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VIRTUAL COMMISSIONING OF MANUFACTURING SYSTEMS. A REVIEW

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Abstract: *This paper examines Virtual Commissioning (VC) within manufacturing systems, presenting it as an innovative solution that transforms industrial automation and enhances control system interoperability. VC fundamentally relies on simulation software to construct a digital twin of the entire system, capturing all relevant components, sensors, actuators, and control logic. The document reviews different VC methodologies, including Hardware-in-the-Loop (HIL), Software-in-the-Loop (SIL), and Reality-in-the-Loop (RIL), each with unique attributes and applications. Highlighted are the substantial benefits of VC—such as cost and time savings, improved system quality and operational efficiency, and enhanced worker safety through virtual hazard identification. The paper also explores VC's synergy with emerging technologies like the Internet of Things (IoT) and Artificial Intelligence (AI), underlining its contributions to predictive analytics and realistic simulations. While these advancements offer promise, the document addresses challenges in scalability and integration, especially with older systems and cloud-based solutions, stressing the importance of strong security practices. Concluding, it emphasizes VC's transformative role in industrial automation and advocates for a holistic approach to VC deployment, integrating both technical and operational considerations.*

Key words: *Virtual Commissioning, Digital Twin, Industrial Automation, Robotic Simulation, Internet of Things, Artificial Intelligence, Cloud Computing, Mechatronic Concept Designer.*

1. INTRODUCTION

The rapid advancements in technology have brought about significant changes in the manufacturing industry, revolutionizing the way products are designed, developed, and produced. A significant advancement in this area is Virtual Commissioning, an effective approach and powerful tool that allows manufacturers to enhance and fine-tune their production processes and reduce time-to-market while ensuring the highest level of quality and efficiency. This essay delves into the world of virtual commissioning, its importance, benefits, challenges, and the future prospects it holds for manufacturing systems.

The traditional engineering process is depicted as a linear sequence beginning with Planning, followed by Concept Design, Detailed Engineering, and culminating in Commissioning (Fig. 1). Each phase has distinct focuses: mechanical concepts, electrical/fluid systems, and software. This approach has been characterized by a clear demarcation between each stage, with minimal overlap and interaction.

The initial phase involves defining the project's requirement that form the basis for the mechanical concept, which is then detailed through design and documentation.

The mechanical concept is developed into a schematic design, involving the initial drafts and layouts. This is where the physical structure of the product is conceptualized.

This phase breaks down into three key areas: mechanics, electrics/fluid, and software. Each area is developed in detail, often in silos, with specialized teams working independently.

The final phase is where the real machine is constructed and goes through real commissioning, involving testing and adjustments to ensure it meets the initial requirements.

Virtual commissioning (VC) is a process that involves creating a digital replica of a manufacturing system, including all its components, processes, and control systems. This digital twin allows engineers and operators to simulate and test the entire production process in a virtual environment before it is physically implemented on the shop floor. The main goal of VC is to identify and rectify any potential issues or inefficiencies in the manufacturing system before they become costly problems in the real world. Virtual commissioning is a part of advanced engineering process which, as proposed by Siemens, is an integrated approach combining Systems Engineering, Multi-disciplinary Engineering, and Digital Twin technology leading to Commissioning. This process emphasizes a mechatronic concept, synergy between disciplines, and the use of virtual commissioning for timesaving [1–4].

VC can be categorized in three ways: Hardware-in-the-loop (HIL), Reality-in-the-loop (RIL) and Software-in-the-loop (SIL) [5]. SIL is also called off-line programming, which means that both plant and PLC program are simulated with a PC, with a single computer

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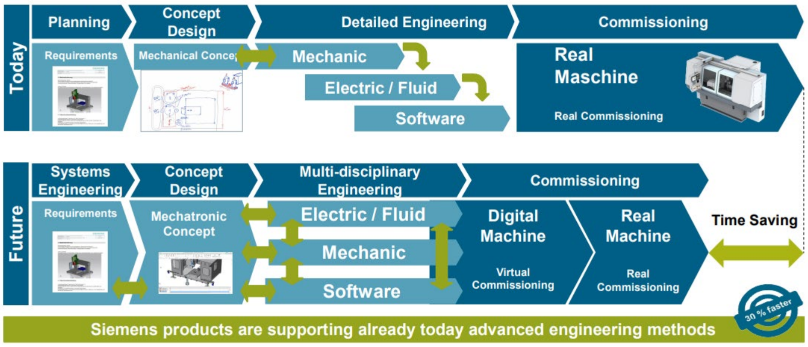

Fig. 1. Evolution of virtual commissioning.

where the entire project can be simulated. On the other hand, HIL, which is called soft commissioning, is a method where a real PLC hardware is connected with a virtual plant or workstation. The difference between these two systems is that the SIL uses a virtual control system and HIL uses a real control system [1].

The RIL methodology involves the utilization of real plant equipment in conjunction with virtual Programmable Logic Controllers (PLCs) for commissioning control applications. This approach offers both advantages and disadvantages due to the use of actual production hardware. In comparison, the RIL approach in relation to HIL offers distinct advantages. It provides a valuable tool for decision support in diagnosing and troubleshooting devices, maintaining current control software, and testing alternative system-control strategies with existing plant equipment. However, a significant drawback of RIL is the potential for expensive repairs or even permanent damage to manufacturing equipment when using this method.

Systems Engineering represents the future, taking a comprehensive planning approach by integrating requirements across various disciplines from the beginning. This strategy ensures all system components are considered in relation to one another, fostering cohesion from the outset.

The mechatronic concept builds on traditional mechanical design by integrating mechanical, electrical, and software elements into a unified framework. This cohesive approach supports a smooth transition to multidisciplinary engineering.

In the multidisciplinary engineering phase, the once-separate fields of mechanics, electrics/fluids, and software converge. Now, teams work within a concurrent engineering environment, allowing for simultaneous development and iteration, which enhances efficiency and minimizes errors.

1.1. Key components of VC

VC is a crucial process in the field of industrial automation and control system, allowing the interoperability of multiple systems. One of the fundamental components is the simulation software. This software is employed to create a digital twin of the intended system, including all its components, sensors, actuators, and control logic (Fig. 2). The digital twin allows engineers to model the behavior of the system under various operating conditions and test its performance in a virtual environment. The choice of the simulation software can have a significant impact on the effectiveness of virtual commissioning, as it must accurately replicate the real-world system [6, 7].

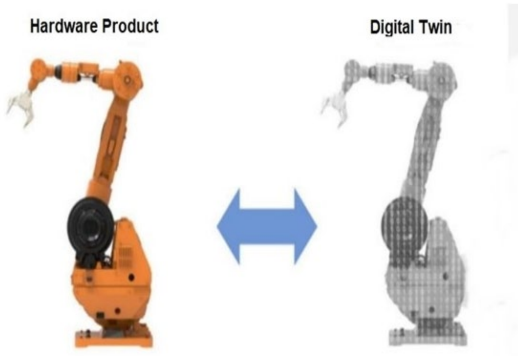

Fig. 2. Digital twin model.

The next component is the development of control logic, which is a critical component of VC. Control logic defines how the system responds to various inputs and conditions. During VC, engineers create and refine the control logic within the simulation environment. This process allows them to fine-tune the control algorithms, test different scenarios, and identify potential issues or optimizations before implementing the control logic in the actual system. VC significantly reduces the risks associated with control logic errors, ensuring that the system operates safely and efficiently.

System integration is another key component of VC. In a complex industrial system, various components, subsystems, and devices must work together seamlessly. Virtual commissioning allows engineers to validate the integration of these elements in a virtual environment, ensuring that they communicate effectively and perform their functions as intended. This step helps identify compatibility issues and ensures that the entire system works cohesively when deployed in the real world.

Testing and validation are ongoing processes within VC. Engineers conduct a series of tests to evaluate the system's performance, verify its functionality, and identify potential faults or weaknesses. These tests can include stress testing, fault tolerance assessments, and performance evaluations under different operating conditions. Virtual commissioning allows for extensive testing without the risk of damaging physical components, making it a cost-effective and efficient method for ensuring the system's reliability.

This work includes a state of art of virtual commissioning and a brief introduction to it. This paper presents all of the fields, which were researched and can be explored in order to improve the digital manufacturing for any industrial process. Since the AI and Cloud capabilities exploded in the last years, implementation of virtualization or VC based on cloud can produce a high impact in the industry 4.0.

2. CURRENT STATE OF ART IN VC

The final phase is when the real machine is constructed and goes through the very commissioning, involving testing and adjustments to confirm it meets the initial requirements.

In the rapidly evolving landscape of industrial automation (Fig. 3), virtual commissioning (VC) has emerged as a pivotal technology, fundamentally transforming how systems are designed, tested, and implemented. The concept of VC involves the use of digital twins, which are virtual replicas of physical systems, to simulate, analyze, and optimize complex machines and processes before they are physically built [8]. The genesis of VC can be traced back to the early 2000 s, with its initial applications primarily in the automotive industry. However, the past decade has witnessed a significant expansion in its scope and capabilities. Today, VC is an integral part of Industry 4.0, offering unparalleled efficiencies in the design and deployment of manufacturing systems [9]. The integration of VC with Internet of Things (IoT) and artificial intelligence (AI) [10] has further enhanced its efficacy, allowing for more accurate simulations and predictive analytics [11–13].

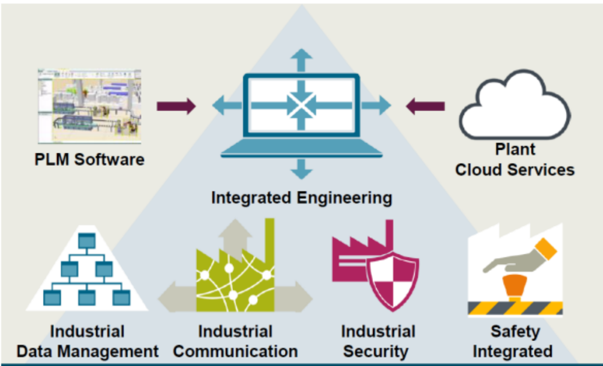

Fig. 3. Fully integrated automation [14].

One of the main advantages of VC is the substantial reduction in time and cost associated with the commissioning of industrial systems. By simulating and rectifying errors in a virtual environment, companies can avoid costly and time-consuming physical trials [15] For instance, in the aerospace industry, VC has been instrumental in shortening product development cycles, enabling faster time-to-market [16 and 17]. Furthermore, VC plays a crucial role in the sustainability aspect of manufacturing. By optimizing systems in a virtual environment, it significantly reduces waste and energy consumption, contributing to environmentally friendly manufacturing practices [18]. Additionally, VC enhances worker safety by allowing the identification and mitigation of potential hazards in a risk-free virtual space [18].

There are numerous tools and the researches on a hybrid model [19] found effective ways to integrate physical testing and VC for emulating industrial systems and processes. Advanced programmable logic controller simulators (PLCSim) advanced can be used to simulate a real PLC. This can be implemented in TIA Portal and can be employed to validate the logic for a specific system before its implementation. SIMIT and Simcenter can be used for modelling machines and simulate the behavior of the devices like sensors. While Process Simulate, Pant Simulation and NX MCD (Mechatronics Concept Designer) provide the possibility of simulating an entire robotic cell within a production line, each of them are specialized on a certain area.

2.1. Tecnomatix Process Simulate as environment for advancing digital manufacturing

Tecnomatix Process Simulate (PS) is a part of Siemens' Tecnomatix software suite. It is a comprehensive portfolio of digital manufacturing solutions. It provides a 3D environment where users can create, simulate, and validate manufacturing processes. By allowing manufacturers to visualize and analyze the entire production process, including assembly operations and human ergonomics, Process Simulate helps in identifying potential issues and optimizing processes before they are implemented on the factory floor [21]. PS provides many digital tools to validate and test the control system of manufacturing processes and equipment in a virtual environment.

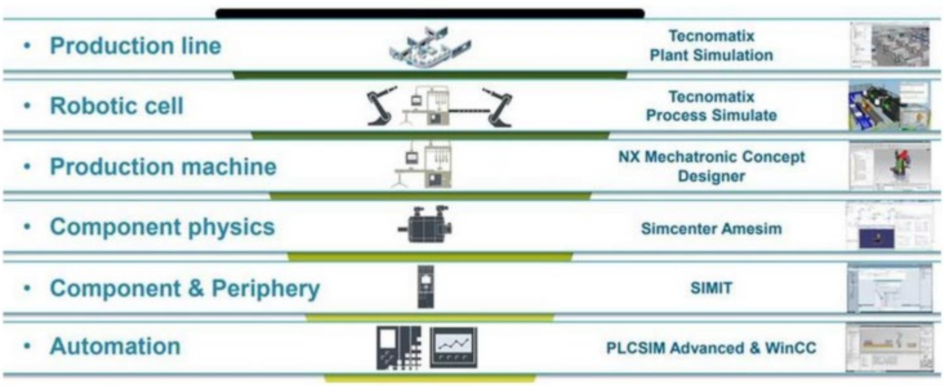

Fig. 4. Effective ways to integrate VC [20].

Virtual Commissioning. One of the most compelling features of Tecnomatix Process Simulate is its ability to perform virtual commissioning of automated systems. This means that manufacturers can validate the control logic of their automated systems, such as robotic assembly lines, in a virtual environment. This significantly reduces the time and cost associated with physical commissioning and helps in ensuring a smooth transition to production [21].

Human Simulation and Ergonomics. Process Simulate offers advanced human simulation and ergonomic analysis tools. It allows manufacturers to analyze human operations and ensures that the design of the workstation is ergonomically optimized. This not only enhances the safety and comfort of the workers but also improves productivity and efficiency [22].

Robotics and Automation. The software provides advanced tools for programming and simulating robotic operations. Users can select, program, and simulate robots from a vast library of robot models. This helps in optimizing robot paths, reducing cycle times, and ensuring that the robots can perform their tasks without any collisions or other issues [23].

PS provides many benefits and advantages by integrating VC, Virtual Reality (VR) , integration of internet of things(IoT), sensors, safety validation and automation (Fig. 5). These benefits are based on the ability of doing the work in a virtual environment instead of physical one. Integration of real-time data and machine learning with AI is another benefits of PS (Fig. 6). Realtime robotics perform some tests in order to automatically generate the robot's trajectory for welding applications. It is based on sensors, which are continuous learning and send real-time data to the robots. After that, the robots can check the fastest and safest route to a specific weld point [25].

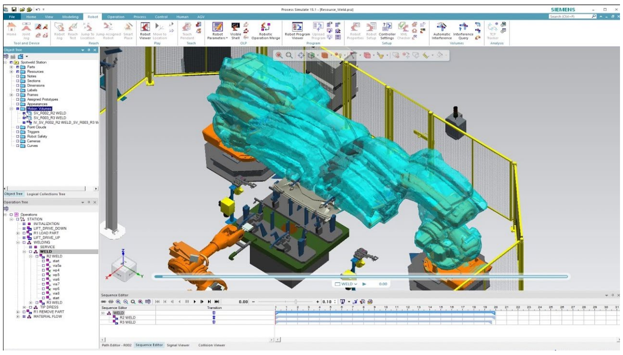

Fig. 5. Automation in robotics [24].

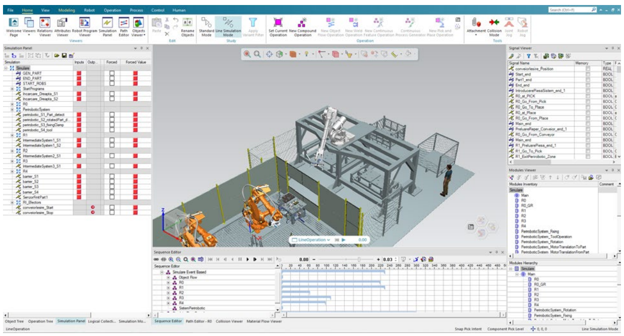

Fig. 6. Integration of VC.

Reduced Time to Market. By enabling early detection and resolution of potential issues, Process Simulate significantly reduces the time required to bring a product from the design stage to the market. This rapid product development capability is crucial in today's competitive market, where the ability to quickly launch new products can be a significant competitive advantage.

Cost Reduction. Process Simulate helps in minimizing the need for physical prototypes and reduces the risk of costly errors and rework in the later stages of development. By optimizing the manufacturing process virtually, companies can save substantial costs associated with material waste, downtime, and inefficient operations [20].

Enhanced Quality and Efficiency. The software enables manufacturers to design their processes with precision and accuracy, leading to higher quality products and operations that are more efficient. By simulating and validating the processes in advance, manufacturers can ensure that the production lines operate at optimal efficiency, with minimal defects and disruptions [26].

Numerous industries, including automotive, aerospace, electronics, and heavy machinery, have successfully integrated Tecnomatix Process Simulate into their manufacturing operations. For instance, in the automotive industry, Process Simulate has been used to design and optimize assembly lines for new vehicle models, significantly reducing the time and cost associated with the launch of new products. In the aerospace industry, the software has been instrumental in simulating and validating complex assembly processes for aircraft components, ensuring precision and compliance with stringent quality standards [27].

Tecnomatix Process Simulate represents a significant advancement in the field of digital manufacturing and it still can be improved by cloud integration, since the use of cloud computing for simulation and VC is becoming more prevalent. This trend can lead to more accessible and scalable solutions.

2.2. MCD accelerates the development of new products and system

Mechatronics Concept Designer represents a revolutionary shift in the way engineers and product designers approach the development of new products and systems. As a multidisciplinary field, mechatronics integrates principles from mechanics, electronics, computer engineering, robotics, and systems design. The heart of this integration is epitomized by the use of MCD, an innovative software tool that facilitates the seamless transition from conceptual design to actual prototype, offering a high-fidelity simulation environment that mirrors real-world physics and logic. This essay delves into the capabilities, applications, and transformative potential of MCD, underlining its role in fostering innovation and efficiency in product design and development. It comprises many capabilities and applications in the industry related to robotics and others domains.

Mechatronics Concept Designer offers an array of capabilities that significantly enhance the efficiency and effectiveness of the product development process.

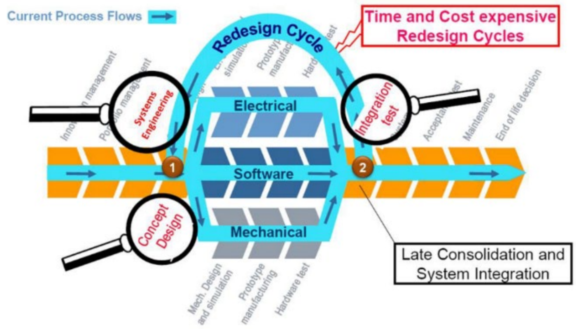

Fig. 7. MCD Cycle.

Firstly, MCD allows for the creation of a virtual prototype, a digital twin of the proposed system, enabling designers to visualize, test, and iterate their designs without the need for physical prototypes. This not only reduces the time and cost associated with the development process but also enables rapid prototyping, allowing for swift adjustments based on simulation feedback [15, 18, 28].

Moreover, MCD is integrated with advanced simulation tools, which allow for the analysis of various physical phenomena, including kinematics, dynamics, and control systems. This integration ensures that all aspects of the system, from the mechanical components to the electronics and software, can be simultaneously designed and tested in a cohesive environment. Such a holistic approach ensures that the interdependencies between different system components are adequately considered, leading to more robust and reliable product designs [15, 18, 28].

The adoption of MCD in product design and development heralds a new era of efficiency, innovation, and quality. By allowing for early detection and resolution of design issues, MCD reduces the risk of costly errors and rework in the later stages of product development. This proactive problem-solving capability is particularly crucial in today's fast-paced market, where the speed of product development can be a significant competitive advantage.

Furthermore, MCD promotes a more integrated and collaborative approach to product design. By providing a shared platform where mechanical engineers, electronic engineers, and software developers can work together seamlessly, MCD fosters interdisciplinary collaboration (Fig. 7). This collaborative approach ensures that all aspects of the product are harmoniously integrated from the outset, resulting in products that are not only innovative but also highly functional and user-friendly [15, 18, and 28].

3. SCALABILITY AND INTEGRATION CHALLENGES OF VC BASED ON CLOUD COMPUTING

Scalability in VC is essential for its success in diverse manufacturing scenarios. The scalability of VC systems faces significant challenges due to the resource-intensive nature of simulating complex manufacturing processes. As manufacturing systems grow in complexity, the computational load increases exponentially, demanding robust and scalable computational infrastructure. Additionally, the integration of emerging technologies like IoT and AI into VC platforms introduces new layers of complexity, requiring VC systems to be inherently flexible and adaptable to incorporate these advancements efficiently [29].

Integration stands as a cornerstone in the effective deployment of VC, yet it poses significant hurdles. One of the primary challenges lies in the integration of VC with existing legacy systems. Many manufacturing facilities operate on platforms that may not be readily compatible with the latest VC solutions, requiring a careful and often complex integration process.

The appearance of cloud computing has ushered in a new era of possibilities for VC. VC based on the cloud valorizes the power of the cloud to simulate, test, and validate manufacturing processes and systems before they are physically built. Cloud computing [30] provides a scalable, flexible, and resource-efficient platform for VC, enabling manufacturers to access powerful computing resources on-demand without substantial upfront investments in IT infrastructure. The convergence of VC and cloud computing addresses some of the traditional challenges associated with VC, particularly in terms of scalability and accessibility. Cloud-based VC solutions can scale resources up or down based on the complexity of the commissioning project, ensuring optimal utilization of computational resources. This scalability is essential for small and medium-sized enterprises (SMEs) that may not have the capital to invest in high-performance computing infrastructure.

The benefits of integrating VC with cloud computing are manifold. One of the most significant advantages is the dramatic reduction in costs and time associated with the commissioning process. Cloud-based VC allows for parallel processing and simulation, drastically reducing the time required for system validation and troubleshooting [29].

While the integration of VC with cloud computing offers numerous benefits, it also presents certain challenges that need careful consideration. Data security and privacy are paramount concerns in cloud-based systems. The sensitive nature of manufacturing data necessitates robust security measures to prevent unauthorized access and protect intellectual property.

4. CONCLUSIONS

The exploration of virtual commissioning (VC) within the manufacturing landscape underscores a pivotal shift towards enhanced efficiency, precision, and adaptability in production processes. As delineated in this review, VC stands at the forefront of modern manufacturing, offering a robust framework for the pre-emptive simulation and optimization of systems through the synergy of digital twins and real-world machinery. The integration of VC with cutting-edge technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI) not only propels the capabilities of simulation to new heights but also embeds a layer of predictive intelligence and dynamic adaptability within manufacturing systems. The utilization of platforms like Tecnomatix Process Simulate and Mechatronics Concept

Designer illustrates the practicality and transformative potential of VC in refining product design and manufacturing efficiency.

However, the journey towards the widespread adoption of VC is fraught with complexities. Challenges spanning from the integration of heterogeneous systems and the scalability of solutions in cloud-based environments to the assurance of cybersecurity necessitate a holistic and strategic approach. Despite these hurdles, the compelling benefits of VC, including reduced time-to-market, cost efficiency, and a marked decrease in environmental impact, firmly establish its role as an instrumental force in the evolution of smart manufacturing. The continual advancement in VC technologies and methodologies heralds a future where manufacturing systems are not only interconnected and intelligent but also inherently sustainable and resilient. As industries relentlessly pursue innovation and sustainability, VC emerges not merely as a technological solution but as a strategic imperative, pivotal in sculpting the future of manufacturing.

REFERENCES

[1] S.M.A. Kazmi, *Methodology for validating mechatronic digital twin*, Master's Thesis, Tampere University, 2019.

[2] St. Flaga, K. Pacholczak, *Demonstrator of a Digital Twin for Education and Training Purposes as a Web Application*, Advances in Science and Technology Research Journal, 2022.

[3] F. Tao, B. Xiao, Q. Qi, J. Cheng and P. Ji, *Digital twin modeling*, Journal of Manufacturing Systems, vol. 64, 2022, pp.372-389.

[4] J.A.C. Armero, M.T. Quezada, L.B. Vázquez, R. R. Serrezuela, Jeidy Johanna Gómez Montiel, Daily Milanés Hermosilla, Roberto Sagaró Zamora, *Digital twin: an option for the integrated design of upper limb robotic exoskeletons for rehabilitation tasks*, Journal of Engineering and Applied Sciences, Vol. 16, No 6, 2021, pp. 423-424.

[5] T. Lyu, U. Dwi Atmojo and V. Vyatkin, "Towards cloud-based virtual commissioning of distributed automation applications with IEC 61499 and containerization technology," IECON 2021

[6] K. Herbus and P. Ociepka, *Determining of a robot workspace using the integration of a CAD system with a virtual control system*, IOP Conf. Ser.: Mater. Sci. Eng. P. Vol. 145, No. 5, p. 052010, 2016, IOP Publishing.

[7] N. Striffler, *Concepts and trends of virtual commissioning – A comprehensive review*, Journal of Manufacturing System, Vol. 71, 2023, pp. 664-680.

[8] Mohsen Soori, Behrooz Arezoo, Roza Dastrez, "Virtual Manufacturing in Industry 4.0, A Review," ResearchGate, 2023

[9] Mohsen Soori, Behrooz Arezoo, Roza Dastrez, "Advanced Virtual Manufacturing Systems, A Review," ResearchGate, 2023

[10] M. Weyrich and C. Ebert, "Reference Architectures for the Internet of Things," in IEEE Software, vol. 33, no. 1, pp. 112-116, Jan.-Feb. 2016

[11] Anton LIDELLa, Stefan ERICSON, Amos H.C. NG, "The Current and Future Challenges for Virtual Commissioning and Digital Twins of Production Lines,", ResearchGate, 2022

[12] Suthida Thongnuch "An approach to generating high-fidelity models for the virtual commissioning of specialized production machines and cells using MCAD models," Disseratation Helmut Schmidt Universitat, 2021

[13] K Herbus, P Ociepka, "Integration of the virtual model of a Stewart platform with the avatar of a vehicle in a virtual reality," IOP Conf. Ser.: Mater. Sci. Eng. 145 042018, 2016

[14] Joonas Taipalus, "3D-Virtualization of a Conveyor Machine," Thesis Seinajoki University of Applied Sciences, 2015

[15] SIEMENS, "Mechatronics Concept Designer Quickstart and User Manual," Siemens, 2010-2023

[16] K Herbus si P Ociepka, "Virtual commissioning of a robotized production cell with use of mechatronic features," IOP Conf. Ser.: Mater. Sci. Eng. 400 042030, 2018

[17] Georg Hackenberg, "Test-driven conceptual design of cyber-physical manufacturing systems," Technische Universitat Munchen, 2018

[18] K Herbus,P Ociepka, "Designing of a technological line in the context of controlling with the use of integration of the virtual controller with the mechatronics concept designer module of the PLM Siemens NX software," IOP Conf. Ser.: Mater. Sci. Eng. 227 012057, 2017

[19] Nicholas M. Putman, Francisco Maturana, Kira Barton & Dawn M. Tilbury, "Virtual fusion: a hybrid environment for improved commissioning in manufacturing systems," International Journal of Production Research, 2017

[20] Berta Carbonell i Vilaplana, "Usage of a mechatronics software for efficient machine development," Master Final Thesis Escola Tècnica Superior d'Enginyeria Industrial de Barcelona, 2020

[21] Luis Villagómez Guerrero, Virgilio Vásquez López si Julián Echeverry Mejía, "Virtual Commissioning with Process Simulation (Tecnomatix)," Computer-Aided Design & Applications, 2014,

[22] Don B. Chaffin, "Human Motion Simulation for Vehicle and Workpalce Dsign," Human Factors and Ergonomics in Manufacturing, Vol. 17 (5) 475–484, 2007

[23] S.Y. Nof, *Springer handbook of automation*, pp. 1379-1396, S.Y. Nof (Ed.). Berlin, Heidelberg: Springer Berlin Heidelberg, 2009.

[24] W Banas, A Gwiazda, A sekala, K Foit si G Cwikla, "Positioning a robot in a robotic cell in Tecnomatix," IOP Conf. Series: Materials Science and Engineering 400 052002, 2018

[25] Ahmed Magdy Ahmed Zakia,Ahmed Mohsen Mohamed Fathya, Marco Carnevalea, Hermes Gibertia, "Application of Realtime Robotics platform to execute unstructured industrial tasks involving industrial robots, cobots, and human operators," , Procedia Computer Science, Vol 200, 2022

[26] Mikell P. Groover, "Fundamentals of Modern Manufacturing: Materials, Processes, and Systems," John wiley & Sons, 2007

[27] V Kishorre Annanth, M Abinash and Lokavarapu Bhaskara Rao, "Intelligent manufacturing in the context of industry 4.0: A case study of siemens industry," IopScience, 2021

[28] Jochen Merhof, "Virtual Commissioning for machines with NX Mechatronics Concept Designer and SIMATIC Machine Simulator," PLMEurope, 2018

[29] Salehi Vahid, Wang Shirui, "Using point cloud technology for process simulation in the context of digital factory based on a systems engineering integrated approach," Munich University of Applied Sciences, 2017

[30] Ali Sunyaev , "Cloud Computing," Internet Computing. Springer, Cham. https://doi.org/10.1007/978-3-030-34957-8_7, 2020.