics Enhancement of Complex Manufacturing Lines

Abstract

For the sake of being competitive in an ever-changing market, industrial companies need a redefinition of traditional design and integration of parts, equipment, and services such a redefinition allows effectively addressing the interaction between machines and operators, particularly in the area of complex production lines. In this context, enhancing ergonomics is crucial to reduce fatigue and stress of workers and increase work-place efficiency and comfort. Moreover, identifying ergonomic flaws in three-dimensional human-machine design problems (e.g., body posture, reach, visibility) at an early stage of the engineering process allows to prevent these issues at a low cost. *Virtual reality* (VR) is emerging as a powerful tool to improve ergonomic assessment in the design of complex production lines. However, VR is not yet a well-consolidated practice for industrial companies, and the state-of-the-art applications are limited to simplified, isolated, and customized experiments. This work introduces an innovative approach centred around the concept and the use of a *virtual golden zone* (VGZ) as a standard and efficient VR method for the ergonomic analysis and optimization of operator activities in manual manufacturing stations. The research underscores the resulting effectiveness and benefits are highlighted through the application of the approach to a real industrial case study. Finally, the outcomes of a usability questionnaire, compiled by the professionals involved in the VR reviews, are presented to comprehensively evaluate the usability of the VGZ methodology in the design process of complex production lines.

Contents

3.1 Introduction

Nowadays, the concept of *Industry 4.0* is leading to the so-called smart factory, where industrial automation is combined with new digital technologies to improve working conditions and foster the collaboration between all components of production: business models [1], design and development environments [2], manufacturing systems [3], equipment and machines [4], supply chain [5], logistics [6], and services [7]. This transformative wave has unleashed a wealth of opportunities that hold the promise of revolutionizing the manufacturing landscape. It allows the reduction of operation cycle times, the swift delivery of goods, accelerated time to market, and most notably, a substantial enhancement of worker safety and ergonomics [8].

Virtual reality (VR) is one of the key technologies that is boosting the digital transformation [9], especially since it is contributing to effectively addressing the interaction between machines and operators in the area of complex production lines [10], [11]. In fact, VR is emerging as a powerful tool to optimize the product design process, which enables users to explore multiple facets of a product before committing to any form of physical production [12]. Moreover, VR tools can integrate different technologies that allow users to interact with the virtual environment representing the real one in a multi-sensory way, such as space and body perception [13]. Nevertheless, there is a lack of understanding of how companies implement VR technologies, especially with regard to ergonomic assessment. In fact, VR is not a well-consolidated practice for industrial companies yet: no standard implementation exists in the state-of-the-art, whilst practical applications only aim at conducting simplified, isolated, and customized experiments, such as the comparison with computer-aided design (CAD) software and the implementation of complex ergonomic methodology. Usually, the classic review approach to the design issues and critical phases is performed directly on a PC with CAD software support, which is not always able to bring out the defects on a two-dimensional (2D) screen, thus creating the risk of losing dimension and scales, particularly important in the ergonomic evaluation [14].

Differently from the related literature, this work is focused on the use of VR as a tool supporting the CAD software, for the design of complex production lines, discussing the benefits offered to the professionals for intuitive ergonomic evaluation (see Fig. 3.5). In particular, a methodology based on the novel concept of *virtual golden zone* (VGZ) is introduced and applied in reference to a real company case study, highlighting the advantages of quickly identifying all the ergonomic areas for the operator activities by a three-dimensional (3D) model in the VR environment. The presented case study is focused on the design of manual manufacturing machines for a complex production line, showing the features of the VR immersive interaction and space perception in organizing the operator tasks, improving worker safety, and reducing fatigue and stress. Finally, this work investigates the applicability of the VGZ methodology in virtual reviews that are incorporated into the development process of the organization, in addition to these observations. A System Usability Scale (SUS) questionnaire created by experts actively involved in the design process is used to conduct this assessment. This thorough investigation highlights the revolutionary possibilities of virtual reality (VR) in the field of ergonomic assessments and complex manufacturing system product design. Professionals can streamline processes, improve ergonomic considerations, and ultimately create a more productive and ergonomic manufacturing environment by incorporating VR into the design process.

The chapter is structured as follows. The chapter is structured as follows. Section 3.2 presents the related literature and its positioning within it. Section 3.3 present the Virtual Golden Zone Methodology. The application of the VGZ methodology to the real case study and the evaluation of the VGZ usability analyzed through the SUS questionnaire results are illustrated in Section 3.4. Finally, some concluding remarks are reported in Section 3.5.

3.2 Related Works

The usefulness of VR for the design of complex production lines has been discussed in various studies [15]. An in this regard, Wolfartsberg [16] describes the development and evaluation of a VR-based tool to support the engineering design review. In-depth design assessment is the basis of the design review activities [12], [17], since experts from different disciplines have to discuss and concur on a design solution while exchanging project information. Indeed, the design phase requires the communication between different departments with different knowledge, co-engineering work with customers, and identification of collaborative needs [18]. The added value of this approach relies in sharing remotly the work with a teamwork including geographically distant participants. Moreover, the VR technology is considered to be useful in the design phase and in the CAD project integration due to the CAD software limitation in offering an interactive analysis with the implemented model.

In the design phase, the main VR advantage is the ability to anticipate eventual design issues before the actual system production starts. Practically, several companies investigate the use of VR for design flaws, styling reviews, and even mere walk-through applications. Traditionally, the assessment of specific aspects such as ergonomics are however carried out only once the physical system is realized when problems can be thus obviously recognized. Instead, VR tools allow us to identify incorrectly designed equipment and ensure the operation ergonomics before the first use. Moreover, completing the ergonomic assessment during the design stage allows problems to be solved at a low cost and without machine modifications [19]. For instance, Peng [20] applies the VR tools for ergonomics evaluation and verifies the reachability of door handles within a vehicle.

Various methods and tools have been developed to evaluate ergonomics-related worker activities in industrial contexts and their exposure to risk factors. The authors in [21] provide a detailed review and comparison analysis of the most commonly used methods for the ergonomic assessment such as the Rula (Rapid Upper Limb Assessment) and Ocra (Occupational Repetitive Action Tool) approaches. These methods have different features and consider different aspects such as posture and force. For the sake of enhancing their effectiveness, these methods can be integrated into VR tools. For instance, Haggag *et al.* [22] describe a framework combining the RULA method for the 3D motion analysis with the Kinect technology: the RULA is associated with a skeleton tracking system and integrated by computer processing. However, these methods are complex and require high time, cost, and effort to be implemented and set up in the design phase. Conversely, in the early phase of engineering the manufacturing industry aims at quickly integrating advanced technologies to improve quality, productivity, and effectiveness. In addition, there is no uniform and optimal method that represents and speeds up the ergonomic assessment using VR. The industrial practice consists of collecting the posture data through subjective observation or picture and video support.

From the above-discussed literature review, it emerges that an effective and efficient tool is needed to enable expert engineers to quickly check if the system design is compliant with the ergonomic requirements. To fill this gap, the contribution of this chapter lies in presenting an efficient and effective VR-based method to be used for the ergonomic evaluation of the production line in the design phase. A real case study shows the practical applicability and usability of the proposed method.

3.3 Virtual Reality Integration in an Industrial Case Study

In this section, we introduce a novel VR method for the ergonomic assessment to be conducted in the design of a complex production line, and we show its application to a real case study related to an automotive company specialising in custom automatic and manual manufacturing systems.

3.3.1 The Virtual Golden Zone Methodology

The proposed methodology aims at providing designers and engineers with an ergonomics assessment tool that imports and utilizes the *golden zone* principle in the VR environment. In particular, the method relies on checking the 3D design of production lines (including specific aspects such as the right equipment positioning) with respect to the 3D model of the volume within which the operator is able to ergonomically perform the given tasks. Such a model is denoted as

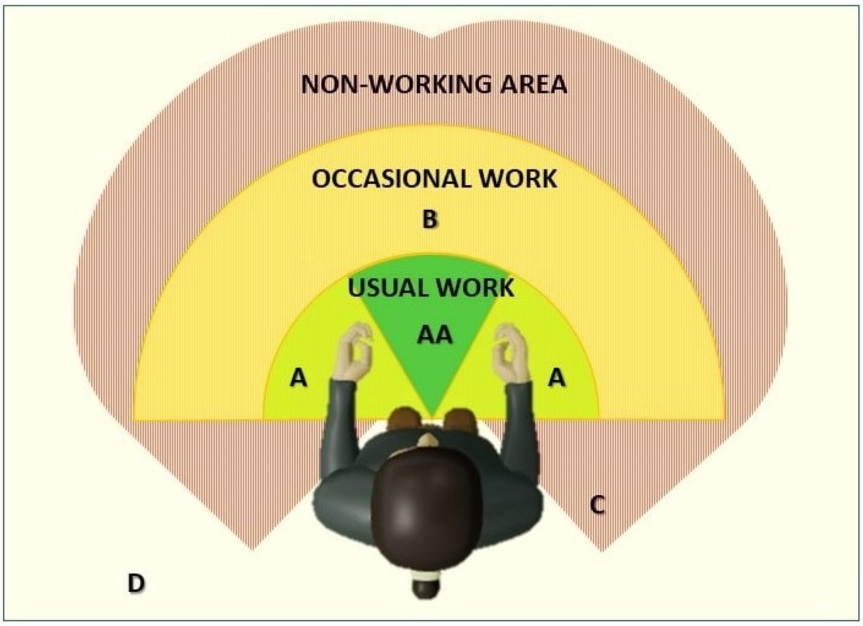

Figure 3.1: VGZ for the ergonomic evaluation of the design of a complex production line. The colored areas outbounding from the manikin represent the three VGZ sub-areas related to the operator activities: usual work (AA-A), occasional work (B), and non-working area (C-D).

the *virtual golden zone* (VGZ) and represents the optimal working and picking volume in reference to a specific area of the human body which ranges from the knee height to the shoulder elevation. The main concept in the use of the VGZ is eliminating the risk of long-term exertion injuries associated with manual material handling processes, thus minimizing the operator activities that require lifting, reaching, bending motions, and strain. The proposed VGZ is divided into three areas: non-working area, occasional work area, and usual work area (as shown in Fig. 3.1 and Fig. 3.2). Because each of these zones has a distinct ergonomic function, designers and engineers can evaluate and optimize operator activity ergonomics comprehensively. This modular strategy offers a methodical framework for assessing how tools, equipment, and workstations are arranged in the VR environment, making sure that they comply with ergonomic best practices and worker welfare. This methodology, taken as a whole, constitutes a qualitative advancement in the field of ergonomics assessment for complex manufacturing systems. Professionals can design and optimize production lines with a strong emphasis on operator comfort, safety, and productivity by integrating the VGZ model within the VR environment. As a result, a revolutionary strategy that improves the overall effectiveness and ergonomics of manufacturing operations while reducing ergonomic risks is achieved.

- **Non-working area (C-D)**: this is the external area where the picking can be done only by stretching a hand and where the operator can not perform the task. Moreover, two sub-areas are identified based on distance from the manufacturing station: sub-area C where the components can be picked by turning the torso, and sub-area D where the components can be picked by walking.
- **Occasional work area (B)**: this is the intermediate area where components can be picked by stretching the arms over the shoulders. It is advisable to use this area only for occasional

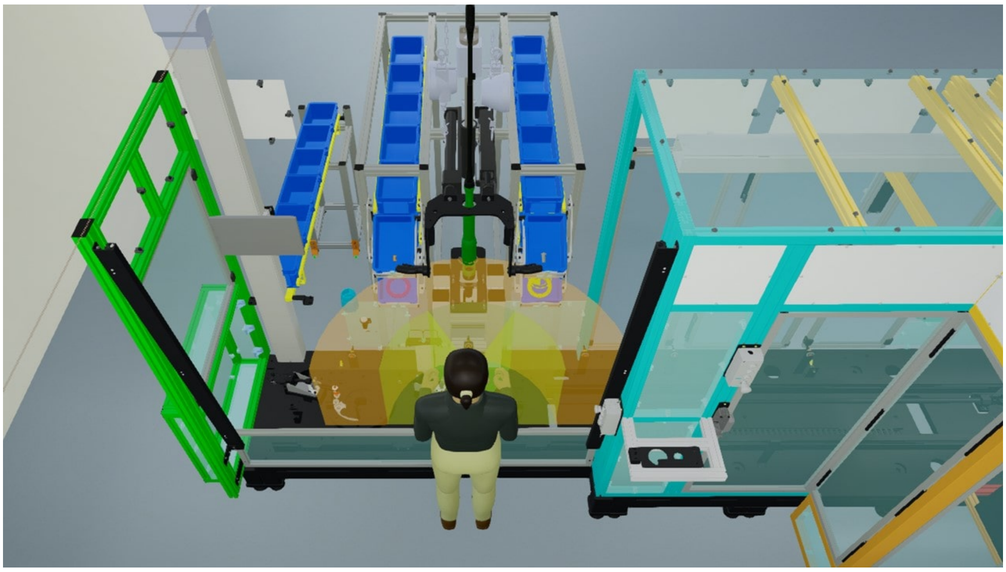

Figure 3.2: Top view of the VR model representing the manual manufacturing station with a woman manikin model and her relative VGZ using the Unreal Engine platform.

work and not to frequently place used tools, since the area is 6 times larger than the work area.

- **Usual work area (AA-A)**: This is the comfortable area where a task can be performed by the operator in the eyes field of view using both hands. It represents the optimal zone for the equipment positioning in order to handle components within the anatomical-physiological movement area. The usual work area is generally splitted into two parts: in sub-area AA all components are located nearby the station in the visual field of view and at a suitable working height; in sub-area A the components are arranged in an area 3 times larger than the work area and thus can be picked up by stretching arms and using both hands.

The size and positioning of the VGZ are different and configurable for each operator; hence, at least two different working scenarios must be considered, related to a woman and a man with a height of 1.65 and 1.75 meters, respectively. Primarily, the definition of working height is crucial to effectively address the interaction between operators and production lines. On the one hand, if the working height is too high, shoulders are often raised to compensate, thus leading to painful muscle contractions at the neck and back. On the other hand, if the working height is too low, the back is overwhelmed by the excess curvature of the trunk, thus giving rise to complaints of back pain (Fig. 3.2).

Comparing the presented approach with the related literature, we remark that manikin and *golden zone* (GZ) models are also used in CAD platforms during the design phase for a preliminary ergonomic assessment. However, CAD tools remain widely dedicated to a single user and do not allow collaborative design and immersive perception. Conversely, introducing the VGZ in a VR environment offers a novel tool of interaction and enables engineers to view projects from a 3D perspective able to consider all arms and body movements (e.g., stretching, flexion, elevation, abduction, and adduction). Thus, the VGZ provides a thorough understanding of the structure and layout of production lines work and allows users to mimic the workers' activities and evaluate the corresponding ergonomic performance.

3.3.2 The VR System Description

To implement the VGZ methodology in the VR environment of the considered manufacturing station, the Creo Parametric software database and Unreal Engine VR platform were employed (see Fig. 3.3), and the Oculus Quest headset was used as hardware. Specifically, the CAD models were built in the Creo Parametric environment, while the scene, trigger, and interaction rules between the user and the virtual environment were developed and coded in the Unreal Engine platform.

In order to define the VR model configuration and start the ergonomic evaluation, the interaction tasks were assigned to the Unreal Engine platform using the Blueprint options. The created VR environment was characterized by easy-to-learn interactions for various stakeholders. The goal was indeed to provide a quick and helpful tool for users with different job backgrounds in the automotive sector, without the need for any CAD or computer science knowledge.

The developed VR system was able to detect users' inputs and modify the virtual world accordingly while providing feedback with the Oculus controllers. Based on the requirement analysis, the system supported the standard features provided by Oculus Quest sensors and the Unreal Engine platform, such as looking, walking, touching, and grabbing.

Since physically walking in the VR room is as dangerous as moving blindfolded in the real world, the teleportation technique was implemented through default interaction prefabs by the Unreal Engine setup. To regulate users' navigation, the thumbstick on the controllers was used to activate the teleporter indicating the desired spot and choosing the direction with an arrow projected on the floor. This mechanism allows it to move quickly to the chosen point near the machine to be inspected. Moreover, by holding up or down the thumbstick, users walk using locomotion and reach the equipment and tools on board the machine. The locomotion interaction was implemented creating a Blueprint where location, rotation, and speed options were suitably imposed.

In addition, the grabbing interaction was developed, with and/or without gravity option, by assigning the collision shapes to the components. Tracking systems enable positioning and orienting physical objects over the allowed space in real-time. The general operation is as follows: as soon as the Oculus controller enters a construction group's collider, the VR tools trigger specific interactions and the system triggers a short vibration (using actuators integrated into the Oculus controller). Hence, users were able to grab equipment, tools, etc. Further interactions were customized, such as the visibility (input-output action) of the manikin and the VGZ in the required position. The visibility actions were linked to a pressed or released event via the nodes related to the "Set Visibility" function in the Blueprint; consequently, a node is fired every time any corresponding key is pressed/released on the Oculus Controller. Indeed, to manage the manikin body (both in the case of female and male) and VGZ visibility interaction, a Blueprint was created to associate the corresponding static meshes to the Oculus controller. Buttons "X" and "Y" on the left-hand controller respectively for female and male manikin's bodies were employed to activate the input and output of models in the VR environment, whilst button "A" on the right-hand controller was used to enable the VGZ (as shown in Fig. 3.4).

After the described VR environment set-up, a work team including designers, engineers, and managers conducted the design ergonomic evaluation. Reviews were organized to check the design of a manual manufacturing station of the production line performing different assembly tasks and characterized by large and customized structural dimensions. Initially, reviews were organized to evaluate the machines' structure dimensions. Subsequently, equipment and tools were imported into the VR environment to perform the ergonomic check regarding the worker activities (see Fig. 3.1). To achieve the correct ergonomics for the operator activities and the final version of the 3D model, 6 reviews which lasted from 1 to 2 hours were conducted with about 16 professionals

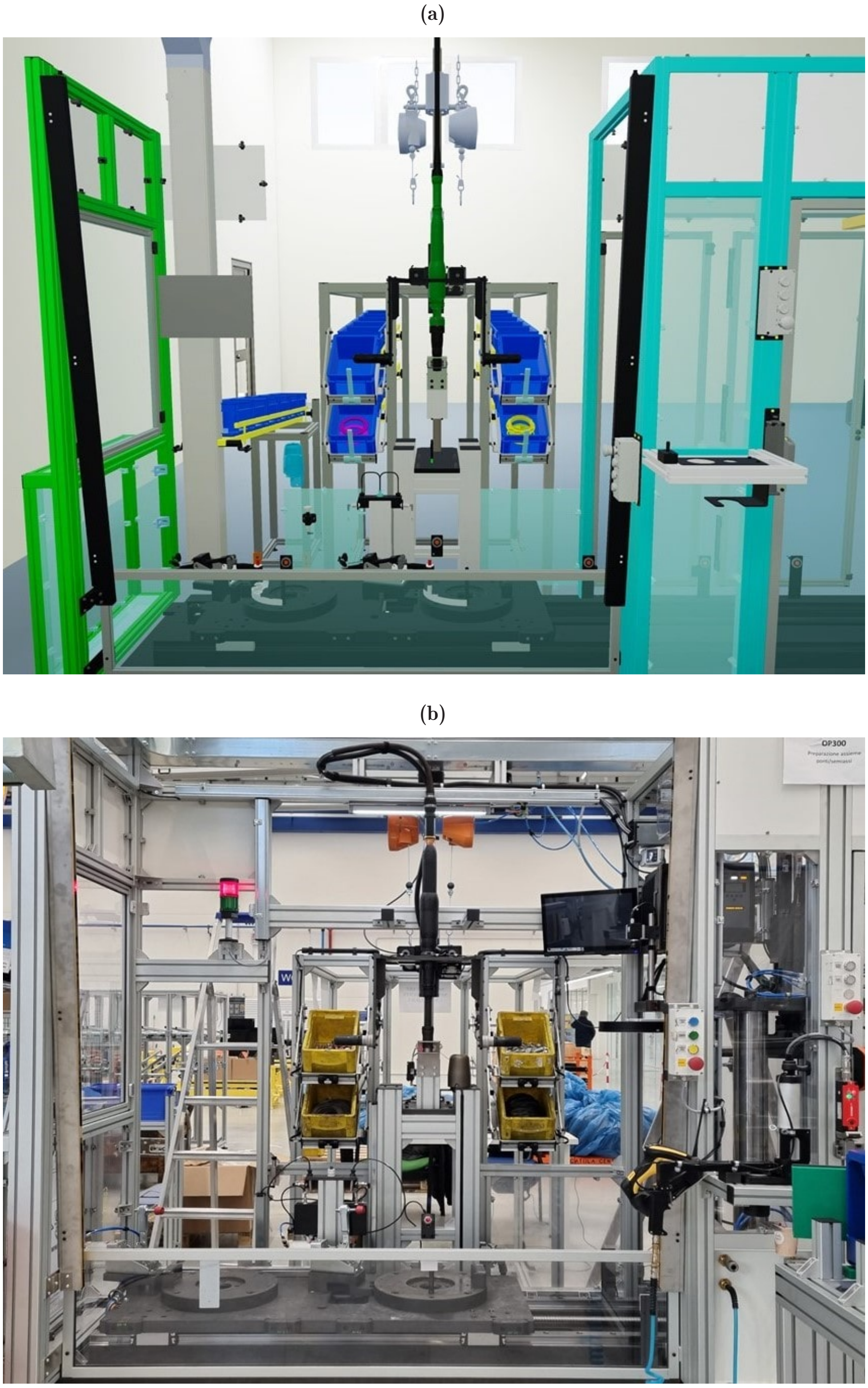

Figure 3.3: From VR to reality: versus the corresponding machine virtualized by using the Unreal Engine platform (a) the rear axle shaft machine assembled in the company plant (b).

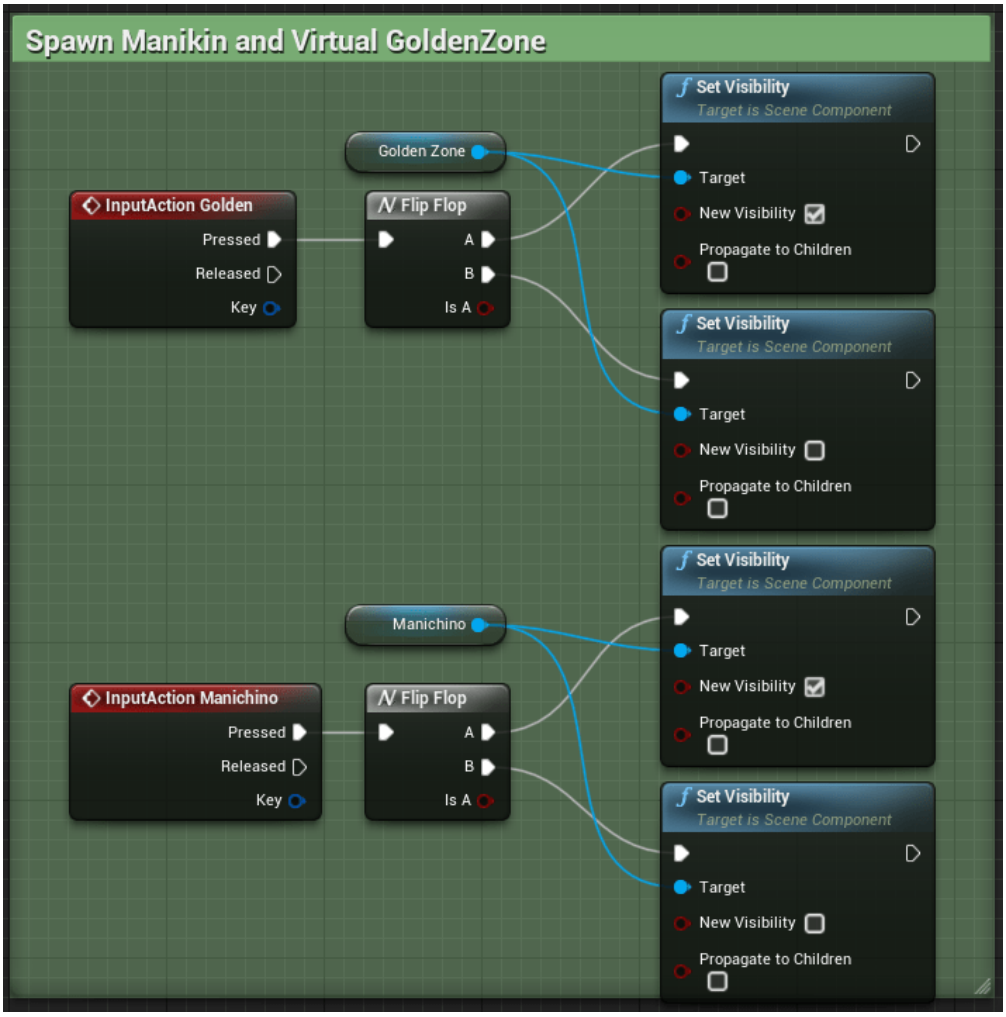

Figure 3.4: Customized Blueprint to activate the visibility action (input-output action) of the manikin and VGZ in the position required by the user via the nodes “set visibility".

(i.e. designers, engineers, managers). In fact, the professionals wearing the VR device first started checking the scene by analyzing the manikin body with the corresponding VGZ positioned near the workplace. Subsequently, they mimicked the operator activities; in particular, they tested the arms movement to verify if all machine and station components are in the correct position (see Fig. 3.5) and then they mimicked the operation cycle grabbing and moving the related objects as shown in Fig. 3.6. Each VR review was focused on a different level of the CAD project with the corresponding updates; in particular, the VR sessions were organized to address and solve the following ergonomics issues:

- the gravity rack height and orientation;
- the distance between the operator and boxes with the components;
- the arms movement for the picking of components;
- the height of the base of the structure;

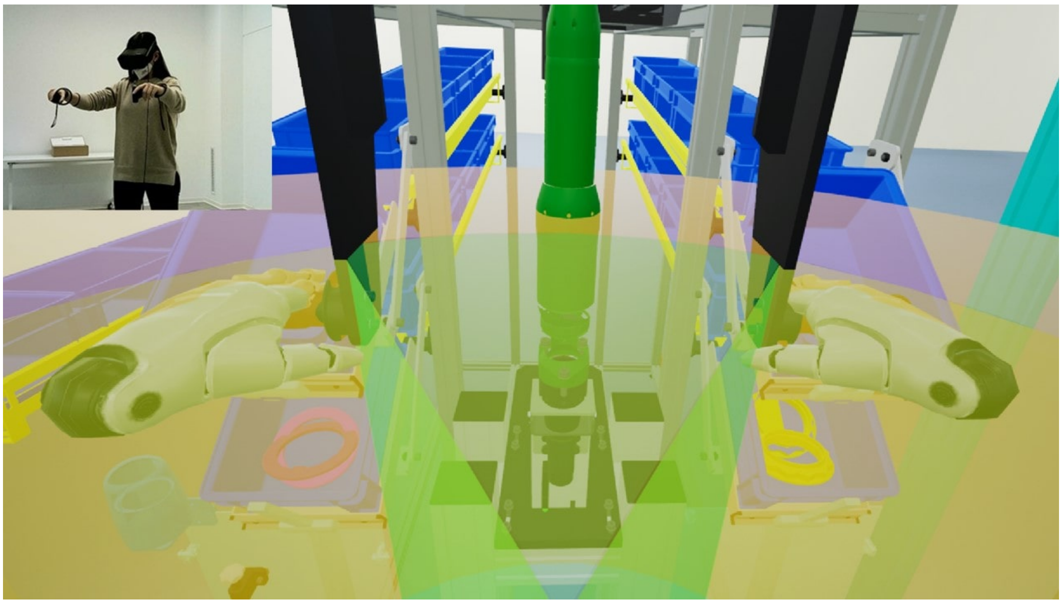

Figure 3.5: User's view of the manual manufacturing station: focus on gears and operator hands. The semi-transparent coloured volumes correspond to the *virtual golden zone.* The subplot in the left top corner shows the user experiencing the virtual scene by wearing a virtual reality head-mounted display and grasping the touch controllers.

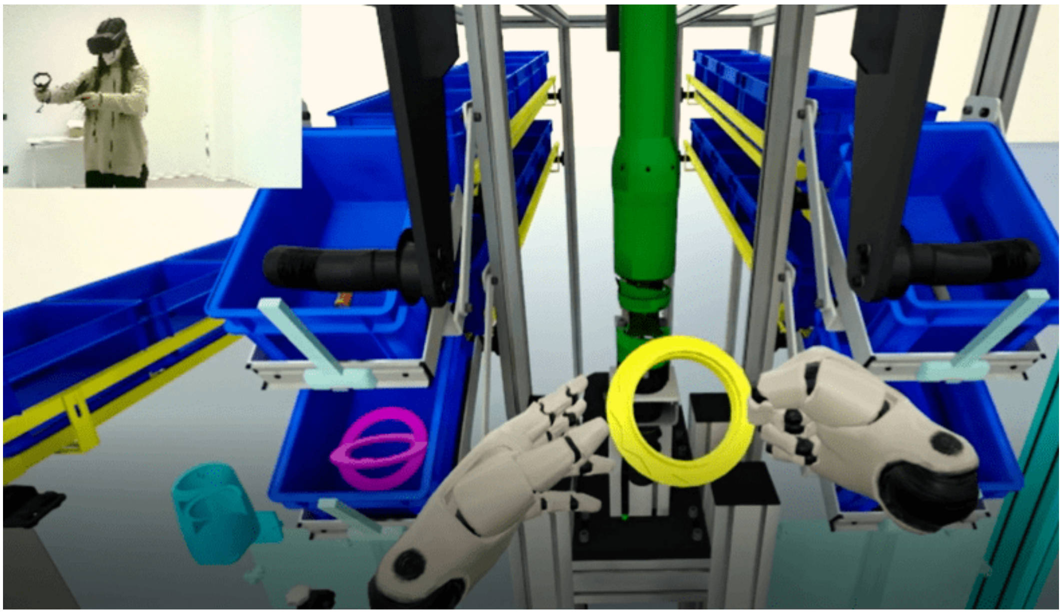

Figure 3.6: User's view of the manual manufacturing station: focus on grabbing interaction through the controllers.

- the sealants tool positioning/handling;
- the powered driver positioning/handling.

3.4 Case Study: The Ergonomics Evaluation of an Operator Manufacturing Station

For the sake of evaluating the usability of the VGZ methodology and highlighting its advantages with respect to traditional approaches (i.e., using the GZ in CAD software), the professionals involved in the ergonomic assessment of the presented case study were asked to fill out a questionnaire using Google Forms. Apart from personal information requests about gender, age, and company role, the core section of the questionnaire was focused on SUS (System Usability Scale) questions. In particular, both for the traditional GZ and VGZ method, the following 10 questions were included with 5 response options on a 5-point Likert scale (1 - Strongly disagree, 2 - Disagree, 3 - Neither agree nor disagree, 4 - Agree, and 5 - Strongly agree):

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

The questionnaire was completed by 16 participants, of an average age of 36 years ranging from 23 to 56 years old: the age mean and the standard deviation (SD) are 34.68 and SD=8.88, respectively. The gender division was as follows: 4 females, 12 males. First, the work team compiled the SUS questionnaire to evaluate the usability of the GZ in the CAD software. Second, the SUS questionnaire to evaluate the usability of the VGZ was compiled after the work team performed the VR reviews, without any debriefing or discussion about the employed methodology.

The result of the SUS questionnaire is a score represented by a number in the 0 to 100 range, which measures the overall usability of the system under analysis. Note that the score related to individual questions are not significant in a stand alone made. To calculate the final rating, each response to all questions is summed in accordance with the following procedure: for questions 1, 3, 5, 7, and 9, the score contribution is determined by subtracting one unit to the scale position; for questions 2, 4, 6, 8, and 10, the contribution is determined by subtracting the scale position to 5 unit; the sum of the above computed contributions is multiplied by 2.5 to obtain the overall SUS score in a scale out of 100. In addition, the SUS score can be converted into the so-called Acceptability Score, i.e., a scale of 5 categories: awful (score is less than 51), poor (score in the range between 51 and 67), good (the score is between 68 and 80.3), and excellent (score is greater than 80.3. As reported in Fig.6, the obtained SUS score for the GZ is 68.44 (with SD=10.61) corresponding to the “good" rating, whilst the SUS score for the VGZ is 81.25 (with SD=10.26) corresponding to the “excellent" rating.

As a consequence, the outcome is that the perceived usability of the VGZ was higher than the traditional GZ usability. On the one hand, the obtained result confirmed that the traditional GZ made a good contribution during the last years. On the other hand, the result highlights that the VGZ implementation enhances ergonomic assessment more than the traditional tool.

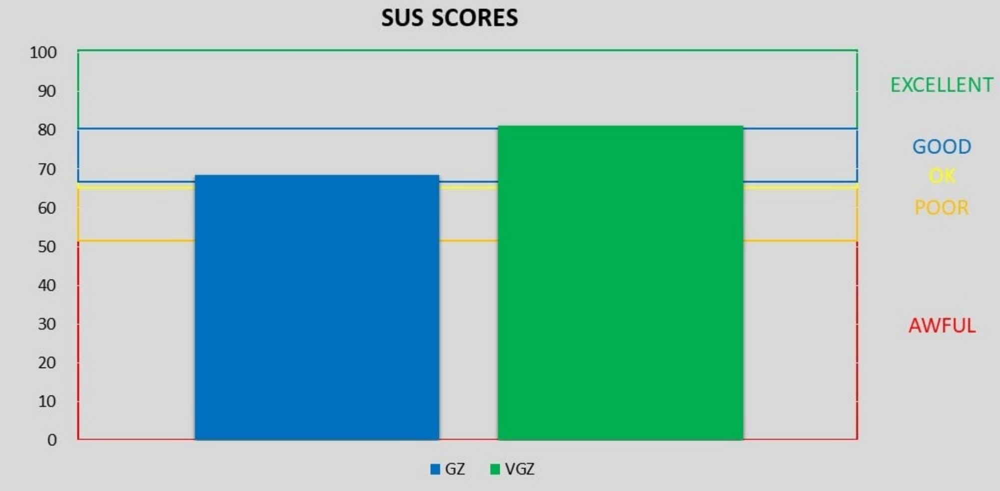

Figure 3.7: SUS scores obtained by the traditional GZ and VGZ methods used in the CAD software and VR enviroment, respectively. The diagram reports the relative acceptability scale.

3.5 Conclusion

Virtual Reality (VR) represents one of the innovative tools that contribute to designing flexible manufacturing systems by leveraging on co-engineering approaches. Focusing on the design check of complex production lines, and specifically on the ergonomic assessment of a manufacturing station, this work shows a novel VR methodology aimed at enhancing the critical design choices affecting the operator ergonomics. The presented method relies on the use of the virtual golden zone (VGZ) to identify the correct and comfortable working area of the operator as well as ensure the safety and efficiency of his/her activities. The effectiveness of the VGZ in providing professionals with an effective tool for ergonomic evaluations is demonstrated through the application of a real industrial case study in the automotive sector.

The chapter also presents the results of a system usability scale (SUS) questionnaire related to the use of the VGZ as a support tool for CAD software for ergonomic assessment in the design of complex production lines. The obtained results confirmed the effectiveness, efficiency, and high satisfaction experienced by users in using such a VR-based methodology for enhancing the ergonomics of manual manufacturing stations.

This work can be considered as a best practice on how the industry can take advantage of implementing VR in the design process. However, the presented findings can be considered only as a starting point for the digitalization of manufacturing companies. For instance, the VR use can be extended to the entire development process for a complete ergonomic evaluation before the production phase. Moreover, having established that the VGZ can enhance the ergonomic assessment of complex production lines, future works will investigate improving the human interaction with the VR environment by using a glove for haptic feedback. The connection between the head-mounted device, VR software, and glove can allow the user to measure the wrist rotation and movement of each finger and further enhance the ergonomics of operator activities.

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Chapter 4

Virtual Reality for the Virtual Commissioning of Complex Manufacturing Lines

Abstract

The design of complex manufacturing systems (CMSs) is challenging, because of the requirements of efficiency, safety, and ergonomics, and the need to optimize resources, i.e., space, machines, operators, and data. Virtual reality (VR) – one of the promising technologies at the base of *Industry 4.0* – is able to address the design issues of CMSs, and even decrease costs and time when employed from the initial conception to the final validation of production lines, since it facilitates their virtual commissioning, i.e., it enables the full verification of systems and related components by virtual inspection and tests. Despite the above advantages, VR is still rarely used in the design of CMSs, and there is no standard VR approach in industry yet. In addition, the related scientific literature is scarce and often limited to small or simplified cases. To fill this gap, this work presents a novel VR-based approach for designing CMSs, composed of four phases: Three-dimensional CAD Export, Model Import, Scene Creation, and VR Review. The proposed approach is applied to a real industrial use case related to the virtual commissioning of an electric axles production line and it is evaluated through a questionnaire from industry professionals. The case study shows that using the VR technology enhanced the technical communication between experts in the teamwork, and it was particularly effective in finding ergonomics flaws like issues in visibility, reach, and posture using a virtual golden zone. In addition, all users found the VR interaction enjoyable and easy to learn, and beginner users perceived a comparable workload as advanced users.

Contents

Contents

4.1 Introduction

The new paradigm of *Industry 4.0* is significantly pushing the implementation of the so-called smart factory, where physical and digital systems are strongly integrated in view of the final goals of achieving efficient product development with flexible mass customization [1], [2] and satisfying increasingly competitive markets that require fast time-to-market and high quality products [3], [4]. To achieve these challenging objectives, industrial complex manufacturing systems (CMSs) – the collection of machines aimed at converting raw materials, components, or parts into value-added finished products – must implement a high level of connection between the physical and the virtual worlds and obtain a high grade of operational productivity and efficiency in terms of costs, time, and space [5], [6]. CMSs are called complex because of their structural, configuration, and operational intricacy and their high variety of components, transportation mechanisms, interconnections, and inter-dependencies [7].

Due to their complexity, the design of CMSs is a challenging activity, requiring multidisciplinary proficiency in the definition of several dependent machines' requirements and constraints, the management of large scale layout, the integration of hardware and software, and the implementation of human-robot and robot-robot collaboration. An additional issue is to the long lifespan of projects (normally, 2-3 years of development), during which requirements can change in terms of design.

The success of the CMS design significantly depends on the ability of teams from different engineering sectors to collaborate and work effectively in solving complex problems [8]. As a common industrial practice in the CMS industry, the design and review phases are typically performed on desktop PCs equipped with a CAD (Computer Aided Design) software and a two-dimensional (2D) screen. However, complex three-dimensional (3D) problems – such as optimizing space, keeping a suitable distance between different sub-systems, enabling the correct interaction between moving parts, and ensuring the human-machine ergonomics and safety (e.g., body posture, reach, visibility) – may be difficultly assessed by using a 2D interface. As a consequence, it is very common that problems arise only during the final implementation of the CMS, causing high cost and time of re-design. To overcome these issues, the commissioning of CMSs is recently leveraging on the benefits of the novel concept of virtual commissioning [9]. This paradigm enables the full validation and verification of a CMS by virtually visualizing and testing the system and related components, thus reducing time to market, lowering costs, and increasing productivity [10], [11].

Against this background, the main motivation of this work lies in the collaboration of the authors with a worldwide leader of CMSs, employing *virtual reality* (VR) as a key technology to address CMSs design issues, with the final aim of achieving ambitious industrial goals and high customer satisfaction [12]. Indeed, VR provides a 3D interactive simulation of the CMS (see the example in Figure 4.1) and supports the multidisciplinary design process, while facilitating the detection of issues in the early phase of the design process [13] and reducing the testing and integration time during the developmental phase [14]. Despite these advantages, VR is not often used in the industrial practice for the design of CMSs and the related scientific literature is still scarce, being mainly focused on the design review activity only, while addressing simplified manufacturing systems or consumer products [15]. Developing and deploying a real VR application in the industrial field is still challenging because there are no well-established and standard procedures to follow. Therefore, this work contributes to filling the above identified gap by presenting a novel and general procedure for the design of CMSs supported by VR. The proposed approach is implemented on a real case study related to the development of an electric axles production line, thus showing a direct hand experience and validation. In particular, evaluating the effectiveness of the proposed approach, by means of the case study, in this chapter we aim to answer the following research questions (RQs):

- *RQ1: Does the presented VR approach support the CMS design process?*
- *RQ2: Which steps of the CMS design process can benefit from the use of VR?*

- *RQ3: What is professionals' acceptance of the VR approach for CMS design?*

Through the case study, these research questions will be investigated in order to provide important insights into the effectiveness of VR technology in CMS design, pinpoint the precise stages that can yield the most benefits from its use, and assess the degree of acceptance and satisfaction among professionals in the field. In the end, this research advances the area by bridging the knowledge gap between virtual reality's potential and its practical application in the intricate manufacturing sector.

The rest of the chapter is structured as follows. Section 4.2 illustrates the state of the art on the use of VR in the industrial setting, positioning the work in the related literature on VR methods used in the design of manufacturing systems. The novel VR-based approach for the virtual commissioning of CMSs is presented in Section 4.3. In Section 4.4, the suggested method is applied to the actual case study, demonstrating how well VR supports the crucial stages of CMS development and going over how the VR approach is assessed from the users' point of view using a questionnaire. Finally, some concluding remarks are reported in Section 4.5.

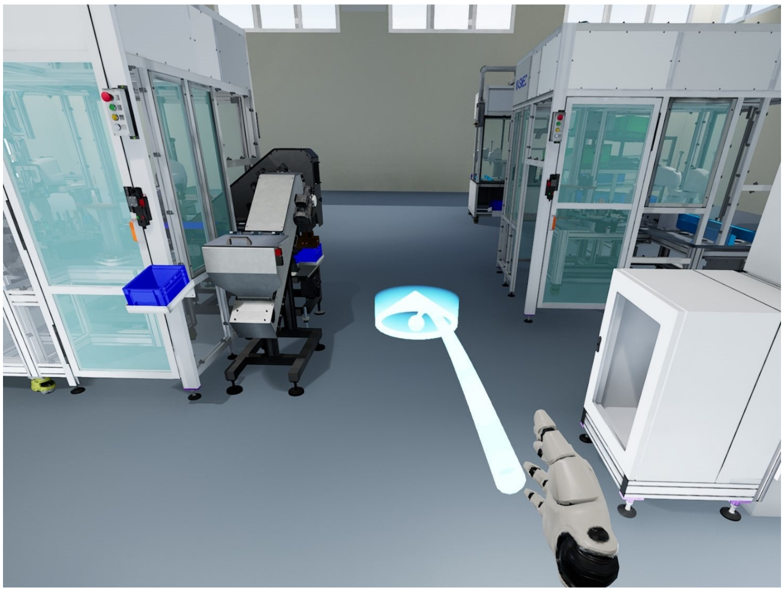
4.2 Related Works

Numerous VR technologies have been proposed over the last years to enable humans to experience a virtual environment. VR is based on computer graphics, which can build virtual scenes and items to be manipulated by the user through input devices, such that the user can feel highly immersed in the virtual scene[16], [17]. VR technologies are widely employed in several industrial fields, such as the automotive, aerospace, bioengineering, and construction sectors, [18], [19]. In particular, the most common and promising applications of VR in the industrial setting employ VR to simulate actual environments and are usually used for training [20], maintenance [21], and design [22]. In particular, efforts to implement design changes in the conceptual development phase require significantly lower resources than late project updates and revisions, and this condition results in the conceptual review having a high impact on a design solution.

Recently, VR has also been used in virtual commissioning in order to facilitate the integration and assembly planning, testing, and debugging steps [23]. In line with the final goals of virtual commissioning, the VR technology allows the immersion of the users into a virtual model of the production system and experience as if they already existed, allowing designers and operators to not only observe the CMS but also proactively interact with it in a virtual environment without any risk of physical destruction. For instance, Dahl *et al.* [14] describe a method where VR provides the interaction with a virtual simulation environment as an extension to the virtual commissioning project.

Nevertheless, the design phase is one of the crucial phases of the CMS development process [24]. For this reason, a large portion of the literature is focused on the use of VR to improve the design. For example, Bordegoni and Caruso [25] highlight the importance of checking the design issues before assembly and during reviews with the customer. The authors present a methodology that enables the collaborative design review of automotive interior components by allowing experts to interact with the virtual product prototype through a mixed-reality design platform [25]. During the design phase, design reviews represent a cognitive process that allows users to see project issues in a 3D model and collaborators to share expert information for efficient decisions [26]. In this regard, Wolfartsberg and Wolfartsberg *et al.* [27], [28] describe the development and evaluation of a VR-based tool to support the engineering design review, presenting an approach to counteract the social exclusion in VR applications and to support the communication among users in a time-efficient fashion. The design assessment is the basis of design review activities since experts from different disciplines have to discuss and concur on a design solution while

(a)



(b)

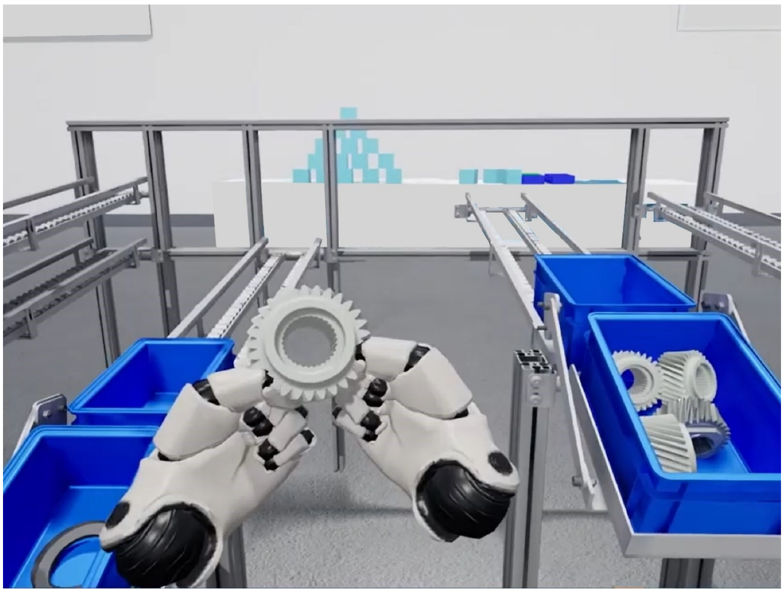


Figure 4.1: Examples of interaction tasks used in the VR environment for CMSs: teleport for exploring large spaces (a), touching and grabbing for assessing ergonomic aspects (b).

exchanging project information according to well-defined standard procedures [29]. Similarly, Gebhard *et al.* [30] present a VR application implemented in the field of factory planning, which provides planners with the ability to perform realistic walk-throughs in digital factory models, while achieving a good integration in the factory planning workflows.

As shown above, VR has been applied successfully in the related literature during the design review with the customer, but it is not yet employed as a common standard tool in the company's internal procedures. The hesitation regarding VR technology integration in the manufacturing world is probably due to the negative experiences with old VR tools generations, to the lack of VR technology know-how and competencies in the companies, and the lack of adequate engineering-oriented VR standards [31]. In this context, user's questionnaires may be helpful. For example, Berg *et al.* [32] presents the empirical results of interviews with VR users and practitioners. Through a series of on-site visits to different factories, participants are asked to outline the steps involved during the common VR use case scenario. The correlation between the design review and the company process has yet to be clearly defined.

We finally would like to remark that the VR environment, differently from a 2D tool, helps stakeholders make realistic evaluations. Indeed, different research also contributes to the field of VR-supported design reviews for ergonomic considerations. For instance, immersive VR has been proposed as a solution to improve workers' safety by virtually replicating the operations of the shop floor [33]. In this context, Manghisi *et al.* [34] describe a design of automatic ergonomic monitoring for the evaluation of postural risks and a training system for increasing operators' awareness. Moreover, Peng [35] proposes the use of VR for ergonomic evaluation and verifies the reachability of door handles within a vehicle. Instead, Caputo *et al.* [36] presents a framework that uses digital twins of stations to minimize the time needed to develop a new assembly line and to enhance the integration of ergonomics in workplace design. Automotive industries employ virtual prototypes to establish design criteria and verify the visibility and reachability of the instrument [37].

In conclusion, the previous literature review highlights that using VR as a support tool for the design of CMSs [38] is effective but also raises various technical challenges. VR is not a well-consolidated practice yet: no standard implementation procedure exists, whilst practical applications present only isolated or scattered experiments, that are usually limited to simplified systems or a single machine or final product [39]–[41]. This work contributes to the virtual commissioning design of CMSs, by providing a novel procedure that explains step-by-step how to integrate the use of VR in the CMS design process and by discussing the benefits offered by VR sessions to stakeholders compared to more traditional methods. The case study – related to a real CMS design scenario – investigates the VR potential in virtual commissioning to define design and parts, competencies, requirements, equipment, and services.

4.3 The Virtual Reality Approach

The project design of CMSs is a central part of the larger business activity of the manufacturing system turnkey providers [42], and it is typically organized into three phases: commercial proposal, CMS development process, and after-sale service (see Figure 4.2a).

The project acquisition is finalized through the acceptance of the *commercial proposal* taylored to the customer, thus allowing the company to set up the *CMS development process*. Conversely, the *after-sale service* consists in following the customer in the system installation, first run, ramp-up, and maintenance. During the key *CMS development* phase of the CMS life cycle, a multidisciplinary team conducts the project activities in accordance with a Gantt chart, that is typically divided into 7 phases (see Figure 4.2b): Analysis, Engineering, Supply Chain, Assembly, Test and Debug, Shipment and Installation, and Service. Each of these 7 phases starts with the corresponding milestone: Kickoff Meeting, Project Start, Procurement Start, Assembly Start, Machine Switch-on, Internal Validation, and Client Final Validation [43].

This chapter is specifically focused on the key *Engineering* phase (see Figure 4.2c), which is in turn divided into 3 sub-processes: Concept, Design, and Finalization. The main outcomes of the Engineering phase are the milestones denoted as Concept Review (CR) and Design Review (DR),

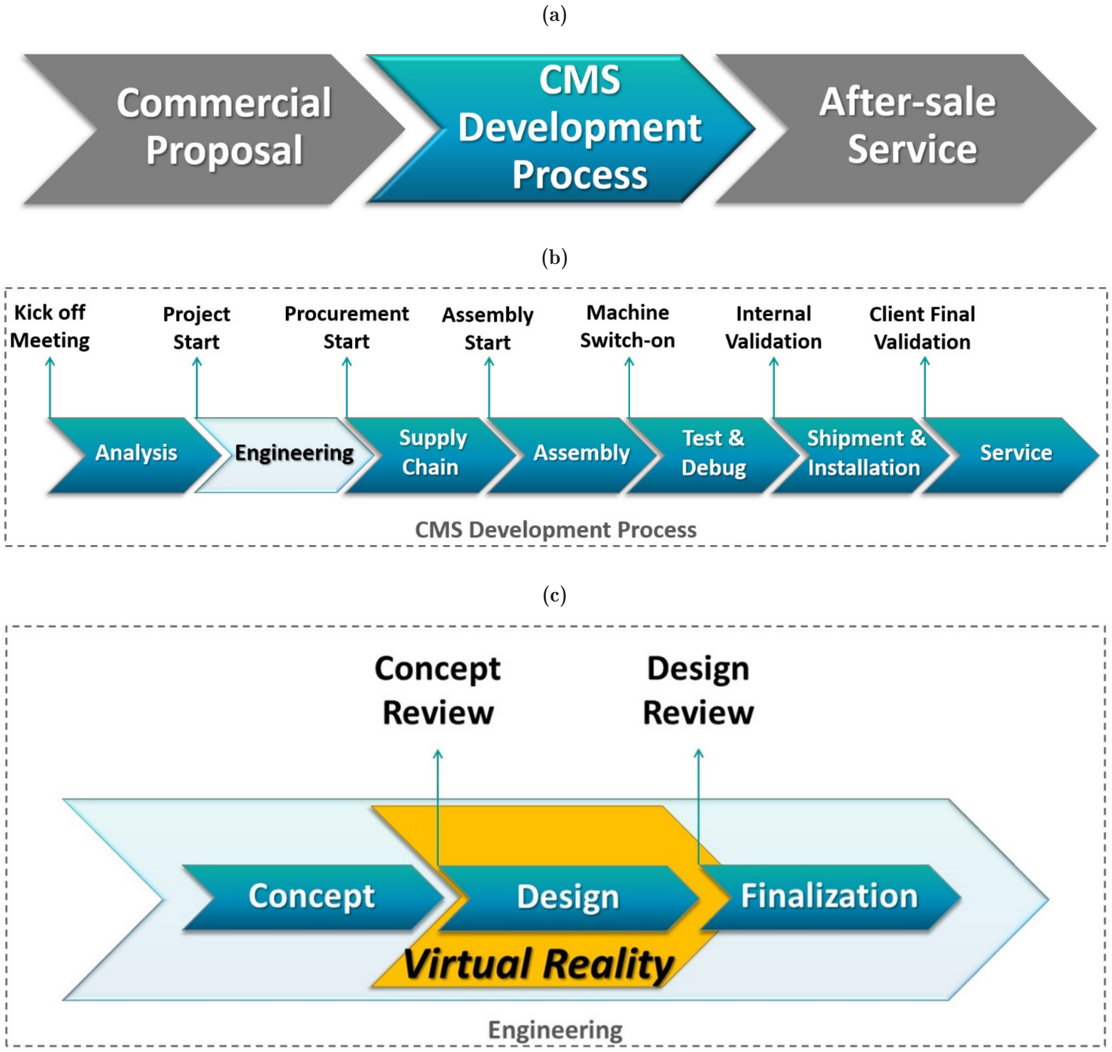


Figure 4.2: VR integration in CMS development process: CMS life cycle (a), CMS development process (b), and Engineering phase with the integration of VR (c).

which are in turn the start and end points of the Design phase. Typically, the involved actors in the engineering phase are: the Project Manager, who defines the timing and costs of the project, the Project Engineer, who is responsible for the technical decisions, the Technical Leader, who is in charge of the designers' coordination, and the Mechanical, Electrical, and Fluid Designers.

In the general engineering phase, the engineering team studies all the customer's requirements for the CMS (layout of the factory, output rate, takt time, number and kind of stations and workers, etc.). This phase typically makes use of different software platforms, ranging from general purpose tools like presentation programs to specific tools like 2D/3D CAD and simulation software. The outcome of the *Concept* phase is a preliminary concept draft of the project requirements that typically has a conceptual 2D CAD representation as a milestone in the CR.

The CMS *Design* is the core phase of the Engineering phase and typically starts by creating a 3D CAD model of the production line, detailed to all the single machine components. These can be fully outsourced systems or, as occurs in most cases, a custom integration of sub-assemblies, supported by complex logic, wiring, and services (compressed air, power lines, water, oil, waste, etc.). Due to the high level of customization, complexity, and multidisciplinarity, this phase requires multiple internal and external design review phases with different design expertise: electrical, mechanical, ergonomic, etc. In addition, it is common to conduct regular audits with the customer to receive comments and feedback aimed at improving the system [44]. Specifically, according to the IEC-61160 standard [45], the DR meetings are key activities that, if properly implemented, enhance the potential for delivering a product with the required dependability, quality, performance, safety, and for reducing costs and delivery times.

Communication has a substantial role during the design process because it allows to exchange of messages and conveys ideas to people with different skills and interests. VR tools can provide a very good representation of space and are used in parallel with the traditional mechanical design tools (CAD, simulation tools) as a complementary communication and review method and support tool for the main 3D CAD software platforms (e.g., NX Siemens, PTC Creo or Dassault System Catia).

After the Design phase, the *Project Finalization* phase includes the bill of material export in the enterprise management software closing the engineering top-level phase, and working as input for the next phase of the CMS development process supply chain.

In summary, the engineering journey within the CMS development process is a comprehensive and multidisciplinary endeavour, encompassing General Engineering, CMS Design, and Project Finalization phases. Each stage contributes to the overall success of the project, with VR technology emerging as a valuable tool for communication, design review, and enhanced collaboration in the modern engineering landscape.

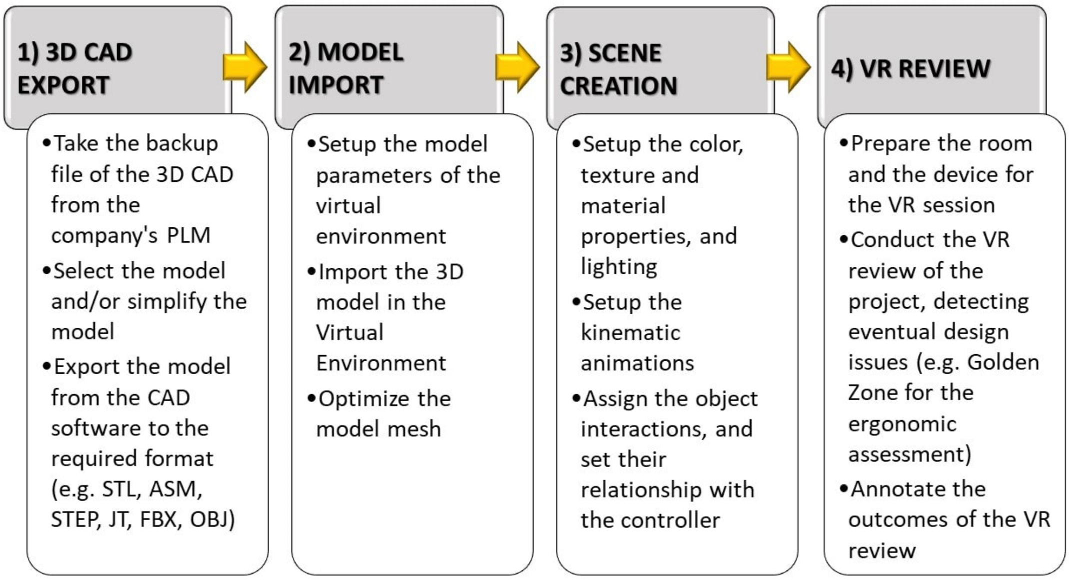
4.3.1 Procedure for VR Integration into the Engineering Design phase

The integration of VR into the core CMS engineering phase, i.e., the design phase, is described in the sequel. For the sake of optimally preparing and executing the VR session, we present a novel approach for the VR-supported CMS design composed by four steps, as shown in Figure 4.3. The final users – comprising not only the internal but also the external staff – play specific technical roles in the VR sessions as indicated in Table 4.1.

Starting from the Concept, the Project Engineer plans the steps for the efficient and accurate manufacturing of the model. The presented approach is based on the four steps detailed in the sequel: 3D CAD export, Model Import, Scene Creation and VR Review.

3D CAD Export

This phase consists of exporting the CAD file of the project – usually stored in the company product life-cycle management (PLM) database – with the final goal of preparing the conversion from the CAD format (i.e., a full geometrical and mathematically exact representation) into a graphical version (employing meshes) that is compatible with the interactive visualization on the VR platform. This conversion is computationally intensive. A common mistake is to export the model without preparation, causing time-consuming operations, since the geometrical complexity of CMSs generally significantly exceeds the maximum number of geometries required by interactive graphics in VR. For this reason, a first effective simplification is performed in this phase by selecting and isolating the key subsystems from the ones which are not important to the simulation and can be thus removed or approximated. An example of this mode of operation occurs in the design review of a specific station, where the rest of the line is just contextual and can be replaced even by a virtual background environment map texture. Further simplifications



1) 3D CAD EXPORT

- Take the backup file of the 3D CAD from the company's PLM
- Select the model and/or simplify the model
- Export the model from the CAD software to the required format (e.g. STL, ASM, STEP, JT, FBX, OBJ)

2) MODEL IMPORT

- Setup the model parameters of the virtual environment
- Import the 3D model in the Virtual Environment
- Optimize the model mesh

3) SCENE CREATION

- Setup the color, texture and material properties, and lighting
- Setup the kinematic animations
- Assign the object interactions, and set their relationship with the controller

4) VR REVIEW

- Prepare the room and the device for the VR session
- Conduct the VR review of the project, detecting eventual design issues (e.g. Golden Zone for the ergonomic assessment)
- Annotate the outcomes of the VR review

Figure 4.3: The proposed VR-based approach supporting the design of CMSs.

are achieved by disabling or deactivating CAD elements through engineering or drawing semantics such as layers, and parts grouping available only at this stage. This operation is very effective in removing elements that are not visible (e.g., internal mechanics) and not of interest in the design (e.g., light projections), thus avoiding generating very complex meshes (like fasteners, or cabling). In this phase, engineers play a crucial role, being responsible for the CAD decisions to be taken on the ground of the simulation. Another critical aspect concerns the setup of the CAD origin and other reference points in a convenient location, e.g., zeroing the system in the desired station, preparing camera orientation axes, placing dummy objects to reuse key positions and axes (e.g. for setting constraints and animation paths) and to save time avoiding retrieving these data on a meshed model.

In the 3D CAD export, CAD data have to be converted into graphical meshes, which may or may not include materials, camera and light positions, and animations. The FBX format (Filmbox) is recommended because it is well supported and can contain material textures embedded in the file, thus resulting more practical than the OBJ format (Object). As a second choice, the STL format (Standard Tessellation Language) [46] is very common but does not contain materials. Recently, other formats, such as ASM (Autodesk Shape Manager) [47] and JT (Jupiter Tessellation) [48], are available; however, they are not properly supported in the graphical libraries used for VR. As an alternative, mathematical formats –such as the CAD native format STEP (STandard for the Exchange of Product model data) [48] and IGES (Initial Graphics Exchange Specification) [48] – can be used in conjunction with external third-party meshes-optimizers to successfully perform the conversion. However, we remark that it is very common that, due to commercial reasons, CAD export rarely transfers all the potentially available CAD data in the target file format; hence, conversion is commonly associated with lost data, such as materials graphical proprieties and textures, kinematic animations, grouping and layering, cameras and lights. Unfortunately, these data must be recreated in the target platform by cost and time-consuming manual procedures, with high risk of creating inconsistencies. On the ground of these considerations and according to

Table 4.1: Team of users involved in the VR reviews and their roles.

Category	Role
Competence Leader	Organization of large projects, management of staff, and definition of goals as a department leader. Her/his participation during the VR reviews is required due to her/his wide experience.
Project Manager	Organization and management of time, costs, and resources that are necessary to complete a project. Partecipation in the VR reviews is needed to update the project's Gantt chart.
Project Engineer	Make all technical decisions, ensuring work is being completed safely and efficiently. During the VR reviews she/he checks the project's updates, confirming and making planned and new decisions, respectively.
Sales Engineer	Prepare and finalize the commercial proposal for the project acquisition and make all the commercial decisions during the project life. Her/his participation during the VR reviews is linked to the economic aspects affecting suppliers and partners.
Technical Leader	Coordinate all the designers from the technical aspect of the project. Participation during the VR reviews is conducted as an expert designer.
Designers	Mechanical, electrical, and fluid-dynamics designers that realize the project and communicate with suppliers. During the VR reviews they check the CAD model issues and analyze how to apply the required upgrades and modifications.
VR Specialist	Building the VR application following the proposed procedure, preparation of the VR environment with objects interaction and animation, and controls that the VR experience meets the intended goals.
Assembly Leader	Responsible for the team during the assembly stage. Partecipation in the VR reviews is needed to anticipate the detection of eventual assembly issues to the engineering stage.

the specific process of CAD and VR libraries, all the possible export paths must be evaluated and tested in order to find the optimal choice.

Model Import

The 3D CAD model must be then imported into one of the available VR platforms: Unity3D [49] and Unreal Engine [50] are the most common. On the one hand, Unity3D supports only mesh formats like FBX, OBJ, or STL; consequently, all CAD data must be converted before being imported in Unity3D [33]. On the other hand, Unreal Engine uses a plugin called Datasmith that directly supports common CAD data formats [51]. We remark that also this import conversion suffers from loss of data such as materials, animations, light, and camera; hence, it is crucial to optimally set the different options offered by the import phase before using the model. For instance, when the scene author applies scales and rotations to each object, ineffective time-consuming operations can raise in the case the model scaling and the main axes rotation parameters are not properly set.

Another key aspect concerns the complexity of the mesh. A complex CMS CAD model conversion generates a huge number of graphical elements (e.g. triangles, materials, animations, etc.) that could lead to an unacceptable level of frame rate [52]. Studies on VR applications show that a frame rate lower than 100 frames per second can produce discomfort to users, and the long term can even lead to cybersickness effects, such as disorientation and nausea [53]. Based on the target VR graphics hardware, it is possible to estimate the maximum number of supported graphical elements (e.g. number of triangles) for achieving the minimum frame rate. The mesh simplification task can be executed inside the VR environment when possible or using third party external tools (e.g. Simplygon [54], Meshlab [55], etc.). These mesh optimization tools implement re-mesh algorithms aimed at reducing the triangle count and the organization of the materials while creating a level of detail nodes checking the performance of the obtained models. Even though the performance of these tools is becoming better and better, engineering supervision is still required, since some key geometries may be eliminated or simplified with benefits in terms of usability and collision evaluation. For instance, using edge selection – which enables the lowest visual change to the model – is an effective trick for producing good low-polygon models [56].

Finally, it should be noticed that the VR hardware requires a dual rendering (one per eye), and the required results by the graphic card and frame rate can vary according to the specific scenario and type of interaction. Therefore, employing a trial-and-error approach with higher levels of simplification is suggested.

Scene Creation

This phase aims at creating a realistic simulation of the CMS, allowing to use of the virtual experience as a decision tool for spotting issues, finding solutions, and even simply showcasing and marketing. For this reason, multiple scenes may be created to fulfil each activity and support the approach and language of the dedicated team. The converted mesh generally lacks materials or is not sufficiently realistic because it does not use shaders or multiple texture maps. Therefore, in this phase, a crucial activity is performed by the VR specialist that improves the model by adding material properties, texture, lighting, sounds, and animations. The resulting level of realism can vary according to the specific needs, ranging from a quick approach using default materials (e.g., space evaluations) to very realistic environments that can help stakeholders visualize the final product in the marketing setting.

Object manipulation is a key aspect of the simulation as it serves for human-machine interaction evaluations. Model files that need to be freely manipulated, such as tools, must be identified in conjunction with the engineering team, which must always have technical supervision to the scene. Differently from what happens using 2D CAD software, VR requires different metaphors that mimic natural (grabbing) or supernatural where traditionally mouse and keyboard are employed on a 2D surface (grabbing with a ray at distance) [57]. Physical constraints between objects previously set in CAD are commonly lost in this phase, hence the VR conversion, so the specialist must group them under a unique node in order to be manipulated as a single element.

A similar problem arises for kinematic animations, as the CAD joints and formulas are lost in the VR conversion. Therefore, the VR specialist must find a viable solution in collaboration with the engineering team. Some options characterized by a growing fidelity and effort are listed in the following: (i) reproduce the animation manually using the authoring tools provided in the VR library; (ii) create kinematic joints manually using the VR library physics; (iii) export trajectories key-frames from CAD files and import them in the VR environment (assuming that CAD files are compliant to VR environment and the integration of custom coding is available). Also, 3D sounds can be inserted into the VR scene to mimic real manufacturing noises and alter them. The VR specialist can record them from real or artificial machinery the manufacturing noises and locate them in the virtual scene together by the conditions to be triggered.

Another important aspect of scene creation is interaction design. Based on the requirement analysis, and the particular objective of the VR simulation, the scene can have different interaction schemes. There are two common approaches: the first is the third person's point of view, which allows the VR user to act as a supervisor and observe the CMS; the second approach is the operator's point of view which allows the VR user to perform the task as occurs in the real

Table 4.2: Interaction tasks performed during the VR reviews.

Interaction task	Description
Looking & Walking	Features provided by most common VR platforms to see and walk around the scene. In the case of CMSs these features help to mimic the operators' paths to reach key positions (e.g., maintenance).
Teleport	Supernatural features that allow the users to be transported across space instantly. In the case of CMSs these features are very helpful due to their large dimensions (see Figure 4.1a).
Touching & Grabbing	Features that mimic the natural interaction of grabbing and moving objects with and without gravity or kinematic simulation. In the case of CMSs these features are used to replicate the workers operation (e.g., picking tools and components) and move pallets on the conveyor (see Figure 4.1b).
Other Specific tasks	Features that implement (through appropriate scripts) specific interactions in CMSs, such as pushing a button to start machinery, opening a door for maintenance, setting a timer using a virtual LCD display, modifying the objects during the production process, showing ergonomic zones.

production line. VR platforms offer default interaction prefabs, using VR controllers, to perform looking, walking, teleporting, touching, and grabbing tasks (see Table 4.2). There is also the possibility to customize the specific interaction to modify the default options such as changing the walking speed and optimizing the buttons on the controller depending on the interaction activation. Moreover, specific interactions can require scripts to program different and personalized behaviours (e.g., when operating machinery).

VR Review

After completing the VR scene, the fourth and last step of the VR design approach, i.e., the VR review can be conducted. First, the VR specialist prepares a room dedicated to the VR sessions, with a large space for the virtual experience without collision objects (such as tables and chairs) for the user's safety. Subsequently, the VR specialist has to set the VR device. For example, Oculus Quest [58] is a standalone device that can run projects in wireless mode under an Android-based operating system. It uses an internal sensor and an array of cameras in the front of the headset that can support positional tracking with six degrees of freedom. Thus, the VR specialist defines a boundary area for the session, useful for the users' safety, where the users are able to know if they are exiting from the area thanks to the camera. As an alternative, HTC Vive [59] is a virtual-reality system that incorporates room-scale tracking, using two infrared tracking stations located in opposite corners of the room to monitor the movement of the users, thus allowing them to freely walk around a play area, with their real-life motion reflected in the VR environment.

Hence the team performs the VR review and analyzes the project. The team addresses different design issues by loading scenes and configurations dedicated to highlighting specific aspects such as visibility, ergonomics, design, and logistics. A key strategy useful to carry out the

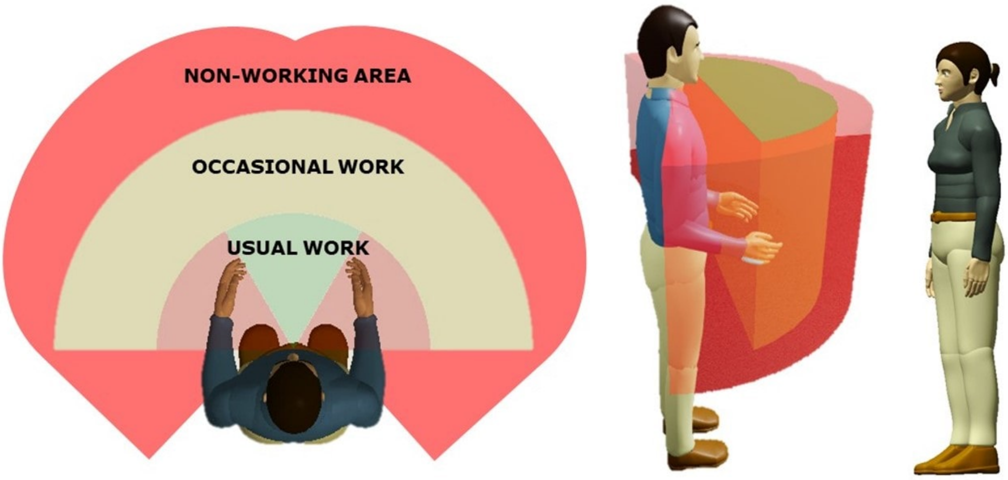


Figure 4.4: Manikins and golden zones used in CAD software and imported in VR environment for the CMS ergonomics evaluation: representation of three safety working areas in the task of manual order picking.

ergonomic assessment is the so-called "Golden Zone" [60], a method that represents the optimal pick volume (see Figure 4.4) that begins at knee height and closes just below shoulder elevation [61]. This window minimizes lifting, reaching, and bending motions, and strain, thus the potential for long-term injury. Accordingly, we define the Virtual Golden Zone. More precisely, the Golden Zone model file is implemented in the VR environment as a tool for highlighting ergonomic issues that we called the Virtual Golden Zone. The VR specialist can implement the interaction during the scene creation to make the user able to activate and turn off the virtual golden zone in the VR scene using the controller. Additionally, during the scene creation could be imported a manikin CAD file with the golden zone to enable the user to analyze the issues as a "spectator" and turn around the machine. At the end of the VR session, the team collects the outcomes as a basis for analysis and evaluation. Generally, one person on the team keeps track of issues when the VR user detects them in the simulation. The VR experience can be organized to be single user or multi-user, while a larger screen is used to share the individual point of view to the other participants in the session.

4.4 Case Study: The Virtual Commissioning of an E-axle Assembly Line

In collaboration with an automotive company leader of the Italian and European market, we present as a case study the design of the production line of a 1.2 tons electric axle (e-axle) of heavy-duty vehicles.

4.4.1 Presentation of the Electric Axles Production Line Design

The e-axle line extends on 1864 square meters and is composed of a core section, with five modules for the e-axle assembling, and three support areas: the kitting area, where operators prepare the sub-assembly of motors and transmissions, the loading and unloading area for the e-axle box positioning on the cart, and the testing area at the end of the line (EoL) (see Figure 4.5). In addition, the core section is divided into two parts: the subline and the mainline. On the one hand, the subline includes a module with the rotor and transmission preparation stations

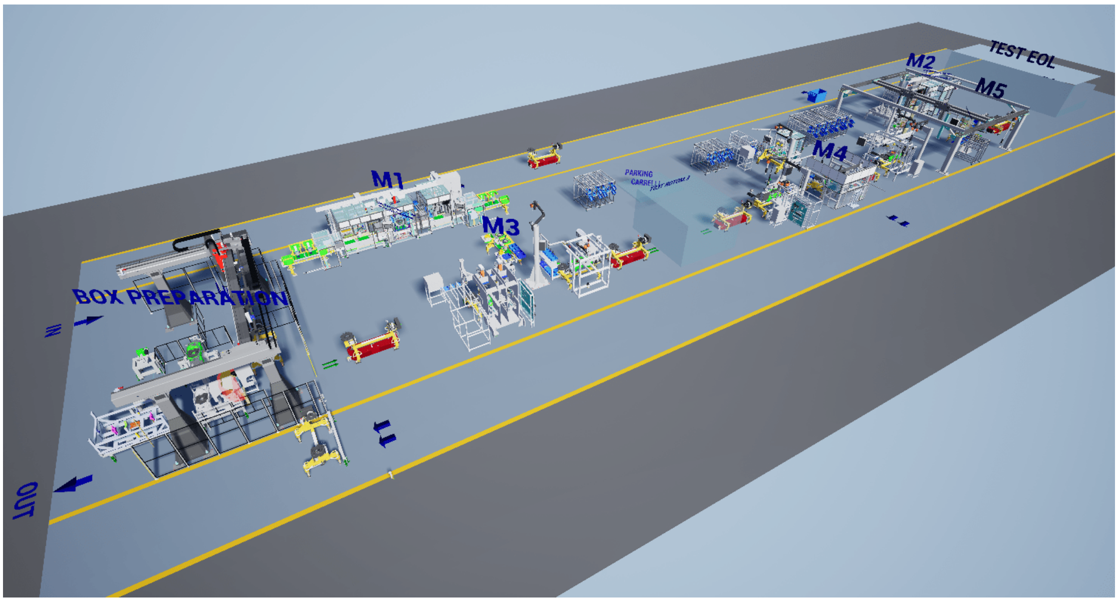


Figure 4.5: Layout representation of the e-axle production line analyzed during the VR review session, including the loading and unloading for the box preparation areas, the core section with five modules divided into mainline (M2, M3, M4, M5) and subline (M1), and the testing area.

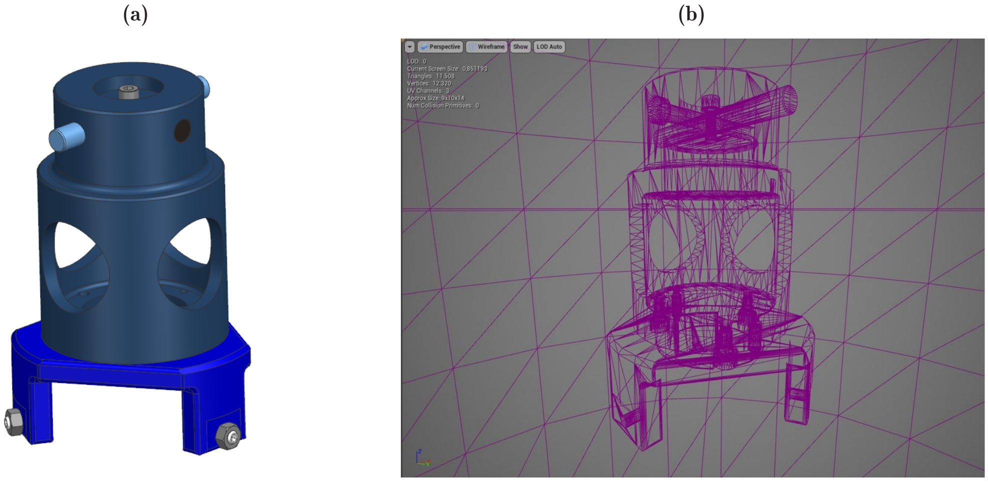
(i.e., some press-fitting stations). On the other hand, the mainline is composed of further four modules, including the area where the e-axle is assembled on a cart and moved by AGVs between the machines.

The VR design was aimed at analyzing only the core section of the CMS, i.e., the portion of the line with five modules for the e-axle assembling, and the loading and unloading area, including a total of 5 workers. The e-axle engineering phase lasted 25 weeks, and the first VR review was scheduled after 6 weeks from the start in the Gantt chart by the Project Manager. The team was composed of internal company members and representatives of the customer and suppliers. Usually, one review per week was organized only with the internal company members, whilst from 1 to 4 sessions per month were conducted inviting the customer staff, according to the updates. Sometimes also the representatives of suppliers took part in the VR reviews. Therefore, each session was generally composed has 2 to 25 people. The VR device was worn by one selected participant, while the rest of the team observed the user's point of view on a large screen or remotely, thus creating an interactive co-working environment.

4.4.2 Implementation of the VR Design approach

The VR design approach described in Section 3 was implemented in the selected company using Windchill as PLM system, NX as CAD software, Unreal Engine as VR platform, and Oculus Quest headset as hardware with a field of view of 110 degrees, six degrees of freedom and inside-out tracking. Moreover, the VR sessions were conducted in a VR room offering a PC equipped with a high-performance graphics processing unit (namely, the Nvidia GeForce RTX 2080 8GB Super). In the sequel, the implementation of each step of the VR procedure is described in detail.

3D CAD Export



```
LOD: 0
Current Screen Size: 0,851193
Triangles: 11.508
Vertices: 12.320
UV Channels: 3
Approx Size: 9x10x14
Num Collision Primitives: 0
```

Figure 4.6: Example of model import results: the press-fitting tool for the rotor pallet in the native NX CAD environment (a) and in the Unreal Engine platform (mesh with 11508 triangles) (b).

A total of 21 assembly CAD files was exported from the NX 3D CAD model (i.e., stations conveyors, tools, equipment, gravity rack, carts, and AGVs) available in the Windchill PLM repository, whilst all the machinery and components (such as screws, nuts, bolts, and other similar small components) that were not important for the simulations were removed. The CAD files were exported using the native NX, STEP, and JT formats. The native NX format was able to realize quick VR reviews during project updates (e.g., checking whether the CAD received from suppliers and partners met ergonomic requirements) since its execution requires low computational effort. The STEP format was used for CAD models with animation because it preserved the configuration of components in the presence of CAD constraints (e.g., for the press-fitting machine with a prismatic constraint, the STEP files allow storing the last position of the piston, which has been used in the previous VR session). Lastly, the JT format required more conversion time but provided better meshes.

In addition to the CAD files related to the production line layout, two CAD manikins (namely, a woman with a height of 1.65 meters, and a man with a height of 1.75 meters) and their relative virtual golden zone were obtained. In the CAD platform, these manikins were usually positioned by the designers in front of the stations to perform a first ergonomic assessment. This method was replicated in the VR environment where the manikins were exploited by the VR users to mimic the workers' movements and safety procedures and thus to improve the evaluation of ergonomics and safety aspects.

Model import

During the Model Import phase, the Datasmith Plugin was employed to compute the optimal triangular meshes of the input geometry for about five thousand components of each model. This operation required the manual tweaking of all the main geometries by setting the Chord Tolerance, Max Edge Length, and Normal Tolerance parameters. By tweaking these values, it is possible to control the complexity and fidelity of the Static Mesh geometry that Datasmith creates for curved surfaces. The values generally used for these import options were: 5.0 mm for Chord Tolerance, 0.0 mm for Max Edge Length, and 20.0° for Normal Tolerance. For instance, using

Figure 4.7: Example of the overall view of the sub-line in the internal environment created by the VR scene.

these values, importing the model of the press-fitting tool for the rotor pallet (see Figure 4.6) produces a mesh that included 11508 triangles.

Scene Creation

For the e-axle project, 7 scenes were created. First, the VR specialist focused on conveying a realistic experience by setting texture, material, colour, and lighting according to the design specifications. The Baked lighting option is required to set up the Lightmap UV channels as "static" flags after the 3D model import. Baking lighting means precalculating the static global illumination which does not change in runtime. Alternatively, for scenes including several components, fully dynamic lighting was used to avoid the computational effort required by the complete baking. The lightmap resolution (usually ranging between 32 and 256 lightmaps) was a trade-off between the requirement on the light simulation quality and the performance optimization: higher resolution produces better shadows, but increases graphic resources. Quality materials were assigned manually to the scene using a library. The used materials were mainly reflective metallic (steel, aluminium, copper, and zinc) and plexiglas for the machinery, plastics, industrial floor, glass for windows and doors. Figure 4.7 represents a simple example of how the subline was realistically loaded in the VR scene, with windows, shadows, and artificial lighting.

Second, the VR specialist assigned the basic interactions *Looking & Walking*, *Teleport*, and *Touching & Grabbing*. Given the complexity of the e-axle production line, particular attention was given to the *Grabbing* command, which allows the user to perceive the relationship with the environment as if it were real. The grabbing interaction was based on a simple or complex collision area created on the object. As soon as the Oculus controller enters a construction group's collider, the VR tool triggers specific interactions and thus the actuators integrated into the Oculus

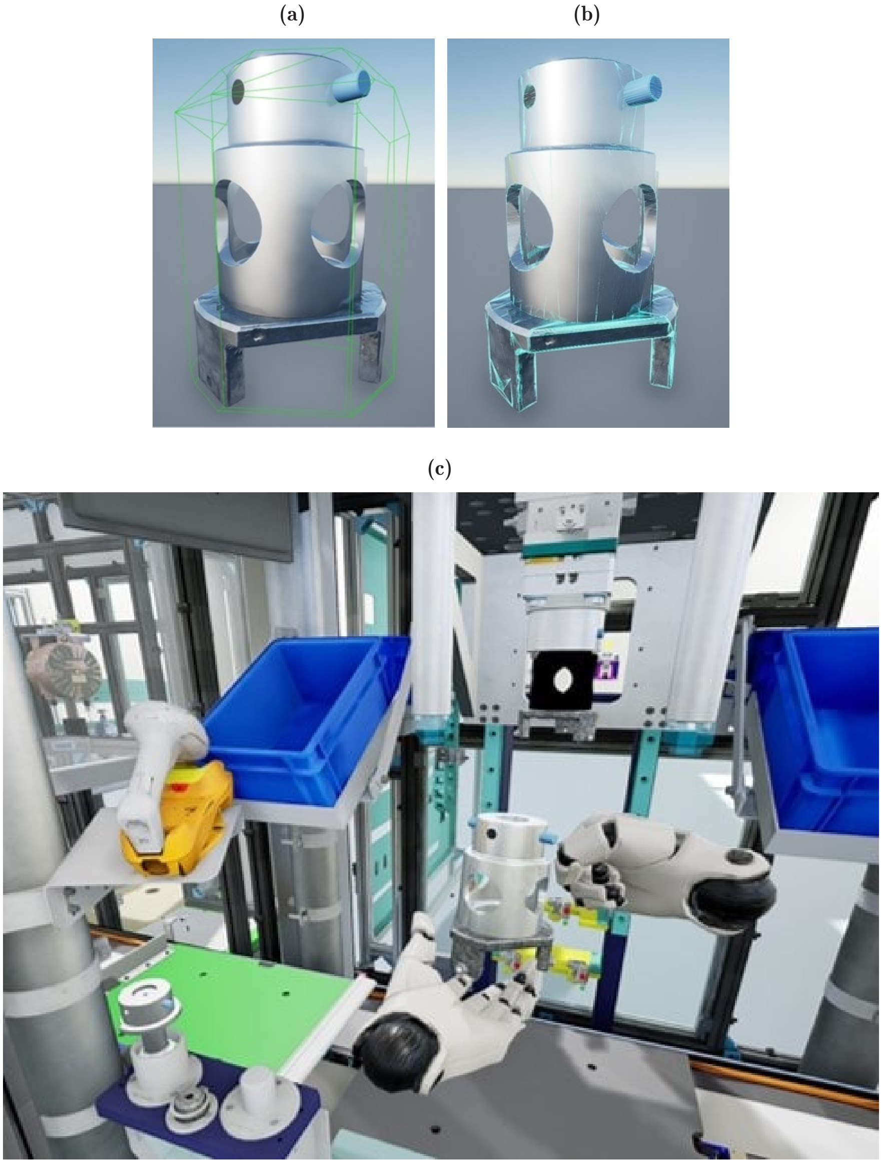


Figure 4.8: Examples of scene creation results. Details of rotor press-fitting tool with 26 DOP (Discrete Oriented Polytope) Simplified Collision (a), and rotor press-fitting tool with Complex Collision (b). Detail of the press-fitting station showing the touching and grabbing of the rotor press-fitting tool (c).

controller trigger a short vibration. To do this, the components including different parts were grouped so that they could be manipulated as a single object to simplify the physic simulation and also to create the requested kinematic animations. For example, the imported press-fitting tool showed each part as an individual part –i.e., screws, bolts, and tool body– (Figure 4.8a-b); however, all static meshes of individual parts were grouped into only one entity. The collision shape needed by the grouped meshes allows the user to grab the whole object (Figure 4.8a-b). The interactions were enabled in the Unreal Engine platform thanks to a visual scripting, called

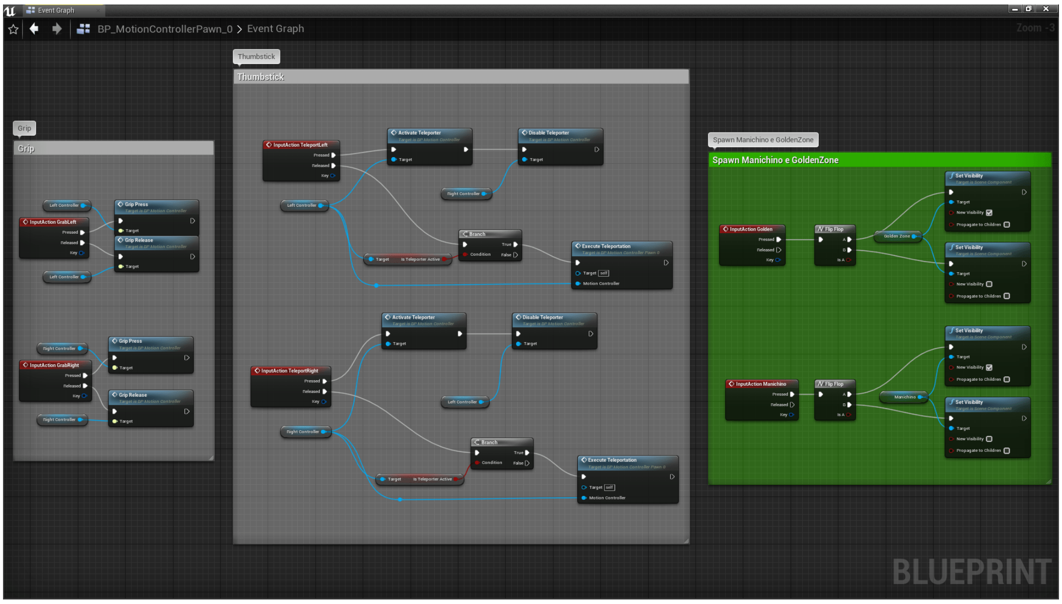


Figure 4.9: Event graph of the blueprint specifying the Scene Creation feature, from left to right: grip, thumbstick, manikin and golden zone.

Blueprint. In particular, to manage the grab interaction, a simple Blueprint was created aimed at implementing the input action for the grip on the controller. Figure 4.8c illustrates the details of the press-fitting station highlighting the touching and grabbing of the rotor press-fitting tools from the user's point of view.

Lastly, some specific interaction tasks were included in the VR scene with different levels of detail. In the e-axle project, three different specific interactions were implemented in the created VR scene: the virtual golden zone, the virtual menu, and training with holograms.

Virtual Golden zone - The manikin and golden zone models were considered for ergonomics assessment. A Blueprint was implemented, based on the visibility interaction, connected with the static mesh of the manikin and of the golden zone. To manage the manikin and/or golden zone visibility (input and output action) the blueprint was associated with the button "X" on the left-hand controller Figure 4.9.

Virtual menu - Another important interaction task was the creation of a virtual menu to control the e-axle box rotation on the cart and mimic the dressing operations. Three faces of the e-axle box (called A, B, and C) were identified to set the machine cycle and optimize the equipment positioning by the worker and obtain the e-axle dressing. To generate the rotation, a custom visual scripting was developed, connected with a virtual menu including the related three buttons (A, B, and C). The visual scripting was created using the Event Graph option available in the blueprint of the Unreal scene project. The blueprint was organized with three custom events blocks to activate the required face, three timelines blocks to manage the start and end positioning, three blocks to set the rotation of the e-axle relative to the environment, and one geometry represented by the e-axle model, all connected to each other. The rotation interaction allowed users to choose the preferred box face without order limitations (as shown in Figure 4.10).

Training with holograms - Finally, to mimic the e-axle dressing procedure as a training method, the "hologram" function was implemented. It was created the hologram for each component that took part in the machine's cycle. The blueprint contained a dressing sequence that brightened step by step the areas of the objects to give the order of the operation.

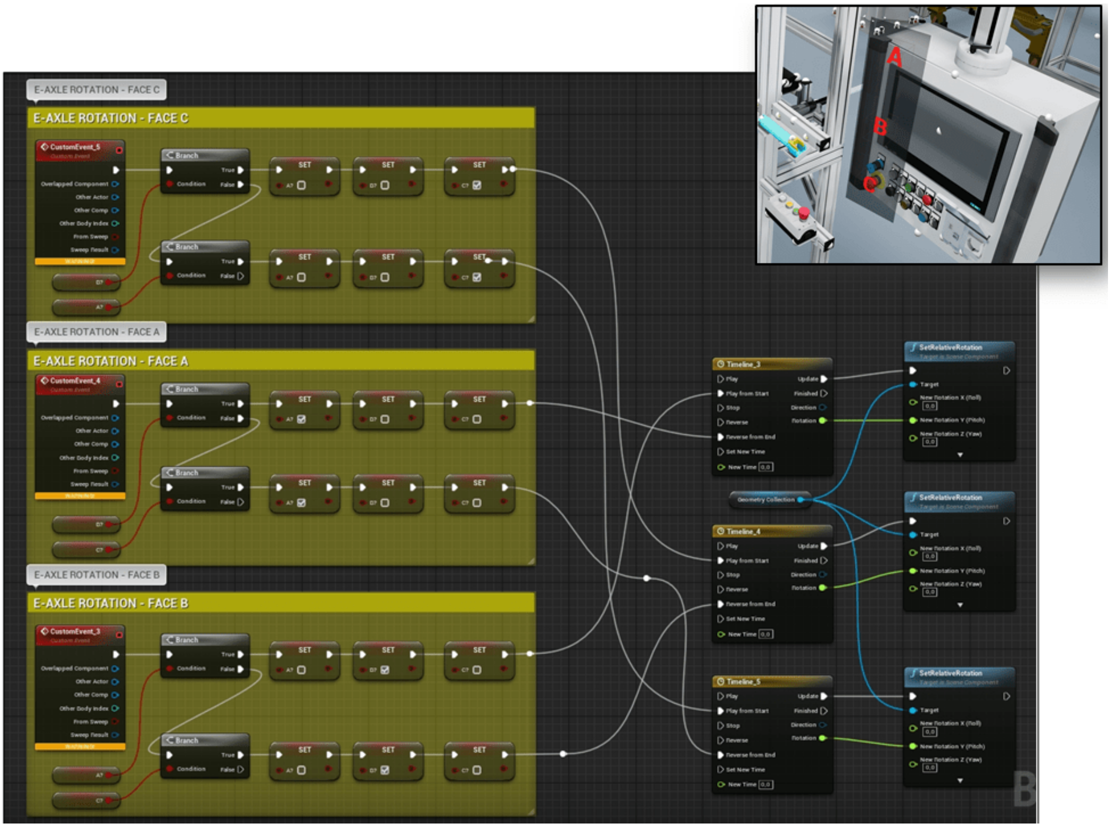


Figure 4.10: Event graph of the blueprint specifying the e-axle box virtual rotation. The subplot at the top right corner shows the interactive menu in the VR environment

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VR Review

After the VR environment setting, the VR Review phase was conducted. The VR sessions lasted from 1 to 4 hours for each session and involved about 20 people. The first VR sessions were organized to visualize singularly each station (i.e., the mainline, the subline, and the loading and unloading area), while the final VR sessions addressed the scene with all modules representing the overall e-axle production layout (reported in Figure 4.5).

Among the different scenarios, one was considered particularly useful for the company: the evaluation of the ergonomics of the operator. Usually, during the traditional design phase, the company already used import that manikin and golden zone in the software CAD to set the heights; differently, in the VR sessions, the scenarios were centred around evaluating the visibility of a worker given a particular setting or posture. In addition, to design an efficient and safe workplace and avoid ergonomics risks due to material handling (e.g., back injuries), the company team analyzed all the stations using the virtual golden zone. Indeed, in order to analyze the worker activities, the manikin and virtual golden zone visibility were managed by the Oculus controllers. The obtained result, shown in Figure 4.11, was a semi-transparent volume with different colours around the Manikin to point out the safety areas within which the operators are able to comfortably perform the tasks. For example, comparing the manikin golden zone placement with the gravity rack location allows the "spectators" to check whether the highest boxes are located in the correct position. Moreover, the users inside the VR scene were able to mimic the operation and check if the arm movements were in the golden zone.

Finally, one of the VR review sessions was focused on checking the e-axle box rotation on the cart and mimicking the dressing operations based on the previously created interaction (see Figure 4.12). During the ergonomic evaluation, three cart configurations were defined and compared before identifying the final version that ensures the worker tasks to be in the golden zone due to the e-axle dimensions.

4.4.3 Outcomes and Implications

In this subsection, we debate the VR approach's usability and advantages reporting the outcomes and implications derived from the analyzed case study.

As a first outcome, we highlight that differently from similar approaches [32], the defined VR approach is not limited to laboratory tests: in particular, the conducted case study in a real industrial setting shows that VR can be effectively integrated into a company process by our standard methodology with well-defined phases. Based on the lessons learnt from the presented case study, the company decided to implement the defined VR procedure as a standard enterprise policy to be followed in the design of CMSs by the different involved departments and in the relationship with customers and suppliers.

Second, we remark that the conducted VR reviews lead to tangible and relevant results. The comparison with traditional methods employed by the company shows that the 2D interfaces of CAD platforms have limits when bringing out the right impressions of the dimensions and proportions and reaching issues in 3D space. Conversely, by using the VR environment the whole e-axle assembly process was successfully analyzed, and various design issues were detected quickly as shown in Table 4.3. In particular, ergonomics and visibility are the two main sources of issues that professionals appreciate throughout the VR scene navigation. During the VR reviews, the professionals were able to use the VR scene to effectively design the equipment and tool positioning as if it were a traditional project CAD. For instance, to design a safety picking by the operators, they determined the optimal equipment position and orientation of the cart near the machine. Moreover, they mimicked the operator task to verify if the picking operation was conducted in an ergonomically correct fashion (i.e., without turning the wrist or the torso).

The last outcome concerns the virtual commissioning of the CMSs. As shown in the case study, virtual commissioning, above all in the automotive field, requires that well-defined phases are conducted by various tasks and responsibilities. As matter of fact, the concept, design, and project finalization phases are indeed strictly connected, with continuous information exchange. In this context, the proposed approach aims at achieving great advantages in terms of cost and time savings due to the correction of eventual design flaws. Time-saving represents the common goal of different similar methodologies (e.g., [36]). However, other methods are available focusing on a specific topic, for instance, using VR to address the ergonomics evaluation only [36]. Instead, as shown in the case study, the proposed VR approach can be implemented in the whole design phase to achieve findings from a wider engineering perspective. Moreover, the case study finalization highlighted that time savings were earned during the assembly phase since typical design issues were in advance fixed in the early phase thanks to the use of VR tools in the company CMS development process. Such time savings were estimated by the company based on the comparison with similar projects that were conducted through with traditional methodologies not relying on VR, experimenting several design issues until the production phase. Conversely, the e-axle project realized using the proposed VR approach layer was finalized with no open points reported through the CMS actual commissioning.

Summing up, the analyzed case study demonstrates that VR technology plays a crucial role in virtual commissioning and supports the engineering process development from the concept to

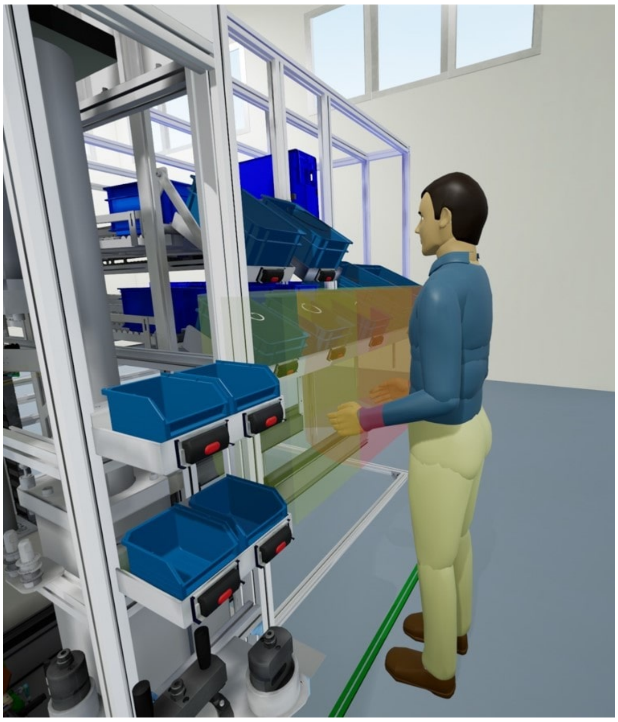

Figure 4.11: Example of the Golden zone method for the ergonomic assessment of the Gravity Rack in the e-axle CMS design.

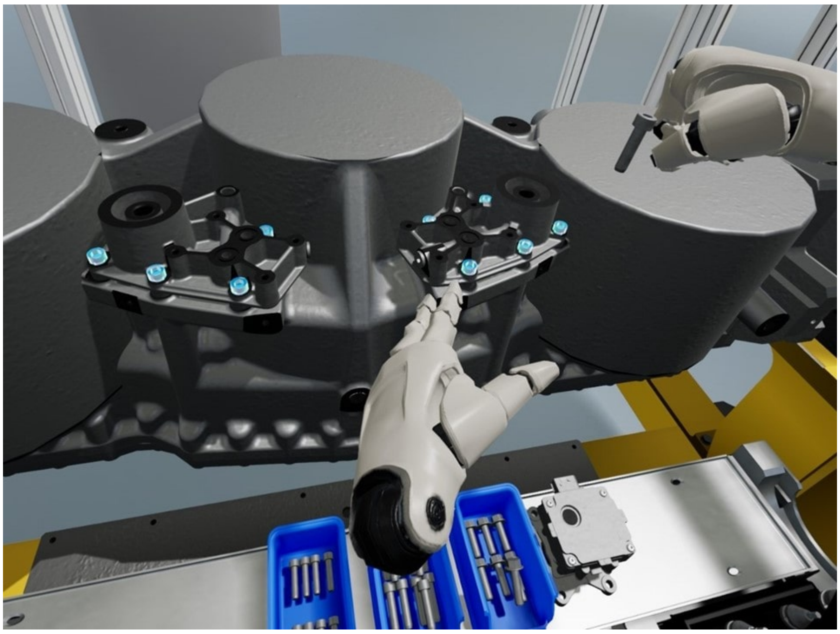

Figure 4.12: Example of touching/grabbing and assembly training tasks in the e-axle CMS design: details of the specific interaction using the light blue hologram to show the worker tasks step by step.

Table 4.3: Example of design issues related to ergonomics and visibility evaluation.

Design Issues	Ergonomics	Visibility
Gravity rack and box positioning	X	X
Press fitting tools positioning	X	
E-axle equipment positioning for kitting	X	
Powered driver positioning/handling	X	X
Tube oil orientations	X	
Ring nut screwing		X
Press fitting tool installation	X	X
Top bracket placement	X	
Return flow filter positioning	X	X
E-axle rotational displacement from cart	X	X
Box's cover handling/positioning		X
Space between cart handles	X	
The machine structure dimensions	X	
Special areas for maintenance operations	X	X
Distance between operator and HMI		X
Rotor and transmission inserting into the e-axle box		X
Stop-pallet sensors		X
PLC positioning		X
Dynamic leak test	X	X

the design phase while monitoring performance and providing optimised design solutions thanks to VR review sessions.

4.4.4 Evaluation of the proposed VR Approach from the Users' Perspective

For the sake of evaluating the acceptance by professionals of the proposed VR approach, in the framework of the e-axle CMS design project, the proposed VR approach was evaluated through a questionnaire. In particular, 23 selected users involved in the VR reviews were asked to fill out a questionnaire using Microsoft Forms. Participants, of an average age of 36 years and ranging from 23 and 60 years, include 2 Competence Leaders, 2 Project Managers, 1 Project Engineer, 2 Technical Leaders, 7 Designers, 2 Assembly Leaders, and 7 others. The gender division was unbalanced (namely, 2 females and 21 males), but was considered representative of the workforce in this kind of industry.

Apart from open-ended questions, the proposed questionnaire comprises three sections: familiarity with CAD-VR-GUI, workload, and VR usefulness and integration.

In the first section, participants were asked about their familiarity with CAD, Graphical User Interfaces (GUI), and VR using a 5-point Likert scale (1, No knowledge - 2, Slight knowledge - 3, Some knowledge - 4, Moderate knowledge -5, Extreme knowledge). In addition, participants were asked to indicate how many times (namely, one, two, or more than three times) they used VR tools during the session reviews.

In the second section, the well-known NASA Task Load Index (TLX) [62], [63] was used to assess the mental demand, physical demand, temporal demand, performance, effort, and

Table 4.4: Questionnaire results related to the interviewed participants' level of familiarity with interface tools.

	No knowledge	Slight knowledge	Some knowledge	Moderate knowledge	Extreme knowledge	Total replies
CAD	1	3	3	4	12	23
VR	5	4	6	6	2	23
GUI	7	5	2	4	5	23

frustration using a 20-point Likert scale (ranging from 1 - Very Low to 20 - Very High). The workload assessment was based on two hypotheses: the work is less than the critical value of 50, and the workload is not affected by the frequency of VR use.

In the third section, users were asked to answer specific questions aimed at investigating the level of "VR usefulness and VR integration" in the CMS design process of the company. In this case, a 5-point Likert scale was employed including the following values: 1 - Strongly disagree, 2 - Disagree, 3 - Neither agree nor disagree, 4 - Agree, and 5 - Strongly agree.

4.4.4.1 Questionnaire Results

As shown in Table 4.4, only a few participants declared a low level of familiarity with CAD: this is not surprising, because CAD software knowledge in the automotive sector is a required digital skill. Conversely, as for familiarity with VR and GUI, only a range between 2 and 7 people declared a high level of knowledge of these technologies.

To study how the so-called initial "wow" effect may have influenced the workload, a preliminary workload analysis was performed, focused on a comparison between two categories of users (i.e., "beginner" and "advanced" users). The group of beginners was composed of 11 people who used the VR device only once or twice during the VR sessions because they used to participate in the design by watching from a large screen. The group of advanced users was composed of 12

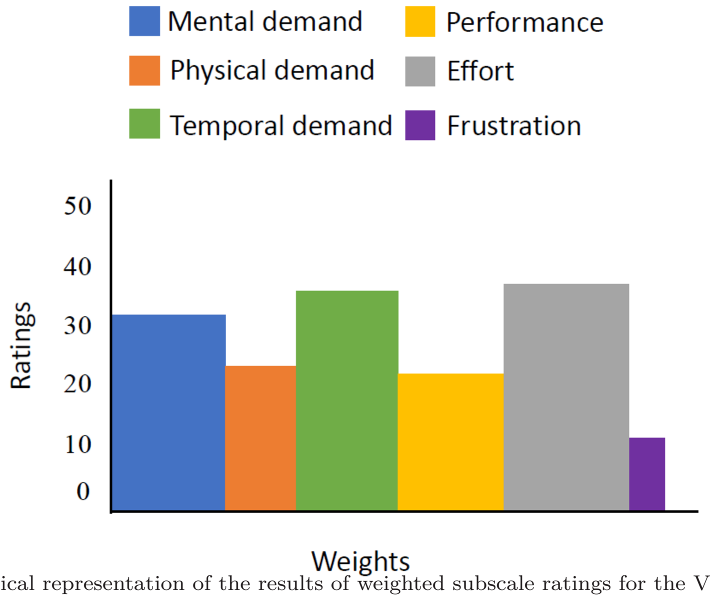

Figure 4.13: Graphical representation of the results of weighted subscale ratings for the VR approach workload using the standard NASA-TLX assessment tool.

Table 4.5: Questionnaire results related to the VR usefulness and VR integration (1 - Strongly disagree, 2 - Disagree, 3 - Neither agree nor disagree, 4 - Agree, 5 - Strongly agree)

Questions	Median Score
VR can help through the product life cycle.	5
VR has a positive effect on communication between departments.	4
VR enables me to see ergonomics flaws.	5
VR enables me to see design flaws.	4
VR enables me to see logical flaws.	4
Interacting with the components is fun.	5
Wearing the device is comfortable.	4
The interaction approach is intuitive.	4
I have been able to easily select and move parts of the power unit.	4
After removing the headset I felt dizzy.	2
Using VR I felt isolated from my team.	3

people who used the VR device more than three times. The Shapiro-Wilk normality test (AS R94 algorithm) [64] revealed that the data from both samples followed a normal distribution. Thus, we compared them as two unpaired samples. The unpaired t-test revealed that there was no statistically significant difference in the workload between the two groups [65] Subsequently, since the two groups belong to the same population, we performed the NASA TLX analysis of all users' responses. The obtained results for ratings and weights related to the six NASA TLX dimensions (namely, Ratings: Mental Demand 29.6, Physical demand 21.1, Temporal demand 35.0, Performance 20.4, Effort 35.9, Frustration 9.8; Weights: Mental Demand 3.17, Physical demand 1.74, Temporal demand 2.83, Performance 3.04, Effort 3.70, Frustration 0.52) are shown in Figure 4.13). The weights were derived for each participant by requiring simple decisions about which member of each paired combination of the six dimensions is more related to her/his definition of workload. For each participant, the rating sub-scale was then multiplied by the appropriate weight, developing a composite tailored to individual workload definition. The overall workload of the proposed VR approach is represented in Figure 4.13, with an average value of 30.14, which thus belongs to an intermediate workload range [62], [63] and is below the critical value of 50. Note that a high-value workload means high work stress producing decreased motivation, low morale and discipline, and poor work performance [66]; conversely, to reach the production target and compete with other companies, the employees must have good work performance in the work [67].

As summarized in Table 4.5, reporting the questionnaire results, we remark that users strongly agreed that the presented VR approach supports the design of a CMS through its whole product life cycle (the median score is 5 of 5 in the Likert scale), and it has a positive effect on communication between the company departments (the median score is 4 of 5 in the Likert scale). Similarly, most users strongly agreed that VR enables users to detect ergonomics (the median score is 5 of 5 in the Likert scale) and logical (the median score is 4 of 5 on the Likert scale) flaws during the project review using the VR device. In addition, a relevant 74% of users strongly agreed that the interaction with system components in the VR environment is fun (the median score is 5 of 5 in the Likert scale), and they agreed that the interaction approach is intuitive allowing to easily select and move parts of the power unit (the median score is 4 of 5 in the Likert scale). Moreover, two surprising results appear noting that wearing the device is almost comfortable (4 of 5 Likert scale), and most users on the fact disagree that after removing the headset they felt dizzy (2 of 5 Likert scale). Finally, the users neither agreed nor disagreed to feel isolated from the team while wearing the device during the VR review (3 of 5 Likert scale).

4.4.4.2 Discussion

As a first finding, we remark that the questionnaire supports the answers to RQ1 (Does the presented VR approach support the CMS design process?) and RQ2 (Which steps of the CMS process can benefit from the use of VR?), showing that the presented VR approach significantly helped the development of CMS, especially during the design phase. In fact, the VR approach was evaluated positively: in particular, interviews indicated that VR can help the CMS development throughout the product life cycle, identifying and addressing ergonomics, design, and logical issues before the assembly phase. Therefore, the VR technology plays an important role as a support tool in the design phase.

Another finding from the questionnaire results is related to the comparison between the use of the VR approach by beginner and advanced users. Such an analysis showed that in the presented case study there was no statistically significant difference in the workload at the end of the VR review between beginner and advanced users. It is worthwhile to highlight that the reported task workload was equal for both user groups; hence, also people using the VR tool for the first time are not significantly impacted by the corresponding workload.

Since all the team members obtained the same workload level that was also under the critical value of 50, we deduce that the proposed approach overcomes traditional methods thanks to the VR methodology integration acceptance by the users. Finally, we remark that the questionnaire analysis supports also the answer to the RQ3 (What is the professionals' acceptance of the VR approach for CMS design?): in fact, the findings obtained from the second part of the "usefulness and integration" questions highlighted that the interaction with the system component is fun and intuitive and wearing the device is comfortable.

4.5 Conclusion

The design of complex manufacturing systems (CMSs) is increasingly characterized by the need for co-design tools aimed at achieving product innovation as well as manufacturing efficiency and effectiveness, while minimizing risks and maximizing performance.

In this context, this chapter presents a novel procedure for the use of virtual reality (VR) as a virtual commissioning design tool for CMS industrial practice. Relying on a real case study regarding an electric axle production line, the proposed VR design approach demonstrated to be effective in the CMS design, especially from the perspective of critical design aspects such as ergonomics and visibility. With respect to traditional 2D tools, VR allowed a better organization of stations equipment and an improved manual object picking for different worker heights. VR also demonstrated its advantages in improving project decision timing and communications between professionals of different sectors and skills, thanks to the new and visual language.

The presented case study was enriched by the analysis of a questionnaire aimed at assessing the users' workload during the VR sessions and their corresponding technology acceptance, as well as evaluating how and how much this innovative technology can provide a helpful contribution to the design of CMSs. The questionnaire results showed a general appreciation of the VR approach, a non-critical workload even for beginners, positive usability, and ease of user feedback. This is an important result that highlights the usefulness of integrating VR tools in the company process also for beginner users.

Although the obtained findings cannot be considered conclusive, this manuscript provides some interesting directions for future work. Having established that VR provides considerable technical support to the design of CMSs, it would be interesting to investigate extending the use of VR to the commercial proposal phase and the concept phase, for instance generating a draft preliminary model aimed at showing the expected result early and making important decisions on time. Moreover, it would be interesting compare the approach with alternatives from in the related literature. Another aspect to be addressed is the application of VR to other steps of the CMS life cycle, such as training and maintenance application, and its integration with discrete-event simulation models of CMS, aimed at optimizing their design and operation (e.g., layout of the plant, performance of the production lines, routes of AGVs).

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Part 2: Optimizing the Operations of Manufacturing Lines through Digital Technologies

Chapter 5

Process Simulation for the Sustainability and Efficiency Optimization of Complex Manufacturing Lines

Abstract

Complex manufacturing systems are recently undergoing a green revolution due to manufacturing customization towards sustainable products. The desire to tailor production procedures in the search for more environmentally and energy-friendly products is driving this movement. A key enabler for the implementation of green and energy-efficient production is simulation-based design, which supports system engineers and designers in making decision choices-aimed at enhancing the performance of smart and sustainable production. In this context, this chapter proposes a simulation approach to support the design of the layout and operation of automated guided vehicles (AGVs) in complex production lines. It develops in response to the urgent need for flexible, environmentally responsible manufacturing procedures. In particular, a case study related to the assembly of electric axles for heavy-duty vehicles is presented: a scenario analysis implemented in the *Plant Simulation* platform is used to determine the optimal configuration of AGVs in terms of number of vehicles and operation (e.g., definition of charging strategies, scheduling of charging stops, routing). As the simulation unfolds, it reveals key insights. The simulation results first show that the reduction of the AGVs' energy consumption and the increase of production throughput are competing criteria; second, the choice of AGV charging strategies has a significant influence on the energy consumption as well as on the productivity performance.

Contents

5.1 Introduction

The industrial sector is undergoing a green revolution, where energy efficiency and sustainable manufacturing are becoming important design issues. The increasing awareness to safeguard the environment is indeed significantly influencing the manufacturing and production processes; simultaneously, manufacturing lines are increasingly becoming complex systems since modern markets require highly customized products in accordance with the *Industry 4.0* paradigm [1], [2]. For instance, in the automotive industry sector, the transition from internal combustion engine technologies to electric propulsion imposes huge challenges on all the involved market players. High-volume manufacturing lines dedicated to assembling electrical automotive components, such as battery packs and electric axles, are strongly requested by new markets.

In order to build sustainable manufacturing systems, several aspects must be simultaneously optimized, thus making engineers and designers face a manifold design problem. Simulation and digital engineering platforms represent a powerful tool to solve such a problem[3].

Independently from the industrial sector, one of the most popular issues addressed by simulation-based design of efficient and sustainable manufacturing systems concerns the layout and operation of material handling systems, used to move raw materials or finished products around production facilities. The efficient and cost effective movement of materials is indeed a crucial element in improving operations of manufacturing plants and warehouses. Material handling is often addressed by automated guided vehicles (AGVs), i.e., computer-controlled, wheel-based, and typically battery powered robots. There are several types of AGVs, generally classified based on the category of items to be transported: order pickers, forklift trucks, reach truck lifts, low-lift pallet trucks, and tugger trains [4]. The use of AGVs in the support of manufacturing lines leads to significant investments for companies, thus requiring designers to perform a tradeoff analysis between AGVs cost, their capability to enhance the production line performance, and their impact on the efficiency and sustainability of manufacturing processes. AGVs are usually equipped with a management and control unit that offers scheduling, routing, and self-adaptive configuration features [5]. Nevertheless, simulation focused on the AGVs layout and operation still plays an important role in the design of modern complex manufacturing systems. On the one hand, from an operational point of view, the objective of analyzing the performance of AGVs via simulation consists in optimizing the automated materials handling and determining the optimal flow paths which minimize the total traveled distance and reduce the traffic congestion, while maximizing the overall task throughput [6], [7]. On the other hand, from a strategic point of view, simulation-based approaches are useful to solve issues related to resource allocation of AGVs (e.g., loading and unloading buffers) as well as to determine the minimum number of vehicles to satisfy production requirements.

In this context, this chapter proposes a simulation approach to support the design of the layout and operation of automated guided vehicles (AGVs) in complex production lines. In particular, a real case study related to the assembly of electric axles for heavy-duty vehicles is presented: a scenario analysis implemented in the *Plant Simulation* platform is used to determine the optimal configuration of AGVs in terms of number of vehicles and operation (e.g., definition of charging strategies, scheduling of charging stops, routing, etc.). The simulation results first show that the reduction of AGVs' energy consumption and the increase of production throughput are competing criteria; second, the choice of AGV charging strategies has a significant influence on the energy consumption as well as on the productivity performance.

The rest of the chapter is structured as follows. Section 5.1 presents the related literature and the work positioning within it. In Section 5.3, we introduce the simulation model devised to scrutinize the optimization of AGVs within manufacturing lines. The proposed case study including the design problem related to the layout and operation of AGVs, the simulation scenarios and obtained results are discussed in Section 5.4. Finally, conclusions are reported in Section 5.5.

5.2 Related Works

The fourth industrial revolution is taking place as a key enabler of sustainable development goals [8], where one of the main challenges for modern manufacturing companies lies in tailoring their products and processes to meet the market needs [9]. To this aim, an important role is being played by several technological advances in the interoperability among different systems, machine semantics, cyber-physical systems, virtualization, and automation [10]–[13] as well as simulation-based design tools [14], [15].

Simulation is defined as experimentation through the digital representation that mimics the dynamics of a real-world system or process over time and helps better estimate and understand the modelled systems or processes through their behavioural analysis. In fact, across industries and disciplines, simulation modelling and analysis aim at giving clear insights into complex systems, by testing new processes, resources, and configurations before physically implementing them [16]. This approach eases the process for specialists to identify production losses forecast the outcome of the most promising improvement measures and increase the Overall Equipment Effectiveness (OEE) [17]. Moreover, simulation tools have the potential to optimize control mechanisms and support real-time decision-making related to optimal system operation and efficient resource exploitation [18]. The growing importance of simulation in the manufacturing field is demonstrated by the exponential increase of research efforts on this topic, which focus on current practices and future trends from the perspective of productivity and sustainability[19].

In the field of simulation-based design of AGVs, discrete event simulation plays a crucial role in project process improvement. Several tools such as the *Arena* [20] and *Plant Simulation* [21] platforms are available to create digital models of material handling systems in production lines and optimize their performance [22]. These simulation tools enable system engineers and designers to test intended changes in a given numerical environment to prevent costly errors that could arise during solutions implementation [23]. The related literature shows that one of the main research goals consists of applying suitable simulation tools to analyze production bottlenecks as well as energy efficiency margins due to the sub-optimal configuration of AGVs [24]. For instance, thanks to quantitative analysis, it is possible to solve bottleneck issues by optimizing logistics flows and introducing the Kanban pull system [25]. Gregor *et al.* [26] optimize and verify AGV logistics supply routes using a computer emulation system. Defining a mechanism that simultaneously schedules the assembly operations on each workstation and the AGVs routes allows for enhancement of the main production performance such as the overall manufacturing time [27]. Neradilova *et al.* [28] propose a simulation approach to model the supply process, which is based on additional programming and implements various analyses on loading and unloading AGVs.

Currently, there is a major trend in the supply process to use various automated systems. In this direction, AGV is one of the high-performance tools in a wide range of logistics activities and processes. It can be used to move objects of different volumes, small and big such as a maritime container [29].

In addition, using model simulation it is possible to quickly summarize the model outcomes based on the advantages and disadvantages of the instrument for the planning of internal logistics [30].

The previous literature review highlights that event-discrete simulations are commonly used to analyze the AGVs number, their paths, battery capacity, and speed, and to optimize their path layout independently from the application field. However, only a few studies investigate the connection between the operation and the energy consumption of AGVs from a sustainable manufacturing perspective [31], [32]. For instance, authors in [31] propose a conceptual tool that integrates sustainable supply chain management with the proposed hierarchical decision-making framework for AGVs. Authors in [32] present a special focus on Industry 4.0 (I4.0) to make an evaluation of sustainable I4.0 innovations.

In addition, to the best of the authors' knowledge, in the related literature, no contribution exists addressing the influence of energy charging strategies of battery-powered AGVs on both the production and energy performance of complex manufacturing systems. To fill such a gap, the goal of this chapter is to present a real case study, where a simulation-based model is used to

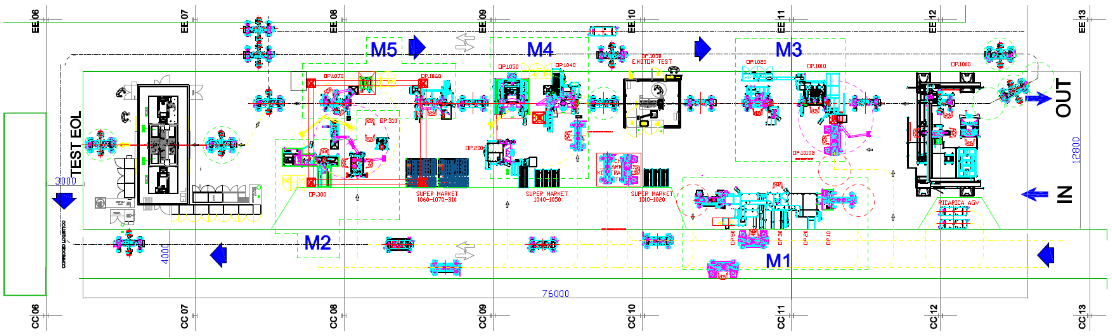

Figure 5.1: The core section of the considered production line on a 1:600 scale: layout of the mainline (modules M2, M3, M4, and M5) and subline (module M1), including the loading and unloading area (IN-OUT) for the box preparation and the testing area (TEST EOL).

support the optimal design of the layout (i.e., the number of vehicles) and operation (i.e., the battery charging strategy) of AGVs from a sustainable and productive perspective.

5.3 The Proposed Simulation Analysis for Optimizing AGVs in Manufacturing Lines

In collaboration with an Italian automotive company leader, we present a real case study related to the simulation model of the production line of a 1.2 tons electric axle (e-axle) of heavy-duty vehicles, where battery-powered AGVs are used to move carts, pallets, and finished e-axles throughout working areas and stations. The AGVs represent the only category of vehicles used to move components in the line.

5.3.1 E-axle Assembly Line Presentation

In the considered assembly line, e-axles are assembled on a cart and moved by AGVs between different stations. For this reason, each station has been completely customized, including the entrance and exit gates for the AGV cart. The overall line extends on 1864 square meters and is composed of a core section and three support areas. The core section is divided into two parts: the mainline and the subline. On the one hand, the mainline is composed of four modules and the workstation is where the e-axle is assembled on a cart and moved by AGVs between the machines. On the other hand, the subline includes a module with the rotor and transmission preparation stations. Three support areas include the kitting area, where operators prepare the sub-assembly of motors (transmissions, e-axle box cover, and axes), the loading and unloading area for the e-axle box positioning on the cart, and the testing area at the end of the line (EoL), as shown in Fig. 5.1.

5.3.2 Simulation Model Description

The production line under consideration has been meticulously modelled using *Plant Simulation* version 15, which is a simulation environment included in the *Siemens Tecnomatix* suite for product lifecycle management and digital manufacturing [33]. In particular, Plant Simulation is a software tool that enables to generate and analysis of discrete events simulations with the aim of creating digital models of complex manufacturing systems. It allows for the examination, evaluation, and optimization of the manufacturing processes and their performance [34]. It is also

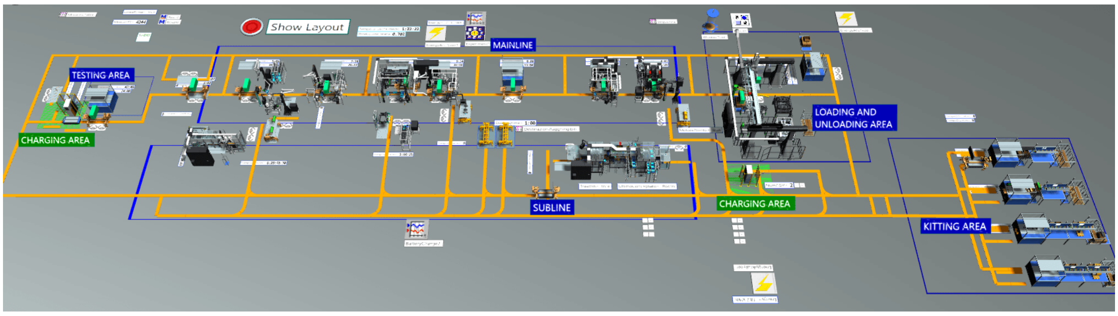

Figure 5.2: Model of the considered production line using the Plant Simulation platform: overview of the kitting area, loading and unloading area, mainline, subline, and testing area

used to optimize material flow, the use of resources, and logistics processes. Furthermore, the functionalities of standard components can be easily extended through the well known embedded programming language *SimTalk* [35].

The simulation model of the case study depicted in Fig. 5.1 consists of a set of assembly instructions that formally specify all the steps to be performed to produce an e-axle. The e-axle assembly order list is an input for the modelling and simulation phase: in particular, each e-axle component must be manufactured and assembled in accordance with a given quantity and an established order of completion. In the simulation model, the boundaries of the production line are delimited, on the one hand, by a source where the elementary parts are created, and, on the other hand, by a drain where the e-axles are delivered. The path of AGVs is guided by tracks that pass through the line stations and are organized into different areas. Some stations are made up of a conveyor to pass the pallet, and there are two buffer areas –located in the centre of the production facility– where the AGVs can park the off-process carts. Finally, two charging stations (one on the mainline and one on the subline) are available for the AGVs: these are also used as standby areas by the AGVs to spend the idle period between consecutive missions. The resulting Plant Simulation model is shown in Fig. 5.2. This digital representation serves as a valuable tool for in-depth analysis, optimization, and scenario testing to enhance the efficiency and performance of the e-axle production line.

5.3.3 AGV Design Problem Formulation

The above described simulation model is employed to address the AGV design problem formulated as follows. First, the optimal number of AGVs has to be determined. In particular, while in the mainline one AGV is enough to ensure the needed flow of materials throughout the corresponding stations, the deployment of additional AGVs in the subline can influence the performance of the overall production line. For this reason, the choice of the number of AGVs is focused only on the vehicles serving the subline. Second, since the AGVs are battery-powered vehicles, the optimal strategy for the battery charge has to be determined, considering not only the energy consumption dynamics but also the effects that the charging mechanisms have on productivity [36]. Summing up, the objective of the simulation model is to test and compare AGVs alternative configurations in terms of number of vehicles and operation (e.g., scheduling of charging stops, routing, etc.).

To this aim, the following key performance indicators (KPIs) are employed to assess the simulation results:

- AGVs Energy Consumption (AEC), measured in kWh: this indicator represents the cumulative amount of energy consumed by the whole fleet of AGVs over all the considered

Table 5.1: Scenarios Parameters

Parameter	Scenario A	Scenario B
Number of AGVs	2	3
Minimum charging time for strategy S_T	1600 s	1500 s
Charge level threshold for strategy $S_{\%}$	10%	15%

production period.

- Average Throughput (AT), measured in pieces/hour: this indicator denotes the average number of units (i.e., e-axles) that are produced within a certain period.
- Average Exit Interval (AEI), measured in hours: this indicator represents the average time that a piece spends moving in the line before exiting to the final destination.

Note that AT and AEI are KPIs directly connected to the Overall Equipment Effectiveness (OEE) index, which is a well-known industry standard for measuring manufacturing efficiency [37]. OEE results from three factors: availability, performance, and quality. This work considers the quality index's unit value and focuses the analysis on the other two factors intrinsic to the analyzed AT and AEI indices.

5.4 Case Study: The Analysis of AGVs Operations in an E-axle Assembly Line

5.4.1 Scenarios Setup

The simulation model is employed to assess two scenarios –denoted as Scenario A and Scenario B– whose main parameters are reported in Table 5.1. Scenario A considers 2 AGVs (one for the mainline and one for the subline), whilst Scenario B considers 3 AGVs (one for the mainline and two for the subline). In addition, for each scenario, two different AGV battery charging strategies are considered alternatively. The first strategy (denoted as strategy S_T) consists of a time-based rule: once the AGV enters the charging area (Fig. 5.3), it remains plugged at least for a minimum time period, before redeparting towards a subsequent mission. Conversely, the second strategy (denoted as strategy $S_{\%}$) relies on a threshold-based rule: once the AGV enters the charging area (Fig. 5.3), it remains plugged until the battery capacity is higher than a given threshold, before redeparting towards a subsequent mission. For the sake of optimizing the performance of the simulation model, each strategy S_T and $S_{\%}$ gets different parameter values for Scenario A and B, as shown in Table 5.1.

The other simulation parameters are the same for both Scenario A and B. In particular, all the considered AGVs are of the same type and have a battery capacity equal to 200Ah. As for the analyzed production time, simulations are focused on a time window of 7 working days.

Finally, an availability analysis is performed by varying the availability percentages of system components (i.e., the stations of the mainline, the stations of the subline, the AGV serving the mainline, and the AGVs serving the subline) in the range from 70% to 99%. Specifically, different numerical experiments are conducted through the "Experiment Manager" (EM) tool of Plant Simulation, which allows setting the experiment input and output parameters and the needed number of observations. In the first set of experiments, all system components have availability equal to 70%, 80%, 90%, and 99%. Subsequently, in order to conduct a more detailed analysis, in the second set of experiments, the availability values are set equal to 70% for all system components (namely, the mainline, the sub-line, and the AGV of the mainline) except for one (i.e., the AGV of the subline), whose availability is instead set equal to 99%.

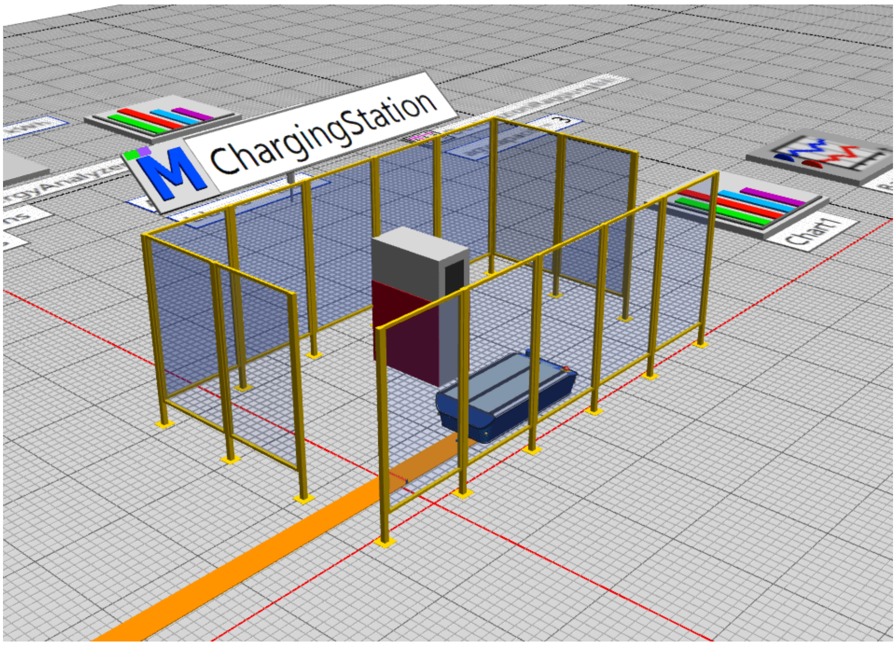

Figure 5.3: AGV charging area in the Plant Simulation model

Table 5.2: Scenarios Results

	Scenario A					
Availability of components	**AT** $S_{\%}$ **[pieces /hour]**	**AT** S_{T} **[pieces /hour]**	**AEI** $S_{\%}$ **[hh:mm:ss]**	**AEI** S_{T} **[hh:mm:ss]**	**AEC** $S_{\%}$ **[kWh]**	**AEC** S_{T} **[kWh]**
70%	0.328	0.327	02:47:42	02:44:02	7.989	7.962
80%	0.368	0.369	02:30:45	02:27:39	8.912	8.803
90%	0.408	0.409	02:17:17	02:14:08	9.863	9.692
99%	0.448	0.45	02:06:22	02:03:14	10.681	10.477
70%–99%*	0.442	0.444	02:07:26	02:04:35	10.549	10.388
	Scenario B					
Availability of components	**AT** $S_{\%}$ **[pieces /hour]**	**AT** S_{T} **[pieces /hour]**	**AEI** $S_{\%}$ **[hh:mm:ss]**	**AEI** S_{T} **[hh:mm:ss]**	**AEC** $S_{\%}$ **[kWh]**	**AEC** S_{T} **[kWh]**
70%	0.483	0.58	01:37:16	01:16:51	9.509	17.636
80%	0.6	0.668	01:26:10	01:24:30	13.115	19.708
90%	0.649	0.76	01:16:33	01:14:56	14.721	21.782
99%	0.654	0.845	01:08:51	01:07:39	13.238	22.601
70%–99%*	0.613	0.61	01:32:54	01:32:59	18.109	26.535

* all system components have availability equal to 70% except for the subline AGV whose availability is instead set equal to 99%

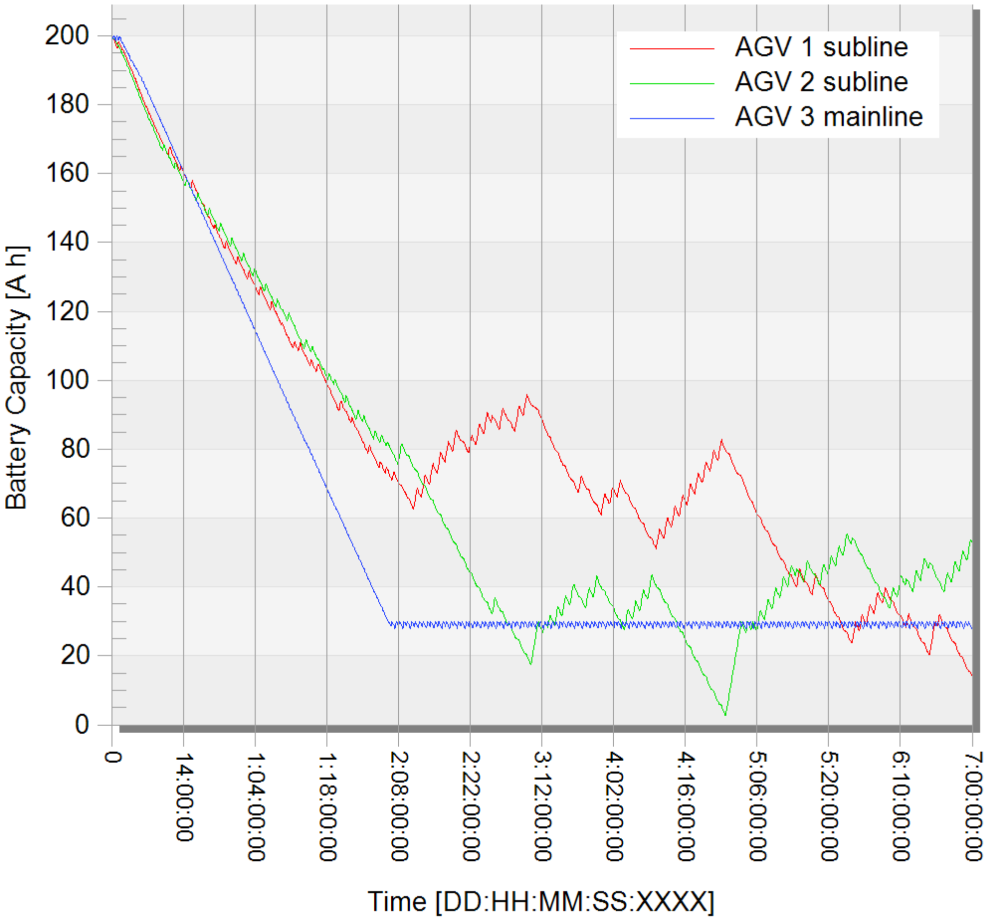

Figure 5.4: Evolution of AGV battery charge in Scenario B with strategy $S_{\%}$.

5.4.2 Results Analysis and Discussion

The results of the numerical experiments are shown in Table 5.2.

As for Scenario A, the obtained results are very similar in the case of both strategy S_T and $S_{\%}$, as shown in the first sub-table of Table 5.2. In particular, there is no significant difference between the AEC, AT, and AEI values corresponding to each case of the first availability analysis (first four rows on the left of Table 5.2). Obviously, for the highest analyzed availability percentage (i.e., 99%), the AT and AEI have the best value, whilst the AEC increases to the highest value. The second analysis shows that the optimal performance indicators values are obtained with availability values equal to 99% and 70% for the subline AGV and the other system components, respectively (fifth row of Table 5.2); however, the obtained performance indicators are very similar to the results achieved with all the parameters equal to 99%. Moreover, also in the second analysis the obtained results are similar for both strategies S_T and $S_{\%}$. This result shows that the number of subline AGV represents the bottleneck of the process.

As for scenario B, as shown in the second sub-table of Table 5.2, a significant difference between the results obtained using strategy S_T and $S_{\%}$ is evident for all the availability percentages of the first analysis (first four rows of Table 5.2 to the right). In particular, the values of AT generated using strategy S_T are much higher than those obtained in the case of $S_{\%}$. Similarly to Scenario

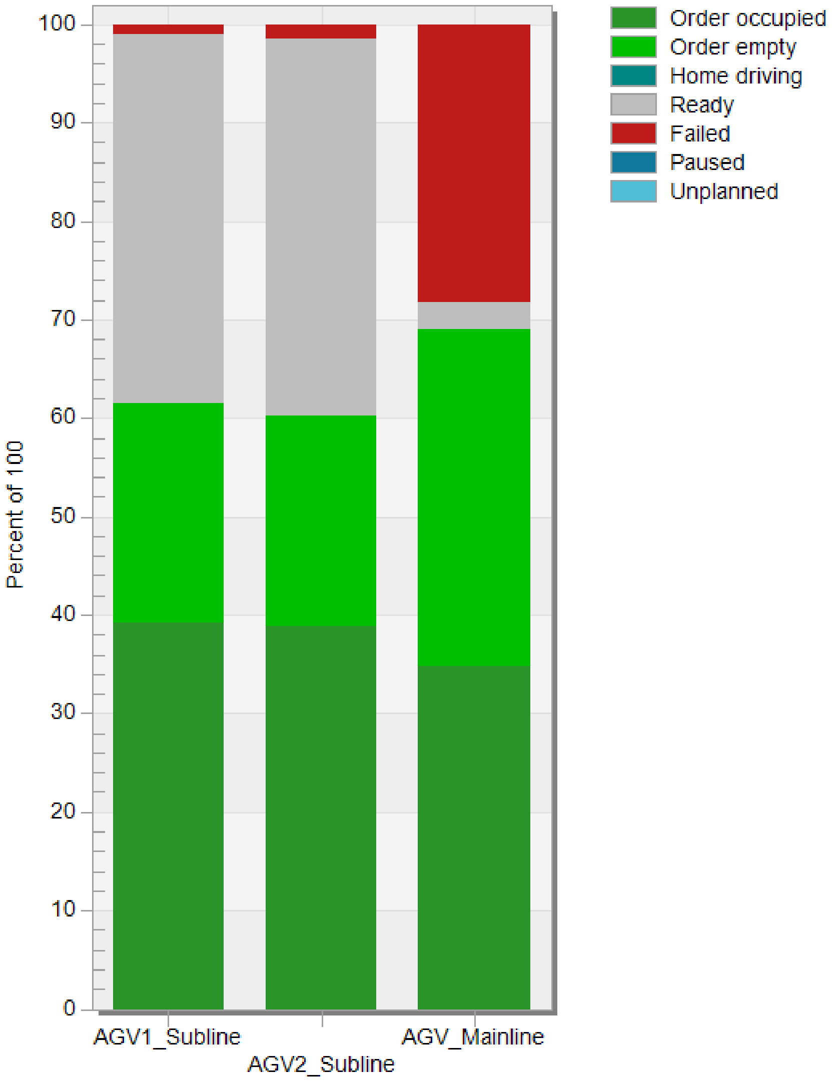

Figure 5.5: Workload of AGVs in Scenario B with strategy $S_{\%}$.

A, the second analysis shows that the best results are obtained with all the input parameters equal to 70% and the subline AGV availability equal to 99% (fifth row of Table 5.2): all the performance indicators are very similar to the results obtained with all the parameters set to 99% and using the strategy $S_{\%}$. In addition, differently from Scenario A, the energy consumption in the case of strategy S_T (i.e., AEC = 26.535 kWh) is higher than in the case of strategy $S_{\%}$ (AEC = 18.109 kWh). Therefore, in Scenario B the deployment of an additional AGV in the subline allows for improving the value of the AT and AEI while generating a non negligible increase in the AEC.

The numerical experiments conducted through the “Experiment Manager" show the AGVs' dynamics by different charts, for instance, in Fig. 5.4 and Fig. 5.5 it is possible to follow some details about the AGVs using strategy $S_{\%}$. In particular, the chart in Fig. 5.4 shows the evolution of theb AGV battery charge in scenario B with strategy $S_{\%}$ and setting all the availability at 99%.

Instead, Fig. 5.5 shows the workload of the AGVs showing failure, occupancy, and other details.

Summing up, the outcomes of the conducted experiments show that productivity and energy performance are competing criteria (e.g., the deployment of additional AGVs both improve the throughput and increase the energy consumption); moreover, the choice of the AGV charging strategies directly has a significant influence on energy consumption as well as on productivity performance.

5.5 Conclusion

This chapter has demonstrated the value of simulation-based models to assist system engineers and designers in making design decisions targeted at improving the performance of sustainable and effective manufacturing systems through the presentation of a real case study pertaining to the arrangement and operation of AGVs in the automotive production line. By using scenario analysis in the Tecnomatix Plant Simulation platform, this research deftly highlights a crucial trade-off between the need to lower the energy consumption of AGVs and the goal of increasing manufacturing system productivity. The case study's findings unequivocally highlight the fact that any productivity-boosting strategy will inevitably result in higher energy usage. The results of this study have significant implications for the current state of manufacturing systems, where efficiency and sustainability are top priorities. The efficient handling of this energy-production performance trade-off is essential for industries trying to strike a balance between the need for environmental sustainability and productivity targets. As a result, this chapter offers insightful information and a useful framework for enhancing AGV operation and design in intricate manufacturing systems.

The presented study is not without limitations, which will be the focus of future investigations. In order to perform a comprehensive assessment, a cost analysis should be added to enhance the simulation results and help the decision maker choose the best AGV configuration. Moreover, the model can be further optimized by including the simulation workers operating around AGVs and line stations, integrating their tasks in the computation of the overall station processing time, and analysing their use of AGVs from an ergonomic perspective.

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Chapter 6

Hierarchical Digital Twin for the Performance Optimization of Complex Manufacturing Lines

Abstract

In the era of industry 4.0, the Digital Twin (DT) serves as a digital replica of real manufacturing systems, capable of representing complex physical assets and intricate system interconnections. The DT is an invaluable tool for industrial professionals, supporting activities ranging from design and monitoring to maintenance and management. While the related literature comprehends various studies on the use of DTs for one of these purposes individually, a notable gap exists in terms of integrating and interconnecting the DT across the distinct phases of the entire lifecycle of plants. This contribution aims at bridging this gap by proposing a hierarchical DT (HDT), which utilizes a unified simulation framework to consolidate data derived from individual digital models created throughout the development of manufacturing systems. In particular, the resulting HDT leverages a hierarchical architecture that combines the process and product virtual spaces from different levels of granularity (i.e., machine, line, plant). This hierarchical architecture enables the creation of logical representations of the entire manufacturing system and the integration of data-driven model within the environment. The presented approach is applied to a company real case study related to the production of electric axles, where the HDT developed for the initial design phase offers an efficient solution for the real-time monitoring of the entire plant operations including intra-logistic activities.

6.1 Introduction

In the last decade, an impressive revolution has changed manufacturing [1]. The new manufacturing paradigm is the result of shorter product life cycle, product customization, and interactions between humans and industrial autonomous systems in close proximity [2]. The *industry 4.0* paradigm is revolutionizing manufacturing enterprises, changing the basic concept of automation toward digitalized products and smart logistics [3], [4]. In order to implement a strategy to quickly and safely design and integrate collaborative systems, Industry 4.0 defines a merging of physical and virtual worlds [5], [6]. In this context, the *Digital Twin* (DT) approach plays an important role in the design and operation of complex manufacturing systems [7]. DT is an intelligent digital representation of a physical system, which allows to enhance the system performance ranging from the design to the operational perspective [8].

As computational and communication technologies continue their rapid advancement, DTs are in turn growing in terms of sophistication and intricacy, while incorporating elements and techniques from diverse domains such as the internet of things, big data, cyber-physical systems [9]. As the backbone of industry 4.0, in the contemporary landscape of manufacturing, production lines work with massive data flows. In response to this escalating demand for data collection and processing, DTs have assumed a pivotal role across all phases of production, spanning design, development, testing, actual production, as well as assessment and the fine-tuning of processes [10]. In particular, the creation of a DT entails the systematic collection and analysis of data from a multitude of sources. These data encompass physical dimensions, manufacturing specifics, operational records, and information streams derived from analytical software. This amalgamation of data is then employed to construct a virtual model [11]. When meticulously designed, this model serves as a highly precise simulator, faithfully replicating the behaviour and characteristics of tangible physical assets and their operational modalities [12]. In the context of manufacturing, one of the most important applications of DTs is thus simulation, aimed at assessing and optimizing the performance of production systems [13] as well as supporting activities ranging from design and monitoring to maintenance and management [14].

While the related literature comprehends various studies on the use of DTs typically for design and operation individually, a notable gap exists in terms of integrating and interconnecting the DT across the distinct phases of the entire lifecycle of manufacturing plants. This paper aims at bridging this gap by proposing a hierarchical DT (HDT), which provides a unified simulation framework to consolidate data derived from individual digital models created throughout the development of manufacturing systems. In particular, the proposed HDT leverages a hierarchical architecture that combines process and product virtual spaces from three different levels of granularity (i.e., machine, line, plant). This hierarchical architecture enables the creation of logical representations of the entire manufacturing system and the integration of causal models from data within the environment. The presented approach is applied to a company real case study related to the production of electric axles, where the hierarchical DT is developed and employed from the initial design phase until the real-time monitoring of the entire plant operations, including the intra-logistic activities.

The rest of the chapter is structured as follows. Section 6.2 illustrates the state of the art on digital technologies for the industrial context setting, specifically positioning the paper in the related literature on DTs used in smart manufacturing. The novel HDT approach for smart manufacturing is presented in Section 6.3. Section 6.4 illustrates the application of the proposed approach to the real case study, showing the effectiveness of HDT in supporting and monitoring several process levels in manufacturing systems. Finally, concluding remarks are reported in Section 6.5.

6.2 Related Works

Among the many manufacturing applications in which digital technologies are applied, the automotive industry is leading the way in the digital transformation of manufacturing processes [15]. Indeed, industry 4.0 is defined by the seamless integration of digital technologies by merging physical and virtual worlds to enhance automation. Additionally, the necessity of environmental sustainability and the ensuing electrification have fundamentally changed how businesses operate, what consumers want, and how consumers behave. The automotive industry has been quick to adopt these new technologies to stay competitive since the emergence of smart factories [16]. The increasing demand for high-quality output, cost-effectiveness, and flexibility in production lines is being met in large part by digital technologies. In such a context, applying simulation tools has been traditionally one of the most common options to analyse and execute performance evaluation of production systems. In particular, three major methodologies are commonly used to build simulation models: discrete-event modelling, agent-based modelling, and system dynamics. Independently from the underlying methodology, simulation models represent the events occurring in a manufacturing system during the operational phase by a sequence of steps that are executed by a computer program [17]. This time-lined sequence is generated with respect to a set of rules modelling the behaviour of the system. Accordingly, the characteristics and relationships between the elements in a production system can be described in detail. However, simulations are often used for specific scenarios and may not persist through the entire lifecycle [18]. In addition, simulation models can vary in complexity, from simple statistical models to complex, detailed representations [19].

To overcome the limitation of traditional simulation tools, recently the DT paradigm has been introduced and widely accepted in the manufacturing context: the main idea of DTs is to provide a link between the physical and digital worlds of manufacturing. DTs are digital replicas of actual systems, processes, or objects that offer performance and behaviour insights in real time [20]. DTs have emerged as a powerful tool to enhance efficiency, quality, and innovation, most often in the automotive domain, although it can be observed that in all manufacturing domains the DT research has experienced significant growth. Following a thorough review of the literature, authors of [21] affirm that DTs are entering a phase of rapid development, supported by practitioners and researchers worldwide. For the sake of fully realizing the potential of DTs in industry, authors are investigating practical applications and approaches of DTs during both the design and monitoring phases of manufacturing systems. In order to simulate, analyze, and optimize the behaviour of machines, processes, and entire production lines, DTs act as intelligent digital clones of real systems. In this regard, authors of [22] propose the idea of next-generation DTs, emphasizing the advantages of DTs in terms of increased productivity, streamlined development procedures, and better product quality. Similarly, authors in [23] show the benefit of DT as a reference model in the design of a physical product. DTs greatly support engineering efforts by helping with problem detection and correction early on in the design process. They offer insights into possible design flaws and enable adjustments prior to the creation of physical prototypes by simulating real-world conditions. Reducing design iterations, minimizing expensive errors, and speeding up time-to-market are all made possible by this capability. DTs also aid in the early detection and correction of problems in design, supporting engineering efforts.

The utility of DTs extends well beyond the design phase [24]. For instance, authors of [25], [26] propose a new DT-driven approach for product engineering, design, manufacturing, and maintenance. In contrast, DTs for monitoring provide real-time information on machine performance, enabling proactive maintenance and effective operation. DTs offer in-the-moment analysis and diagnostics during the monitoring and production phases, being able to anticipate prospective issues or maintenance requirements when combined with sensors and real-world data, and improving the production efficiency and downtime reduction. Through monitoring and predictive analytics, DTs can anticipate machine failures or performance degradation, allowing for timely interventions and preventing costly disruptions [27]. Supply chain simulation with DTs allows for end-to-end visibility and optimization [28]. This ability is especially important in the automotive industry, where intricate and interconnected supply chains are common [29]. DTs enable automakers to cut lead times, increase overall supply chain efficiency, and make well-informed decisions by providing real-time data on inventory, demand, and logistics.

In summary, the previous literature review highlights that simulations of manufacturing conducted using DTs aim at enhancing productivity, streamlining development, and improving product quality. Even though the DT paradigm could be applied to complex systems, a notable gap exists in terms of integrating and interconnecting the DT across distinct components of a manufacturing system, while supporting the design phase and optimizing the corresponding operations. Nevertheless, by concentrating on a practical application inside the automotive industry, this study adopts a pragmatic approach. By identifying digital technologies and assessing their possible integration into the proposed methodology, we aim at addressing particular issues associated with increasingly complicated and highly customizable manufacturing systems. The considered case study recognizes the variety of needs within the organization and classifies them according to the levels of the product and process. In contrast to previous research, this work attempts to close the gap between theoretical understanding and real-world application in the operational environment. As research on DTs continues to evolve, our goal is to make a significant contribution by analyzing various levels of DT application and defining a hierarchical DT structure that empowers the company to thrive in a dynamic and evolving business landscape. The added value of our proposed methodology is to preventively analyze different production scenarios, evaluate and debug solutions, and make human-machine interaction simpler and more effective, while improving time, costs, and quality.

6.3 The Proposed Hierarchical Digital Twin

The proposed approach relies on a hierarchical framework composed of three levels of DT:

1) Machine DT - At the lowest level, all machines and working stations included in a production line are represented by Machine DTs (first level). This stage involves a thorough analysis of the functionality and interactions between machine parts.

2) Line DT - Moving up in the hierarchy, the manufacturing line is modeled as a whole in the Line DT, which includes all components as well as performance metrics and parameters related to machine-to-machine and process-wide communication (second level). This stage offers a thorough understanding of the production line features in terms of efficiency and interconnection between the machines.

3) Plant DT - Finally, at the top of the hierarchy, the Plant DT represents the entire manufacturing facility (third level). This stage takes all the facility's operations into account, including the logistic flows needed to connect each machine with the production lines.

The above cited DTs are grouped as all-encompassing models in accordance with a matryoshka framework (Fig. 6.1). From the macroscopic perspective of the plant down to the microscopic point of view of individual machines, the HDT hence provides a comprehensive representation of the entire production system, enabling an in-depth analysis of interactions, dependencies, and efficiencies over the defined levels. The architecture and features of the DTs employed at each level are described in detail in the following.

6.3.1 Machine Digital Twin

The implementation of a Machine DT can be applied to the equipment or individual machines of a production line, By using this DT, machine components may be thoroughly examined, including the software logics that are typically coded into Programmable Logic Controllers (PLCs). An integrated hardware and software architecture is used to make virtual commissioning of complex machines easier. This architecture provides a solid foundation for simulations designed to examine the system's mechanics, kinematics, and automation logic. It represents the model base for monitoring and oversight of the machine's operation using the real machine and the related DT simulation.

The main architectural components of the Machine DT include the Mechatronic Module, which utilizes Computer-Aided Design (CAD) software along with electrical and software module, and the PLC modules, as shown in Fig. 6.2.

Mechatronic Module: CAD software, in conjunction with electrical and software modules, is the mechatronic core part of the DT. CAD modelling software simplifies the management of constraints and kinematic properties, creating precise digital models of machinery and equipment. The electrical component defines and simulates the behavioural models of each equipment piece, while the software component finalizes the design definition and behaviour of the equipment, sensors, and actuators through coding specified for the automation part.

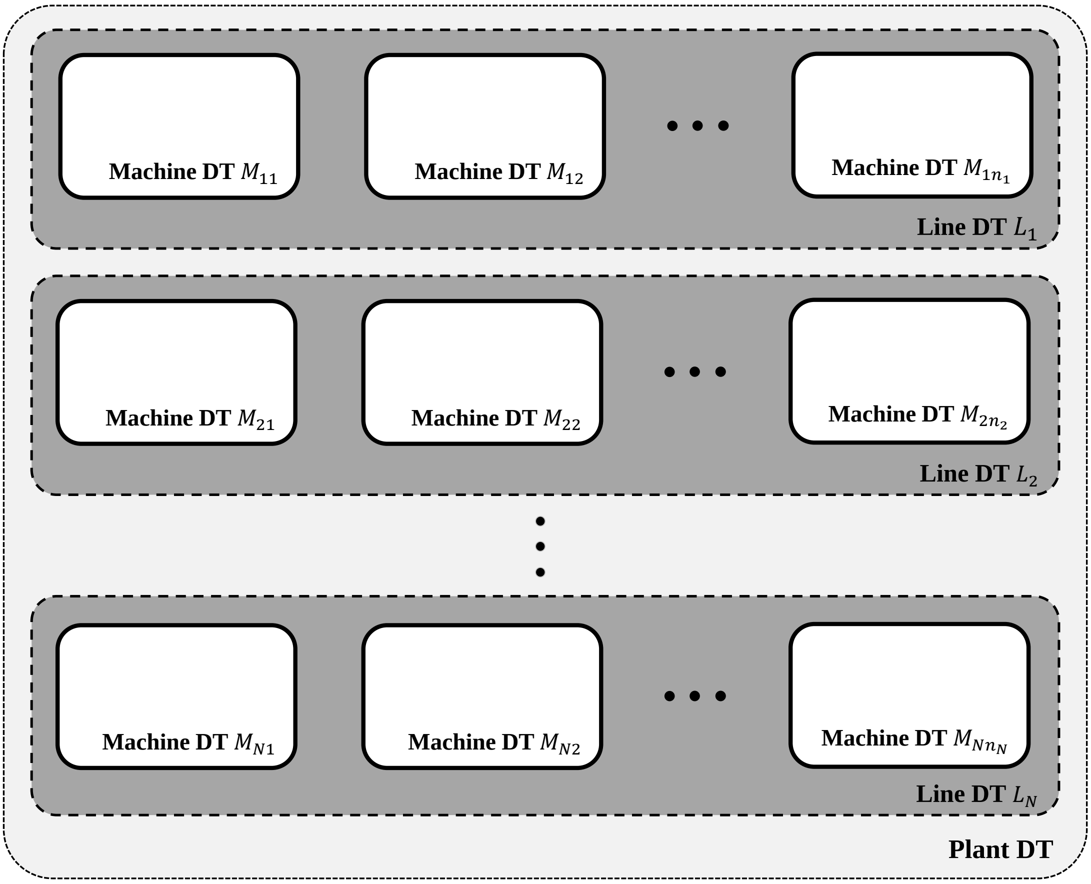


Figure 6.1: Architecture of the proposed Hierarchical Digital Twin for smart manufacturing.

PLC: Control logics are integrated into mechatronic module for real-time control, testing, validation, and simulation, enabling accurate manufacturing process replication and data-driven optimization. Specifically, PLCs are employed to perform both laboratory simulation and real-time monitoring. On the one hand, laboratory simulation allows to perform debugging in a virtual environment using an emulated or real PLC. This allows for in-depth testing and analysis of CAD-designed software logic, preparing for real commissioning procedures. Depending on the type of deployed PLC, Hardware-in-the-loop (HWIL) or Software-in-the-Loop (SWIL) arrangements facilitate seamless transitions. On the other hand, the monitoring mode of operation typically involves using a real PLC for assembly and production, providing data for predictive analysis, maintenance requirements prediction, performance optimization, and smooth operations.

The development process of the Machine DT comprehends the following steps.

Step 1- Define Module Scope: The basis for building an accurate digital model needs to be laid in this initial stage. The goals and parameters of the mechatronic module are precisely defined well as all system objectives and constraints, with an emphasis on determining the precise machinery or equipment that will be duplicated in the DT. In this phase the intricacies of the system are delved, determining the kinematic characteristics, rigid bodies, and limitations that apply to the desired assembly.

Step 2 - Utilize CAD Tools for Mechanical Modeling: Following the definition of the

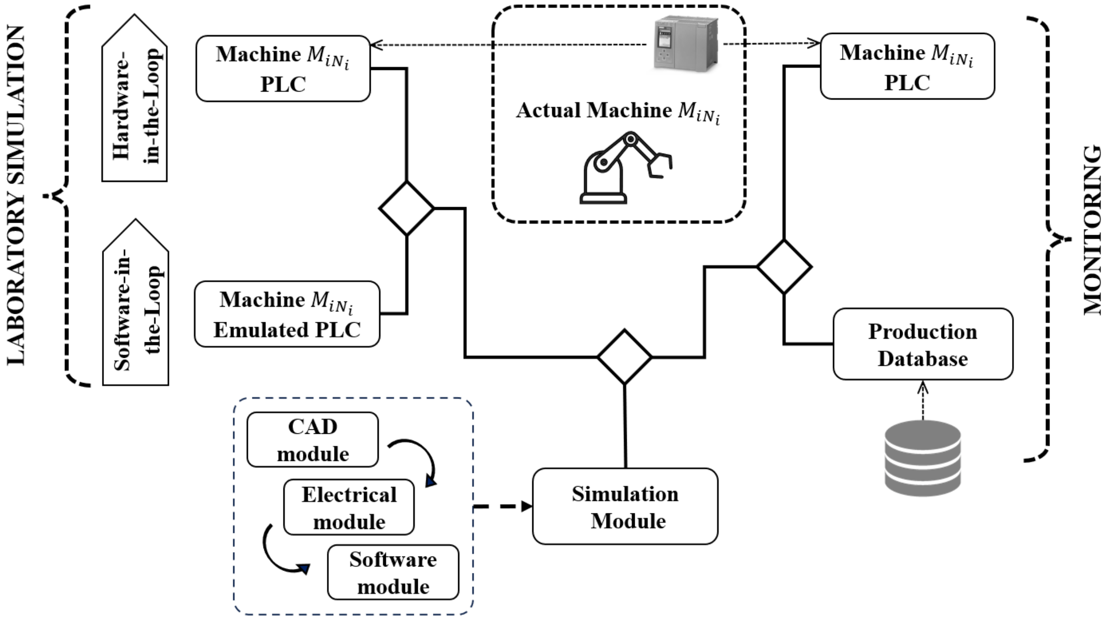


Figure 6.2: Scheme of the proposed Machine Digital Twin: the mechatronics module links with the software part in two ways: on the left, the connection to PLCs (emulated PLC and real PLC) for laboratory simulations; on the right, real PLCs for real-time production monitoring and memorizing the machine data.

system specifications, the next step involves the utilization of CAD tools to generate a digital representation of the machinery. The characteristics of CAD solutions aim at straightforwardly representing rigid bodies, restrictions, and kinematics, thus simplifying the creation of an accurate and comprehensive virtual model. After that, engineers create a thorough virtual representation more easily with the use of CAD and ensure accuracy in the DT, using the CAD model to represent the machine's geometric, kinematic, and operational features.

Step 3 - Integrate Electrical and Software Modules: This step completes the mechatronic project by integrating the software and electrical design, and each component relation. The electrical component defines and simulates equipment behaviour in design analysis, while the software component finalizes design definition and automation behaviour through coding. An electrical scheme is needed for each machine and function to enhance the mechatronic design of the electrical component. Simultaneously, it is necessary to develop the code facilitating the automation of functions, associating it with the corresponding components outlined in the mechanical project, thereby bringing the CAD design to life.

Step 4 - Integrate Automation Logics (PLC): This step consists of creating a link between the mechatronic module and the PLC, where the latter is an essential component for testing, validation, simulation, and real-time control. An emulated or a real PLC is selected based on the application. In the latter case, an intermediary hardware device, such as a specialized unit, serves as a bridge connecting the simulation environment with the physical machinery defining the HWIL connection. In the SWIL arrangement, instead, the PLC is emulated to provide a seamless transition from simulation to reality. Then, the applications of PLCs are categorized into two main areas: Laboratory Simulation and Monitoring. Laboratory Simulation, involving using the DT for thorough debugging in a virtual environment using either emulated or real PLCs. This process ensures in-depth testing and analysis of CAD-designed software logic before deployment. This step is crucial for understanding the machine behaviour and serves as an introduction to the real commissioning procedure. For monitoring purposes, real PLCs are used during the assembly and production phases, creating a database to record data and continuously monitor the machine's condition.

The resulting Machine DT serves as a virtual counterpart of the mechatronic machine and its associated equipment, enabling the simulation and testing of its real-world performance. Hence, machine validation, offline software debugging, early error detection, and other advantages are just a few of the ways this technology is essential to the manufacturing process. In particular, the functionalities of the Machine DT are detailed in the following.

Early-stage error detection and refinement in machine design: engineers can identify and rectify potential issues in the machine design, functionalities, or interactions before the physical production starts. This proactive approach greatly lowers the possibility of expensive rework and modifications later in the process.

Early validation of machine: by subjecting the DT to simulated operational scenarios, manufacturers can check whether the machine meets performance requirements, ensuring that test results are aliged with intended specifications. Prior to actual production, this virtual validation process offers insights into the behaviour and performance of the machine and optimizes the behaviour of machines through extensive testing, modelling, and analysis.

Offline debugging of machine software: software components controlling the machine functionalities can be tested and optimized within the digital realm. Through the digital environment, engineers test software to improve reliability and reduce the possibility of operational issues during deployment on real machine.

Real-time monitoring of machine performance: Engineers can examine and improve the behaviour of the machine by using the Machine DT to monitor and record real-time performance data during simulated operations and the real assembly phase. This feature pinpoints areas that need work and offers insightful information about the machine efficiency. Moreover, predictive analysis makes good use of the recorded data to help with performance optimization, maintenance requirement prediction, and smooth operation.

Resource utilization tracking: Cycle times, material consumption, material handling, and energy consumption can all be monitored by the Machine DT. This monitoring capacity contributes to sustainability goals, while guaranteeing effective operations and optimizing resource allocation.

6.3.2 Line Digital Twin

A Line DT is a powerful tool that models a complete production line, offering the capability to comprehensively assess the corresponding performance. The digital model enables the simulation and optimization of logistics and production flows through a scenario analysis conducted during the conceptual and design phases of the production line. The Line DT serves as a vital component for studying and simulating production processes, pinpointing bottlenecks, optimizing resource allocation, and conducting thorough analyses of various scenarios using Key Performance Indicators (KPIs).

The architectural components of the Line DT include the Simulation module, which utilizes CAD models and communicates with PLCs, as shown in Fig. 6.3.

Simulation Module and CAD Model: The foundational element of the Line DT is the simulation module, which is generally based on discrete event simulation. Importing CAD models enables the creation of detailed digital models of physical assets, including machinery, equipment, and assembly line layouts. These CAD models capture the geometric, kinematic, and operational aspects of the production line. In addition, the created simulation environment incorporates not only the physical attributes of the production line but also the dynamic behaviours and interactions of its components.

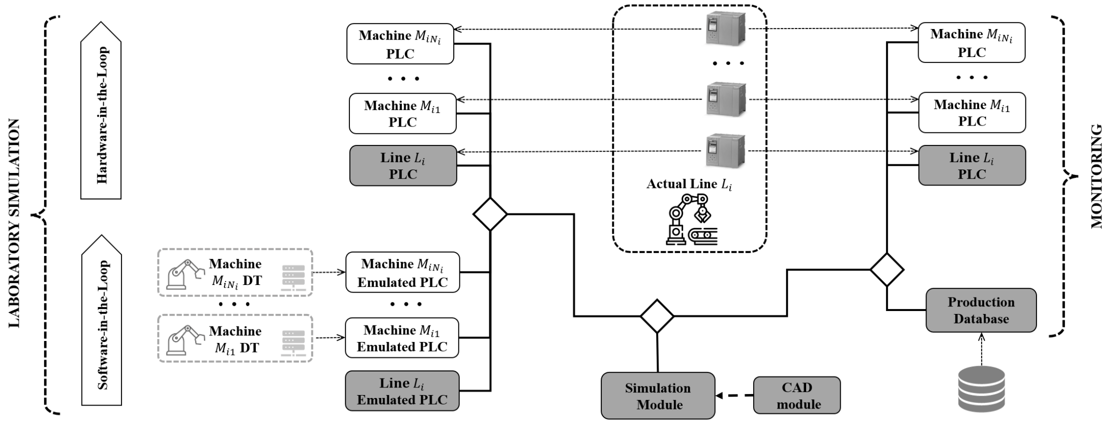


Figure 6.3: Scheme of the proposed Line Digital Twin, the simulation model links with the software part in two ways: on the left, the connection to emulated PLCs for laboratory simulations; on the right, real PLCs for real-time production monitoring and storing the production's data.

PLC: The Line DT includes the integration of a PLCs, which can be either emulated or real for SWIL and HWIL application, respectively. Similarly to the Machine DT, PLCs are employed to perform both laboratory simulation and real-time monitoring. In the case of PLC emulation, the Line DT architecture allows for extensive testing and analysis. Moreover, in a SWIL setting, PLCs are emulated to provide a seamless transition from simulation to reality. Conversely, with a real PLC, the Line DT becomes a powerful tool for monitoring and managing the actual production line processes within a manufacturing plant. In fact, such as the Machine DT, in the cases where real PLCs are employed, an intermediary hardware device, such as a specialized unit, serves as a bridge connecting the simulation environment with the physical machinery defining the HWIL connection.

Once the requirements are defined, creating a Line DT involves a series of steps to model and simulate various aspects of the manufacturing and logistic processes of the production line for implementation in the simulation module.

Step 1 - Set up the Simulation Environment: After defining the scope and objectives of the simulation model, the environment settings are configured and layout of the production and logistics system is defined. This layout serves as the digital environment for simulation, where further elements are inserted representing the various component employed in the line. Common objects might include workstations, conveyor belts, robots, and storage areas.

Step 2 - Model the Production Line Processes: Production processes, assembly sequences, and logistics flows are then modelled to define the workflows occurring within the production lines. The model is further enriched by allocating anticipated resources, including both direct production resources and those allocated to logistics activities.

Step 3 - Define the Automation Logics: After configuring the initial conditions of the simulation, including the machine cycle time, conveyor speed, workloads, and any other relevant parameters, the performance metrics are defined. Beginning with a foundational scenario, successive iterations can uncover solutions that optimize the KPIs, material flows, resource utilization, and, crucially, the layout of the assembly line. By manipulating various input parameters through the software, diverse production scenarios can be simulated.

Step 4 - Run the Simulation and Optimize: The collection of performance metrics and the subsequent analysis of collected data are performed for the sake of improving and optimizing the model. The outcomes of simulating diverse scenarios are illustrated through graphical representations, facilitating the final interpretation of the results and providing enhanced clarity regarding critical issues. Both the simulated and acquired generated data are methodically stored in a designated database, with a production database being used for real-time monitoring simulations and an environment test database for strictly simulated scenarios. Simulations are repeated over changes to the model until the expected performance is achieved.

The resulting digital counterpart of the production line obtained by the previous Step 4process ensures a smooth and effective production process by offering a comprehensive examination and optimization of specific machine functions. The modelling of various scenarios and the early design error detection and correction may make it easier to analyze the data in the end and make important points more apparent. Thus, the initial phase of designing the production line necessitates a rigorous formalization of customer requirements. These requirements encompass crucial aspects, all of which depend on the effective management of logistics flows within the production process.

The functionalities of the Line DT are described in the following.

Line Performance Expectations: a production line's foundational step in design is setting precise goals. It offers a road map for evaluating and quantifying actual performance by outlining expected levels of achievement in clear terms. The identification and application of specific KPIs help to facilitate this process. These KPIs are metrics that provide directions for on enhancement, guaranteeing that the production line runs as efficiently as possible.

Cycle Time and Takt Time Targets: Targets for Cycle Time and Takt Time are also included in the Line DT domain. Cycle time is the amount of time a machine needs to run through a particular task or production line process in its entirety. In addition, Takt Time—which is derived by dividing the available production time by the rate of customer demand—indicates the speed at which orders must be filled. The Line DT optimizes production workflows, guaranteeing alignment with customer demand while optimizing operational efficiency by setting precise targets for these temporal parameters.

Resource Allocation: Effectively allocating resources becomes a crucial task in the Line Digital Twin (DT) domain. This entails distributing labour and equipment as production resources wisely in order to optimize overall production efficiency. The Line DT strategically reduces the chance of damage while carefully allocating resources and minimizing idle time. The DT enhances productivity and streamlines operations in the manufacturing environment by making the best use of available resources.

Timely Delivery: it is crucial to guarantee accurate delivery synchronization. The production line's timely delivery of finished goods, raw materials, components, and supplies is coordinated by the DT. It is because of this careful planning that delays and downtime are avoided, resulting in a smooth and continuous workflow. The manufacturing process is made more operationally efficient overall when the Line DT is able to optimize delivery timelines.

Efficient Material Handling: material handling optimization is the central function of the Line DT. This entails the careful planning of the flow of materials throughout the manufacturing plant. These procedures are streamlined by the Machine DT to maximize overall efficiency and minimize handling time. A smooth and damage-free production flow is greatly maintained by the Machine DT, which reduces the possibility of damage during material handling.

Facility Layout Optimization: the production facility's spatial arrangement and design are managed by the Line DT, which carefully optimizes the layout. Planning the machinery, workstations, storage spaces, and routes strategically is part of this. The Line DT improves the production facility's overall functionality by emphasizing space utilization and flow efficiency, which helps to create a streamlined and well-organized manufacturing environment.

The described functionalities of the line DT are foundational for comprehensive analyses across multiple machines and are essential for coordinating a manufacturing process. Optimizing

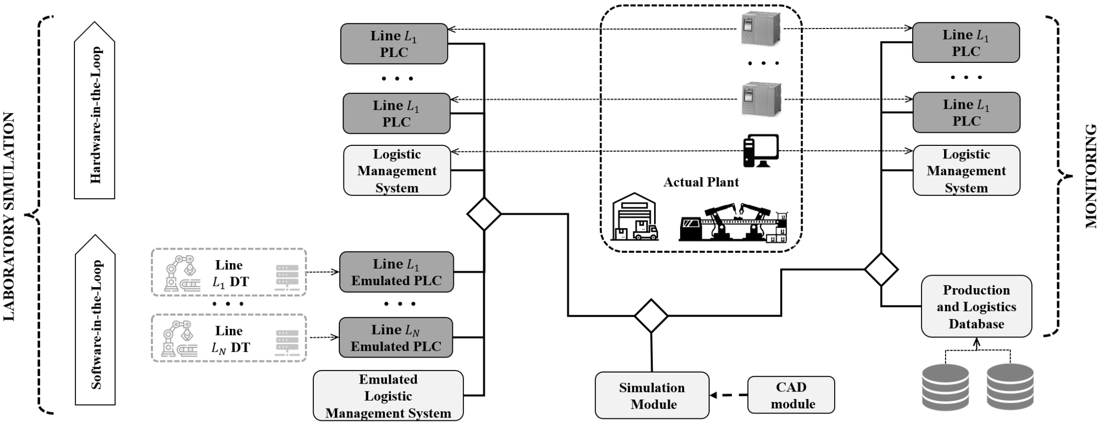


Figure 6.4: Scheme of the proposed Plant Digital Twin: the representation of logistic flows and manufacturing mechanisms enables synchronized monitoring, optimization, and communication for efficient production performance.

efficiency is based on a defined resource allocation, cycle time precision, and line performance expectations. Optimizing the spatial arrangement of a production facility to maximize space utilization and flow efficiency is known as facility layout optimization. All of these functions provide the foundation for thorough analyses involving several machines, which guarantees the efficient operation of the production line as a whole by generating the Line DT.

6.3.3 Plant Digital Twin

The highest level of the proposed HDT is the Plant DT. This cutting-edge process unifies and manages every aspect of production, providing a thorough model of the whole manufacturing plant, including lines and supply chains. As shown in Fig. 6.4, the architecture of the Plant DT is created to capture the intricacies of a manufacturing plant, enabling a comprehensive realization of the complete manufacturing process, where each layer influences and encapsulates the one below it, and vice versa.

Hierarchical DT layers: As previously discussed, the Machine DT, an exacting virtual duplicate of a single machine, sits at the centre of this hierarchical system. After that, the Line DT coordinates the coordinated actions of several machines to create an accurate simulation of a production line. The Plant DT, which combines logistics and Line DTs to manage the whole production facility, is at the top of the hierarchy.

Connection tools: The link between PLCs and the virtual model enables a comprehensive study of the problem, fully virtual or in a hybrid mode that combines virtual and actual equipment. Through this integration, machine behaviour may be dynamically explored, changing settings that have an impact on the entire production line.

Communication with Logistics: The logistical component of the production process is added to the Line DT. The communication protocols need set up to make data transfer between the logistics system and the production line easier. Real-time data use from production schedules, inventory systems, and material availability is made possible by this integration. The focus lies on streamlining transportation routes and cutting down on waste to guarantee effective material flow throughout the facility.

After the requirements are established, creating a Plant DT involves a methodical process. In these steps, various aspects of the production line's logistical and manufacturing processes are modelled and simulated. The aim is to incorporate these elements into an all-encompassing simulation model, thereby enabling efficient execution and examination. The development process of the Plant DT comprehends the following steps.

Step 1 - Integration of All Levels: As seen in Fig. 6.4, the Plant DT is built to combine all production levels, including the logistical flow. This top-level DT establishes the linkages between individual line simulations. Data from the Line DT need to be used to build a thorough simulation that takes into account the monitoring features of earlier DT levels.

Step 2 - Real-Time Monitoring and Oversight: As a watchful supervisor, the Plant DT keeps an eye on up-to-date data about supplies that need to be supplied or taken out of production lines and machinery by the warehouse. PLCs are linked to enable this real-time monitoring and give a thorough insight into the complete production process.

Step 3 - Optimization Techniques Application: Standardized and secure communication between the machine's PLC and its DT is ensured by defined, secure protocols, and the use of real PLCs makes it possible to identify inefficiencies in the production process. The production process is actively influenced by the simulation, which makes it easier to find inefficiencies and apply optimization strategies.

Step 4 - Dynamic Visualization of Material Availability: The Plant DT must integrate real-time data from inventory systems and production schedules to dynamically depict material availability. Simulation can offer a clear visual indication of a material status during the production process by using a monitoring system. In order to quickly and easily visualize data, information, and material movement, it is crucial to define a better mood. The data collected and generated in this step is also methodically stored in a production database to facilitate thorough analysis and well-informed decision-making, which adds to the efficient operation of the whole manufacturing facility. The manufacturing facility as a whole must function cohesively, with the HDT architecture boosting productivity, optimization, and smooth production processes.

Summing up, the Plant DT is a multi-level framework that offers a thorough and integrated simulation environment for improved operational excellence and decision-making. In particular, we envision the implementation of multiple digital abstraction layers designed to efficiently separate the intricacies of the physical layers from intelligent services. This hierarchical architecture introduces a logical abstraction that can:

Depict Industrial Assets: Industry assets are effectively represented by the HDT, which eliminates the need to directly handle the physical complexities of those assets—such as data formats, interaction styles, and communication protocols. Inherent interoperability is fostered by this method.

Standardize Processes: In order to promote uniformity throughout the DT architecture, the logical abstraction standardizes and homogenizes the data collecting, pre-processing, and formatting procedures.

Enable Initial Data Analysis: Using learning algorithms, the DT operates in a distributed learning architecture to facilitate initial data analysis and decision-making.

Enhance Raw Input Signals: The DT improves raw input signals by producing extra variables, which yields useful information that the learning process can use.

To sum up, the Plant DT is a multi-layered abstraction framework that offers an integrated simulation environment for improved decision-making and operational efficiency. Through taking into account these features as a whole across several machines, the groundwork is set for in-depth analyses of a production system as a whole. Moreover, the addition of logistical elements strengthens this framework and confirms its function in forming a comprehensive comprehension of the plant's overall operation. This method creates a logical abstraction that represents industrial assets, standardizes processes, allows for advanced data analysis, and improves raw input signals. It is a significant step forward in the implementation of DTs across the plant.

6.4 Case Study: The Performance Optimization of E-axle Assembly Lines

In collaboration with a manufacturing company that is leader in the Italian and European automotive markets, this section presents an application of the proposed HDT framework to a real case study related to the vehicle electrification field. The considered company structure encompasses several key areas for production, such as the Engineering (mechanical, software, electrical), Warehouse, and Supply Chain departments: each of these is vital in ensuring smooth operations, from designing and developing products to managing logistics, resources, and maintenance tasks. In this regard, DT is a conducive technology for resolving challenges of complexity and volume of information in different areas. In particular, the presented case study shows a valuable example of the potential offered by the HDT approach in monitoring and optimizing the production of electric axles through simulation and digital models.

In the considered application, all the three levels of the HDT, namely the Machine DT, Line DT, and Plant DT, have been defined and implemented, as described in the sequel from the lowest to the highest level.

6.4.1 Implementation of the Machine Digital Twin

The development of the lowest level DT implies the creation of a detailed and accurate representation of each machine within all the production lines. As an example, a screwing station for the electric axle assembly line is here analyzed. The considered station is an automated screwing station with a pallet lifting and clamping unit, an XYZ handling gantry with three electric axes, and an electric screwdriver installed on the gantry.

The development of the corresponding Machine DT involved using several key simulation tools, namely:

Siemens NX-MCD: This CAD modelling tool, augmented with the specialized *MCD (Mechatronics Concept Designer)* plugin, allows engineers to manage constraints, manipulate rigid bodies, and characterize the kinematics of designed assemblies (Fig. 6.5) [30].

Siemens TIA (Totally Integrated Automation) Portal: This simulation environment is used to define the PLC logics, enabling seamless integration with the system to be controlled [31].

Siemens PLCSIM Advanced: The PLC is emulated using PLCSIM Advanced simulation platform in a SWIL approach (as shown in Fig. 6.6) or, through the real HWIL setting. In the latter case, the *Siemens SIMIT* unit –which is a specific hardware device– is employed to bridge the gap between simulation and real-world deployment [32].

Siemens SIMIT: This simulation platform allows to model the equipment, sensors, and actuators included in the system (Fig. 6.7). The obtained simulations are integrated into the MCD framework through connections with the PLC (emulated or real) [33].

The Siemens NX-MCD tool enabled engineers to design the station model mechanical components, ensuring a precise representation of each part defining constraints, rigid bodies, and kinematic attributes referred to as the XYZ handling gantry. The interplay of mechanics, electronics, and automation was verified by engineers using sequence information of the operation or motion sequences. Before the model was actually obtained, the main properties were verified using an integrated simulation to find eventual design flaws. To accurately replicate the control systems, the TIA Portal framework enabled engineers to define the PLC coding. In addition, the Human-Machine Interface (HMI) component was used as the bridge between operators and the DT (Fig. 6.8), providing a user-friendly graphical interface for monitoring and controlling the simulated mechatronic system. This framework accurately replicates the operations of each machine, while enabling the recording of essential variables, such as machine setups, production rates, tooling, and material handling procedures. An accurate virtual representation of the actual

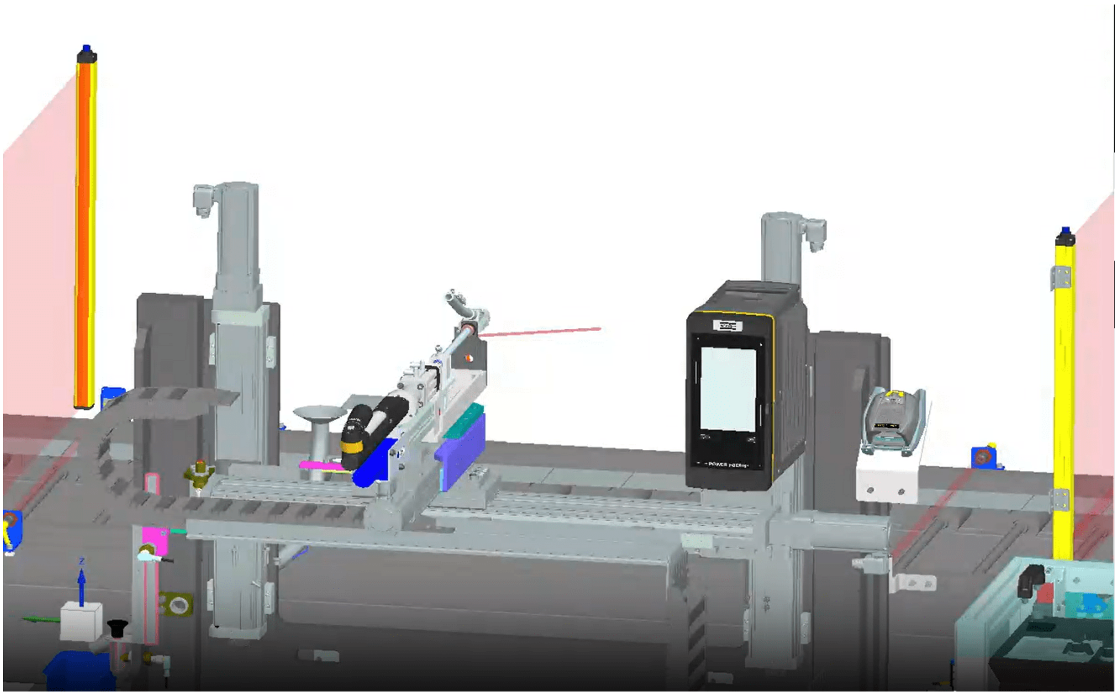


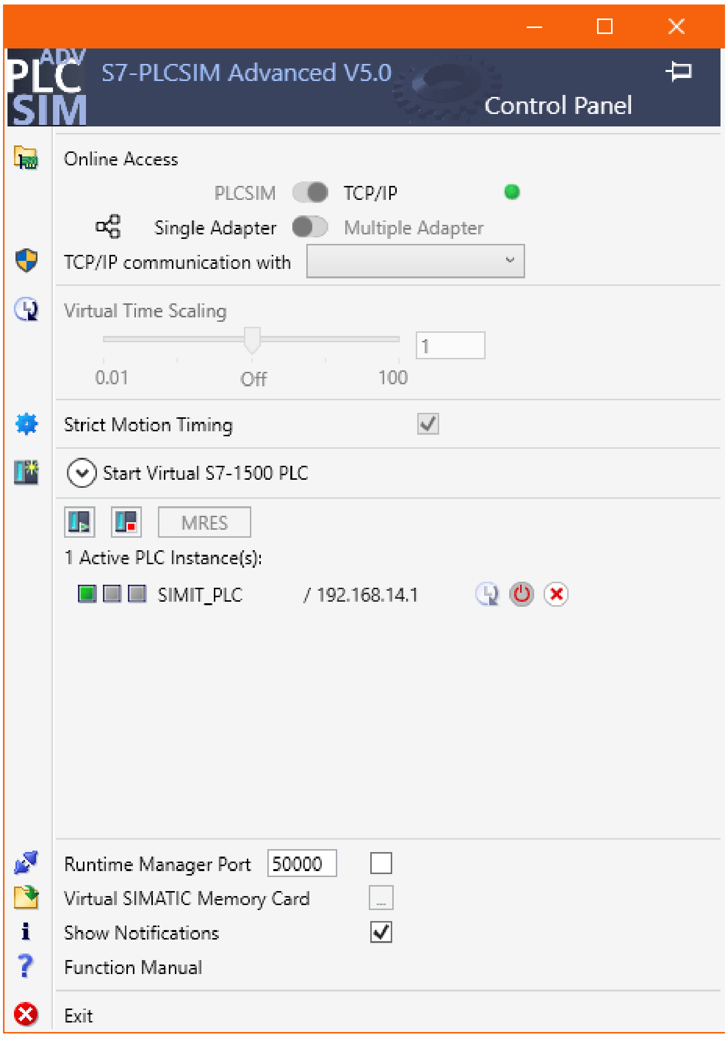
Figure 6.5: Machine DT of an automatic screwing station: mechatronic perspective through the Siemens NX-MCD software. The interface shows the CAD environment for a precision XYZ handling gantry, providing detailed control over XYZ axis movements for enhanced accuracy and efficiency in assembly processes.

apparatus was created by including these specific details in the DT. A hardware infrastructure, including the Siemens PLCSIM Advanced, was put in place to enable smooth and real-time communication between the physical equipment and the low-level digital counterpart. In order to provide a standardized and secure communication framework, the Open Platform Communications Unified Architecture (OPC UA) protocol was employed. The OPC UA scheme, whose main functions and interactions of both the client and server components is shown in Fig. 6.9, allows a fast, dependable, and real-time synchronization of data between the physical machines and their virtual counterparts. The Machine DT is thus able to mirror and communicate with the physical machinery in through a dynamic and responsive connection.

For the sake of highlighting the effectiveness of the Machine DT in monitoring the described screwing station, three KPIs were assessed and compared with the performance of a similar machine equipped with no DT. The considered KPIs are: the Cycle Time (i.e., the time needed for a complete screwing operation), the Fault Frequency (i.e., the frequency of unexpected faults or errors during the screwing process, thus indicating the reliability of the machine), and the Scrap Rate (SR), defined as:

$$\mathrm{SR} = 100\,\frac{\text{Number of Defective Units}}{\text{Total Produced Units}}. \tag{6.1}$$

As reported in the second column of Table 6.1, the screwing station equipped with the Machine DT maintains a low Scrap Rate of 1%, indicating high precision, while achieving a Cycle Time of 54 seconds, guaranteeing quick and effective assembly processes; moreover, thanks to real-time insights and the accurate depiction of machine states in the DT, a high level of reliability is reached, as demonstrated by a fault frequency equal to only 0.5 errors per hour. Conversely, for a



Virtual Time Scaling: 1

Strict Motion Timing ☑

1 Active PLC Instance(s):

SIMIT_PLC / 192.168.14.1

Runtime Manager Port 50000 ☐

Virtual SIMATIC Memory Card

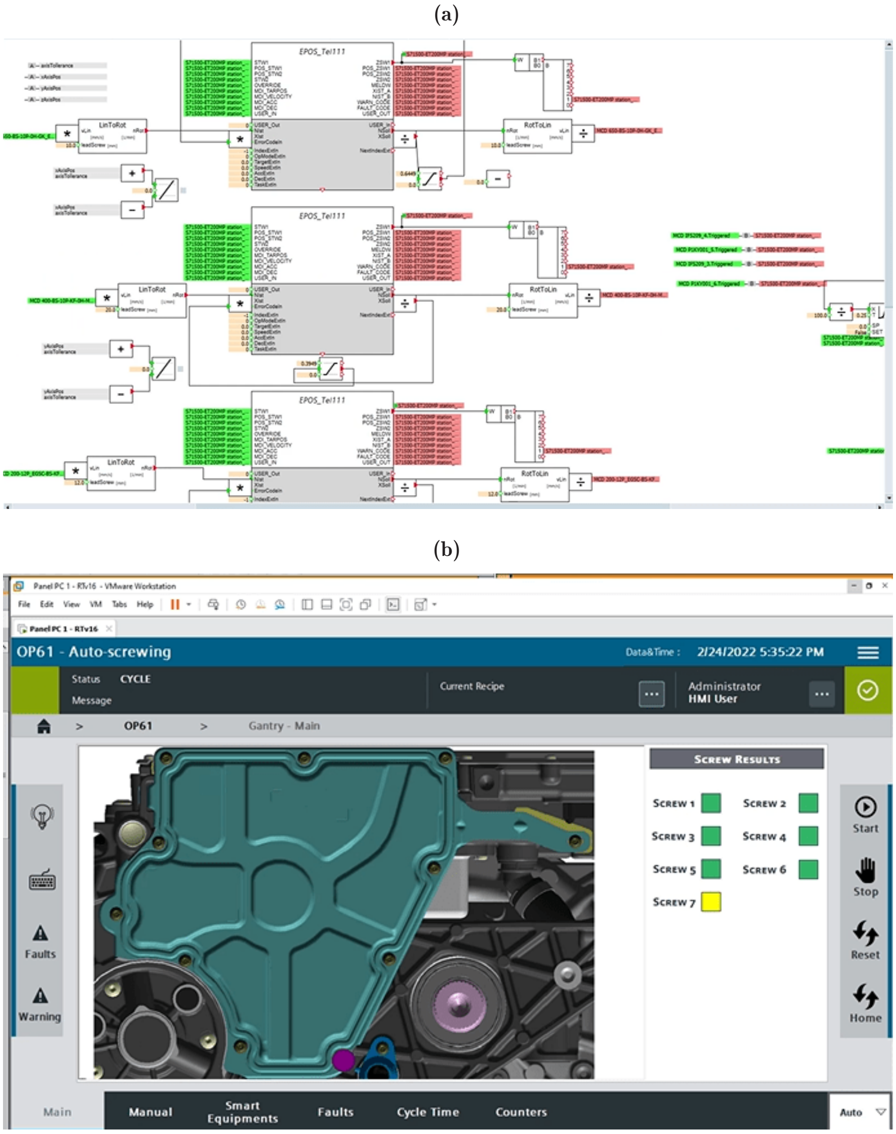
Show Notifications ☑

Figure 6.6: Machine DT of an automatic screwing station: Siemens PLCSim interface showcasing instances and IP addresses of addresses of machine PLC related to the XYZ handling gantry of the screwing station case study.

Table 6.1: Screwing station performance with and without Machine DT

KPI	Machine with DT	Machine without DT
Scrap Rate	1%	6%
Cycle Time	54 sec	58 sec
Fault Frequency	0.5	0.7

similar traditional screwing station with no DT, the corresponding KPIs get worse values (as reported in the third column of Table 6.1). This demonstrates that the Machine DT is effective in optimizing the performance mechatronic system.



OP61 - Auto-screwing

Data&Time : 2/24/2022 5:35:22 PM

Status CYCLE

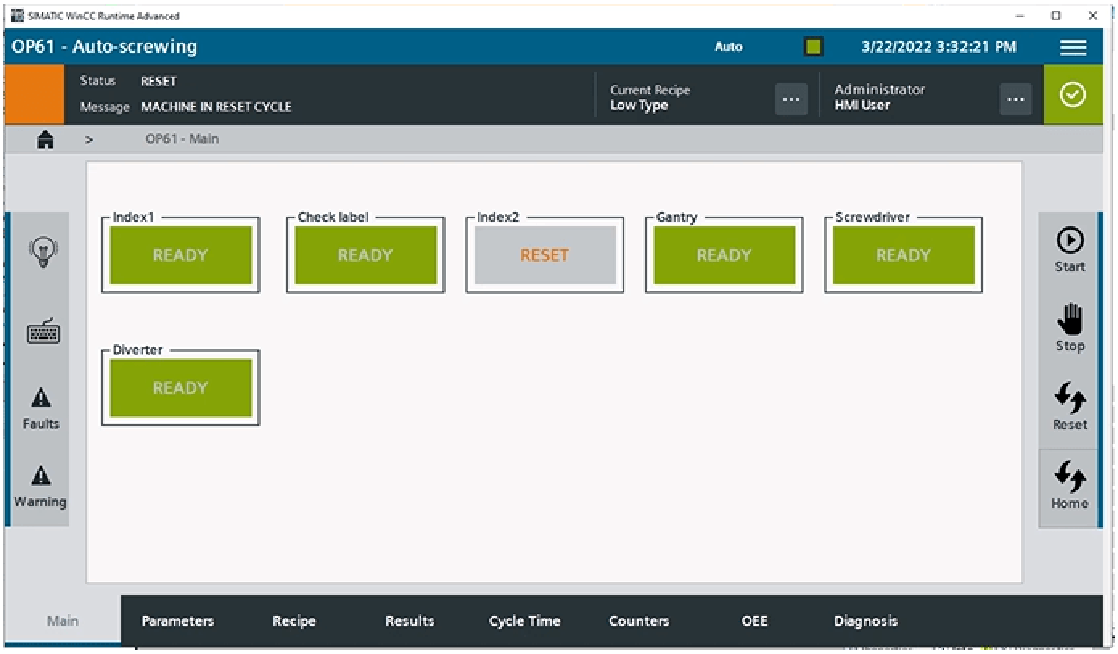
Message

Figure 6.7: Machine DT of an automatic screwing station: the Siemens SIMIT simulation platform shows the XYZ handling gantry drives, providing detailed data conversion over XYZ axis movements (a). The screwing process in action is illustrated in the Siemens SIMIT interface (b).

6.4.2 Implementation of the Line Digital Twin

The second level DT involves the development of a Line DT comprising a simulation model for each production line within the entire plant. Real-time data from the production line, such as machine capacities, material flow, and production schedules, are incorporated into each simulation model. The virtual representation uses a suitable protocol to integrate real-time data, enabling analysis, optimization, and visualization of the connected production processes.

As an example, the assembly line for the transmission of the electric axle is analyzed here and comprises multiple stations with distinct functions, equipment, and gravity racks for the materials, defining an integrated production process for assembling components like gears, shafts,



SIMATIC WinCC Runtime Advanced

OP61 - Auto-screwing

Auto

3/22/2022 3:32:21 PM

Status RESET

Message MACHINE IN RESET CYCLE

Current Recipe Low Type

Administrator HMI User

OP61 - Main

Index1 READY

Check label READY

Index2 RESET

Gantry READY

Screwdriver READY

Diverter READY

Figure 6.8: Machine DT of an automatic screwing station: Human-Machine Interface as a user-friendly control panel for efficient monitoring and control.

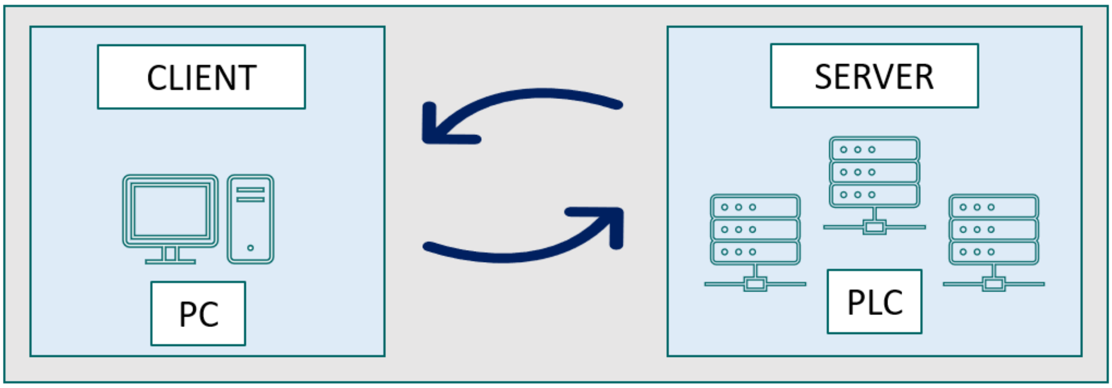
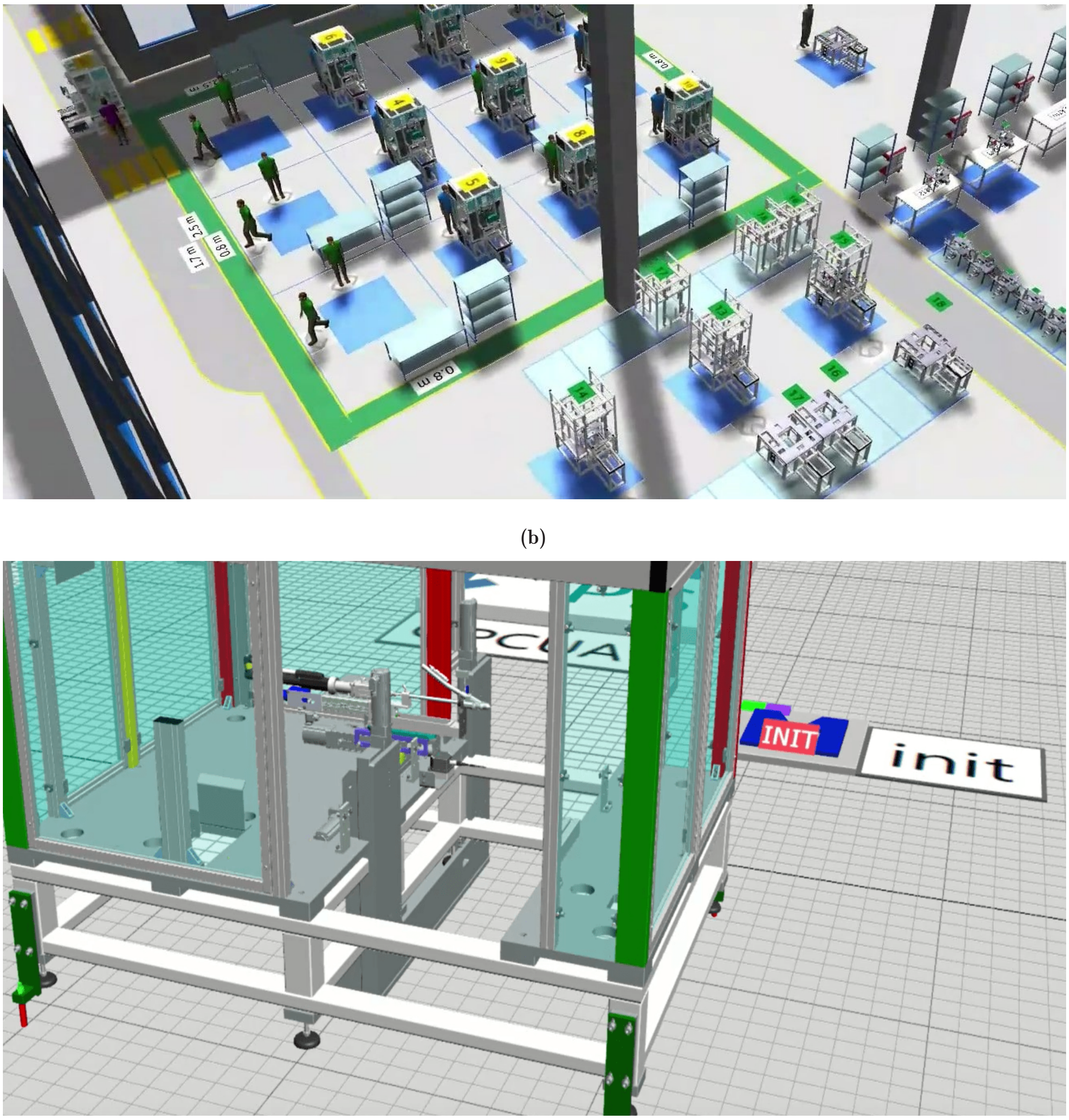


Figure 6.9: Client-Server Interaction Scheme of the Open Platform Communications Unified Architecture (OPC UA).

and housing. The development of the corresponding Line DT involved the use of the *Siemens Plant Simulation* platform [34]. The developed DT was used mainly to track progress, such as the ramp-up of the line, by monitoring the production data with simulation models. Additionally, “what-if" analyses enabled the simulation of various scenarios to assess the effects of changes on the production process (e.g., evaluating the performance over different production volumes, introducing new products, changing the production order, or modifying the resource allocation). Manufacturing engineers made knowledgeable decisions and optimized the process for increased efficiency and productivity by simulating these scenarios and analyzing the results.

By integrating the digital model defined in Siemens Plant Simulation (Fig. 6.10.a) with the real PLC through the OPC UA protocol, the entire production line with multiple machines

(a)



(b)

Figure 6.10: Line DT of a transmission assembly line: layout designed using Siemens Plant Simulation software (a). Zoom of a specific element of the line: depiction of the screwing station within the broader production line environment (b).

was monitored, while recording and optimizing in real-time the performance of the underlying machines, for instance the screwing station previously seen. Through the OPC UA protocol, data exchange created a strong connection between the real PLC embedded in each station and the digital counterpart in Siemens Plant Simulation software (Fig. 6.10.b). Thanks to this connectivity, in the case of the screwing station, the positions of the screwdriver's X, Y, and Z axes are continuously monitored. As a result, the machine behaviour within the Line DT is accurately and dynamically represented, providing insights into the machine actual performance.

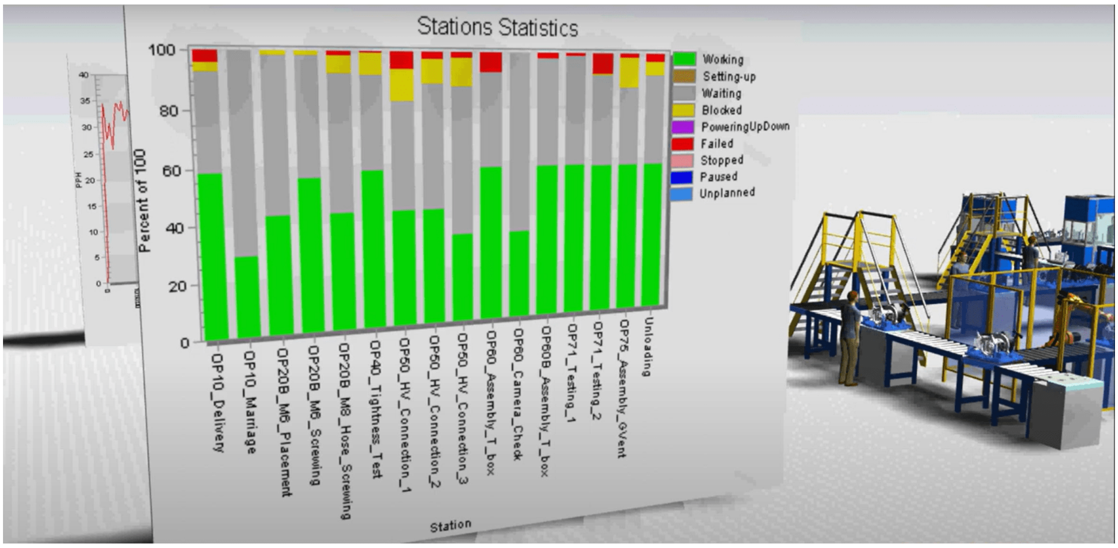


Figure 6.11: Line DT of a transmission assembly line: visualization of performance optimization procedure through Siemens Plant Simulation. Bar chart illustrating the line performance breakdown over the underlying machines, showcasing the percentage distribution of work, waiting periods, blocked states, failures, and pauses. The visual representation provides insights into the operational dynamics and efficiency of stations in the line.

Table 6.2: Transmission assembly line performance with and without Line DT

KPI	Line with DT	Line without DT
OEE	97%	92%
Resource Utilization Rate	93.7 %	89.9 %
Scrap Rate	2.4%	4.5%

The production line L_i as a whole, including N_i machines, is affected by this integration, which is significant even for individual machines. The developed digital model provides a synchronized and comprehensive view of the production process through communication between the PLC onboard each machine and their corresponding Line DT. Thanks to this connectivity enabled by the OPC UA protocol, the production line overall efficiency is ensured through monitoring and optimizing of multiple parameters, as well as identifying bottlenecks, maximizing resource utilization, and carrying out exhaustive examinations of multiple scenarios through the use of KPIs. For instance, as shown in Fig. 6.11, the graphical results are an invaluable tool for decision-makers as they provide information about the effectiveness of various scenarios and support ongoing process improvement in the manufacturing line.

For the sake of highlighting the effectiveness of the Line DT in monitoring the transmission assembly, three KPIs were assessed and compared with the performance of a similar assembly line equipped with no DT. The considered KPIs are: the SR as defined in (6.1), the Overall Equipment Effectiveness (OEE) and the Resource Utilization Rate (RUR), respectively defined as:

$$\text{OEE} = \text{Availability} \times \text{Performance} \times \text{Quality} \tag{6.2}$$

$$\text{RUR} = 100\,\frac{\text{Actual Production Time}}{\text{Planned Production Time}}. \tag{6.3}$$

As reported in the second column of Table 6.2, the Line DT for the transmission assembly line achieved an OEE of 97%, indicating a high efficiency. With a RUR of roughly 93.7%, efficient resource management is also demonstrated. Operational agility is improved with a quick bottleneck identification and resolution time of 15 minutes. With a SR of 2.4%, the defect percentage is low. These KPIs are excellent examples of how real-time data can be successfully integrated for continuous optimization and well-informed decision-making. Conversely, results for a similar traditional transmission assembly line get worse values (as reported in the third column of Table 6.2). Moreover, in this case bottleneck identification and resolution need more days of analysis. This demonstrates that the Line DT is effective in optimizing the performance of production lines.

6.4.3 Implementation of the Plant Digital Twin

The considered production plant is organized into three production lines (namely, the first and second are aimed at assembling the transmission and clutch, respectively, while the third is devoted to the assembly of the entire electric axles) and a warehouse, as shown in Fig. 6.12. The Plant DT was implemented with the final aim of analyzing and optimizing the couplings between each production line, and the individual machines, with the material logistic flow, such as the milk run path, organized by the warehouse, as shown in Fig. 6.13.

The first step involved creating a simulation model of the production plant using the *Siemens Plant Simulation* software. The Plant DT represents the entire production plant, connecting all the Line DTs with the milk run flow, thus creating a top-level simulation. This comprehensive view of the entire production process enabled the identification of inefficiencies and the implementation of optimization strategies. For instance, integrating the logistics flow with the HDT supported the identification of areas for improvement, such as optimizing transportation routes or reducing waste.

As the core part of the Plant DT, a discrete event simulation software was employed to accurately represent the production environment and the underlying inter-dependencies. The developed model incorporated real-time data from the inventory systems and production schedules of Line DTs, thus allowing to visualize the availability of materials over all the production areas using a traffic light system (Fig. 6.14). The traffic light system served as a visual indicator to represent the availability of materials within the production process. Green indicated sufficient material availability, yellow indicated low availability, and red indicated critical shortages. This system allowed production managers to quickly assess the material status and make informed decisions to optimize the milk run route and flow, as well as identify critical material shortages and take immediate action, such as adjusting production schedules, expediting orders, or reallocating resources to mitigate potential disruptions. An extensive analysis using the Plant DT was performed to identify bottlenecks, areas of inefficiency, and potential disruptions due to material shortages. What-if scenarios were also employed to evaluate the impact of different production schedules, material ordering strategies, and inventory management techniques on material availability.

For the sake of highlighting the effectiveness of the Plant DT, a comparative analysis between two scenarios was conducted. On the one hand, the plant with the proposed HDT is considered: specifically the milk-run process is regulated through the above described traffic light system. On the other hand, the same plant is considered in absence of the HDT, relying on a traditional on-demand logistics approach. The two scenarios were analyzed based on a comparison of KPIs, as indicated in Table 6.3, and using some important production data such as delivery status, station name, material description, time of arrival and departure from the station, and delivery time. In order to reduce the response time, the analysis was conducted on the production real-time system. Numerical experiments show significant improvements in favour of the Plant DT approach: the reaction times are reduced by 50%, the transportation efficiency is increased by 20% through

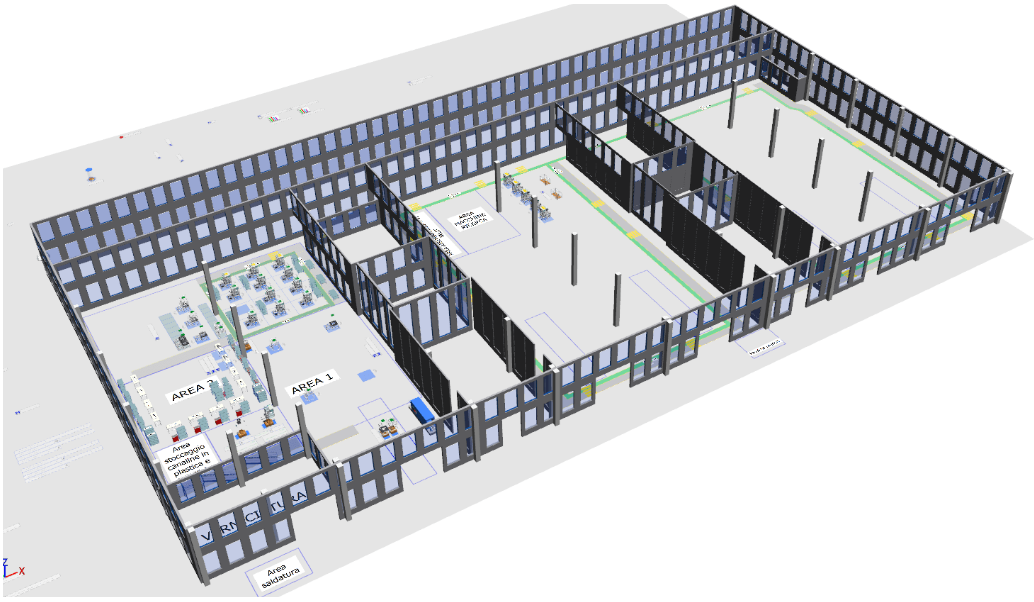


Figure 6.12: Plant DT of the electric axle production system: illustration of the layout composed of three interconnected production lines and a warehouse through Siemens Plant Simulation.

Table 6.3: Electric axles production system with and without Plant DT

KPI	Plant with DT	Plant without DT
Reaction Times	50 minutes	75 minutes
OEE	96%	85%
N° of milk run turns/days	4	7

milk run optimization, and an astounding 100% prevents the interruptions. In order to reduce the response time, the analysis was conducted on the production real-time system. Numerical experiments show significant improvements in favour of the Plant DT approach: the reaction times are reduced by 50%, the transportation efficiency is increased by 20% through milk run optimization, and the interruptions are prevented by an astounding 100%. Additionally, the milk run route was adjusted by the DT, which increases transportation efficiency by 20%. Since the Plant DT could identify and handle crucial problems ahead of time, 100% of disruptions are prevented. With regard to continuous analysis, the DT guaranteed a 100% gain in retroactive and continuing optimization capabilities, which helped to improve resource management and reduce the related operating costs by 30%. These results highlight the critical role that the Plant DT plays in proactive production optimization and management, with observable advantages such as faster response times, more efficient transportation, and lower operating costs than traditional approaches.

6.4.4 Outcomes and Discussion

As a first outcome of the case study, it emerges that the process of gathering and analyzing data from many sources is necessary to create a HDT. Physical parameters, production details, operational logs, and information streams from analytical software are all included in these data, whose collection forms the basis for building the HDT. This digital model thus enables

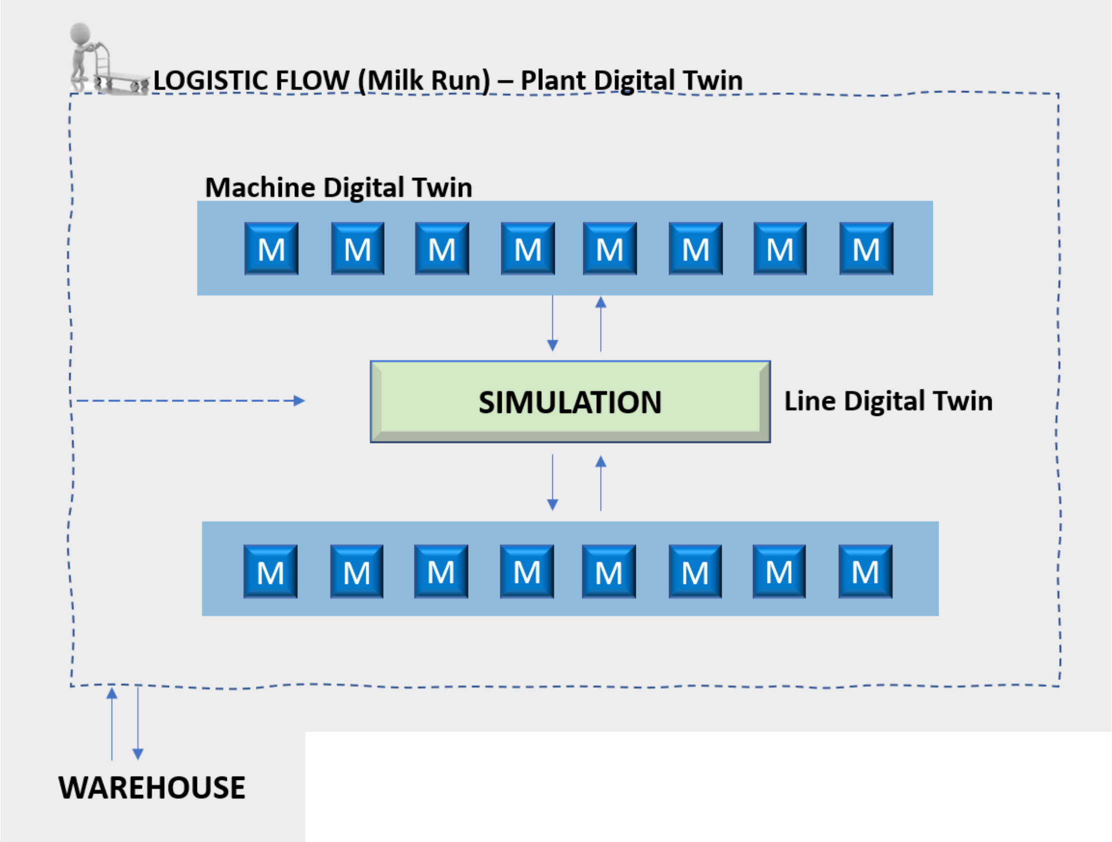


Figure 6.13: Hierarchical Digital Twin scheme of the electric axle production system: the Machine DTs at the lowest level are denoted by M, the Line DTs at the intermediate level are represented through the machines connection, and, finally, the Plant DT at the highest level acts as the central integration point connecting all lines to the plant logistic processes such as the milk run.

us to accurately simulate the behaviour and characteristics of real physical assets as well as of their operational modalities. Similarly to advanced manufacturing systems, the foundation of the proposed HDT environment is the OPC UA protocol-driven client-server communication scheme. At each level, the DTs are based on this protocol, which offers a standardized and secure framework for smooth data exchange between real machinery and the digital counterpart. In order to guarantee a smooth and effective data flow, the OPC UA scheme carefully outlines the roles and interactions of the client and server components, as reported in Table 6.4. Efficient communication and synchronization between the physical production processes and the DTs are guaranteed by the client-server architecture. In this scenario, typically DT tools are employed, such as Siemens Plant Simulation and Siemens NX-MCD: these tools act as the clients that request to and receive data (e.g., control commands) from the server, which is the PLC. The PLC acts as the data source and control point for the physical machines and processes within the production environment. The OPC UA protocol is also used to interconnect the DTs of different levels (e.g., communication between the PLC of the Line DT and the Machine DT).

As a second outcome of the case study, it is apparent that the HDT approach offers a comprehensive picture of operations in an industrial environment marked by quick changes and complexity. It serves as a centre that connects disparate parts and provides an integrated, real-

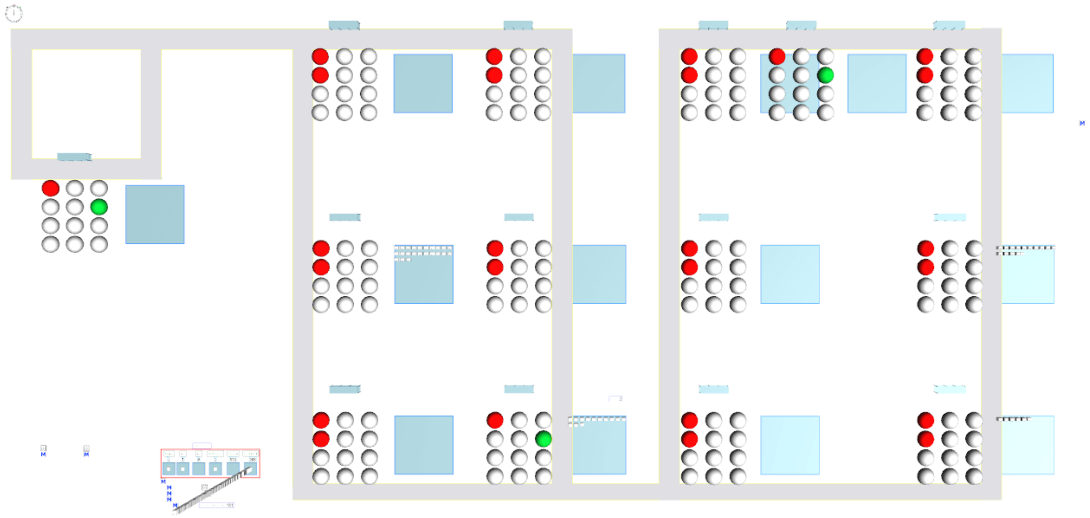


Figure 6.14: Plant DT of the electric axle production system: visualization of the material availability through the Traffic Light System in Siemens Plant Simulation. Green, yellow, and red light indicate sufficient material availability, low availability, and critical shortages, respectively.

Table 6.4: Client-Server Roles in HDT Integration for Production Monitoring

DT layer	Client	Server
Machine DT	Siemens NX-MCD	PLC (SWIL)
Machine DT	Siemens NX-MCD	PLC (HWIL)
Line DT	Siemens Plant Simulation	PLC (SWIL)
Line DT	Siemens Plant Simulation	PLC (HWIL)
Plant DT	Siemens Plant Simulation	PLC (SWIL)
Plant DT	Siemens Plant Simulation	PLC (HWIL)

time picture of the whole manufacturing process. The enhanced coordination and communication among various operational aspects resulting from this interconnection facilitate efficient production, prompt problem-solving, and great adaptability. Table 6.5 reports the results of the in-depth analysis conducted through the HDT, highlighting the main inefficiencies intercepted in various phases of the manufacturing system design and operation. Moreover, it emerges that the HDT framework offers a dynamic and synchronized platform for production activity management, which makes a significant contribution to Industry 4.0 vision. The ability to promote cooperation and communication between production components at the individual and global levels establishes a new benchmark for modern industry production, monitoring and management. This leads to increased output.

Summing up, applying the HDT approach in a real industrial setting can bring significant benefits. In the presented case study using the proposed approach, the comprehension of the manufacturing system has been made easier by the integration of DTs at various stages, namely from the Machine DT, to the Line DT, to the Plant DT. The proposed approach has contributed to identifying errors early, improve designs, and maximize the production process as a whole. The capacity to model and examine various production scenarios in a virtual setting has resulted in notable increase of productivity, reduction of downtime, and improvement of the overall quality.

Table 6.5: Inefficiencies intercepted in various phases of the manufacturing system operations

Criticality	**Challenge**	**Issue resolved via the HDT approach**
Uncertainty about input data	Inability to predict possible interferences, sizing issues, and ergonomic problems in advance	The virtual ergonomic analysis through the DT makes it possible to identify ergonomic problems early on and make preventative adjustments during the design stage
Lack of precise information	Inability to assess the effectiveness of individual implemented cycles and their correlations	The HDT allows for correlation analysis between various cycles, providing insights into their interdependencies and preventing excessively long online debugging times
Heterogeneous and hard-to-retrieve data	Inability to verify fault management, asynchronous and cyclic functions (counters, rejects, Time Cycle, OEE)	Real-time monitoring and analysis of asynchronous and cyclic functions are provided by the HDT, which also offers information on production KPIs
Product not yet finalized	Inability to verify human-machine interaction through HMI	The HDT allows for user experience testing in a virtual environment, enabling the evaluation of user interactions and the user experience with the HMI
Unexpected stop work	Establishing proactive maintenance strategies to prevent unplanned machine downtimes	The HDT facilitates real-time monitoring, and preventive maintenance scheduling, reducing machine downtime
Delays due to inadequate material availability	Ensuring consistent material supply to avoid production delays	The Plant DT optimizes material tracking, triggering fast reorders based on real-time inventory levels, and preventing shortages

A structured framework for data flow has been enabled by the hierarchical architecture, allowing for smooth communication between machinery, production lines, and logistics. Such a flexible and adaptable manufacturing environment has facilitated the activities of engineers through real-time monitoring and predictive analysis capabilities at every level.

6.5 Conclusion

This paper has proposed a Hierarchical Digital Twin (HDT) approach to enhance the design and optimize the operations of smart factories. The presented framework extends the monitoring and control capabilities of a digital Plant (DT) beyond individual machines and to the whole production lines, providing a comprehensive approach for the entire manufacturing plant: a vast and interconnected network enables smooth communication and real-time coordination between all systems, equipment, and data, including logistic components, thus allowing significant advancements in process optimization and overall operational efficiency. The effectiveness of the HDT is shown on a real case study in the automotive sector, highlighting that this approach improves the responsiveness, flexibility, and efficiency of manufacturing systems and provides a single, integrated, and real-time view of all production-related entities. The HDT provides a dependable framework to handle the increasing complexity and demands of contemporary industrial processes.

Despite the potential of the proposed HDT approach in enhancing production processes and optimizing resource utilization, it is not free from limitations. For some businesses, the initial investment and the high cost of specialized software, in addition to the complexity of setting up and maintaining the infrastructure, may be obstacles. Moreover, these tools necessitate a deep understanding of the particular manufacturing processes they are to be simulated, as well as advanced knowledge and skills in mechatronics, Computer-Aided Design modelling, and electrical and software engineering. Organizations or professionals lacking specialized expertise could find it difficult to employ these platforms due to their complexity. Our research efforts will be focused on making DTs easier to set up and maintain so that a larger range of industries can use them. Further research on subjects like artificial intelligence integration, real-time analytics, and enhanced predictive modelling is also needed in order to enhance and expand the potential of DTs.

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Chapter 7

Findings and Conclusions

The main conclusions and contributions of this thesis are outlined in this section, and prospective future research directions are suggested.

The dual focus of this thesis on two separate but related areas highlights how digital technologies have the ability to drastically alter the manufacturing landscape. These technologies, which are exemplified by simulation, virtual reality (VR), and digital twins (DTs), are critical in helping to solve difficult design problems, improve production procedures, and advance manufacturing efficiency and sustainability.

Part 1 emphasizes how important virtual reality is to the creation of adaptable and effective manufacturing systems. VR is a cutting-edge co-design tool that opens up new possibilities for interaction and collaboration. This section highlights the benefits of VR's virtual golden zone methodology with an emphasis on ergonomic assessments and design checks of complex production lines. The methodology is an effective means of improving worker ergonomics, encouraging safety, and guaranteeing task efficiency. The high level of satisfaction and usability of VR-based methodologies in design reviews is attested to by the inclusion of the System Usability Scale (SUS) questionnaire. As time goes on, the addition of haptic feedback via gloves should improve the human-visual Reality interaction even more and lead to new opportunities for optimizing operator activities. However, it is crucial to remember that creating a detailed model calls for knowledge, effort, and specialized resources and that integrating digital tools with plant systems can be difficult. Furthermore, future research ought to think about improving glove-based haptic feedback for VR environment interaction with people. By measuring finger and wrist movement, this invention could enhance operator ergonomics even more.

Part 2 of the thesis focused on the use of simulation and digital twins in manufacturing system optimization. As intelligent models of physical systems, DTs provide thorough insights and aid in decision-making during the phases of product design, development, testing, production, and evaluation. With the ability to replicate real-world systems and provide behavioural analysis, simulation technology is becoming a powerful analytical tool that empowers industries looking to improve Overall Equipment Effectiveness and optimize workflows. In particular, it was discovered that raising production throughput and lowering Automated Guided Vehicle (AGV) energy consumption are conflicting goals. Future studies should include a cost analysis to give a thorough evaluation, and simulation workers working near AGVs and line stations can help the model be even more optimized. Moreover, it was noted that the defined DT's hierarchical architecture integrates causal models from environmental data to produce logical representations of the entire system. The effectiveness of the hierarchical DT in real-time monitoring is illustrated in a real company case study through the use of operations like milk-run logistics as examples.

The future lies in these digital technologies being seamlessly integrated to form a coherent framework that guarantees an innovative and productive user experience. Manufacturing could be completely transformed by these tools as they develop and grow, fully integrating from the conceptualization to the product lifecycle stages. Collaboration across sectors, benchmarking against alternative approaches, and expansion into training, maintenance, and other critical areas will further refine and expand their utilization. With these two interconnected parts, the path toward a digitalized manufacturing world is revealed, with each part adding its own special touch to the continuous change. The manufacturing sector is poised for a paradigm shift brought about by the continued advancement of digital technologies. This shift will reinterpret established methods and open up new avenues for efficiency, sustainability, and innovation. The conclusions and insights of this thesis offer a strong basis for the next phase of manufacturing evolution, driven by the potential and promise of digital technologies.