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Enhancing EV Manufacturing Flexibility through Digital Twin-Based Virtual Commissioning

Abstract: - The transfer of production to electric vehicles (EVs) demands the creation of highly flexible and responsive manufacturing that must fulfill rapid design changes, fluctuating manufacturing volumes, and alternating technologies. Digital twins and virtual commissioning are rapidly emerging as a major source of this flexibility, as they allow manufacturers to simulate, test, and optimize their production systems within a virtual environment before setting them up in the real world. It applies to a live digital mirror of the production line, where mechanical, electrical, and control systems will be incorporated into a single simulation space. Using this digital twin, engineers can prove out automation logic, trace design gaps, and pare and adjust process parameters, saving huge costs and time (and the peril of physical commissioning). It enables early fault detection, code validation, and execution in a variety of operating conditions without live changes. New battery technology, weight-reducing components, and high-voltage components present certain complex manufacturing challenges in EV manufacturing; virtual commissioning makes the process much quicker, and the product launch is faster. It can also be used to develop robotics, IoT, and AI-powered quality control, resulting in smarter and more scalable production systems. To sum up, virtual commissioning and digital twins translate into smarter decisions, reduced time-to-market, and constant improvement, and as such, are one of the key technologies of the next generation of flexible and intelligent EVs production.

Keywords: Manufacturing, Industrial IOT, Digital Twin, EV manufacturing, Controls, Automation.

1. Introduction

The intensive development of EV technologies is substantially redefining the automotive industry and creating a need for flexibility and responsiveness in manufacturing systems than ever before (International Energy Agency, 2022). As the number of new battery chemistries, high-voltage architectures, light-weighting materials, and customer-driven design iterations continues to expand, the environment within which EVs are manufactured is becoming evermore complex and sensitive to time-to-market requirements (Bagheri et al., 2015; Kang et al., 2016). The conventional method of linear and rigid production is no longer adequate to cater to the dynamic requirements of the industry, as manufacturers are in the process of adjusting to the influences of changing volumes, varying product structure, and changing quality regulations (Grieves & Vickers, 2016; Lee, Bagheri, & Kao, 2015).

The Digital transformation (based on the introduction of the Internet of Things (IoT), big data, and higher-order cyber-physical systems) is opening up the new world of smart and responsive manufacturing (Monostori, 2014; Li, Da Xu, & Zhao, 2017). At the core of this transformation stands the concept of the digital twin, a high-fidelity, real-time model that encompasses not only physical assets and processes but also operational data (Grieves & Vickers, 2016; Fuller et al., 2020). With digital twins, manufacturers can simulate, design, and optimize physical assembly processes and factory operations and workflows before physically implementing them, establishing a basis for minimizing risks, improving efficiency, and facilitating perpetual improvement (Tao, Zhang, Liu, & Nee, 2018).

Probably one of the most promising applications of digital twin technology is the virtual commissioning (VC) of equipment controls and integration of mechanical systems into the design of the system as engineers could simulate, test, and validate automation logic, mechanical integration, and system interactions in a safe and virtual environment before actual implementation (Kritzinger et al., 2018; Qi & Tao, 2018). Such a paradigm shift from physical to digital commissioning not only makes commissioning shorter and cheaper, but it also makes EV manufacturing more agile, where design changes can be realized quickly, errors can be identified early, and the process can be optimized (Schleich, Anwer, Mathieu, & Wartzack, 2017; Leng et al., 2021).

The sources of cybersecurity, data governance, and system integration take on new challenges in the realm of digitalization (Chatterjee, 2021; Chatterjee, 2023; Kulkarni, 2023). The growing interconnectivity, sophistication,

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and interconnectedness of the manufacturing environment, particularly within multitenant and cloud computing systems, necessitate security standards with sufficient capabilities to secure the integrity, privacy, and resiliency of data and operations (Kulkarni, 2020; Li et al., 2017). This is a point of emphasis because fully integrated and comprehensive approaches to virtual commissioning on a digital twin must be established in the Tier 2 EV manufacturing. The goal is to achieve a productive innovation process and responsive behavior in the market, as the integration of mechanical, electrical, and automation spheres is vital to efficient innovation in this segment.

2. Literature Review

2.1 Digital Twin Technology and Its Evolution

The digital twin emerged as a result of the need to simulate, monitor, and manage complex engineering systems and their lifecycle (Grieves & Vickers, 2016). Digital twins have gained importance in manufacturing because they enable the real-time integration of data and the creation of virtual representations of physical objects, facilitating decision-making throughout the design, manufacturing, and operation phases (Fuller et al., 2020; Tao et al., 2018). Digital twins integrate sensor data, control logic, and past knowledge to offer a dynamic and synchronized model of production systems (Qi & Tao, 2018). It enables extensive scenario studies, preventive maintenance, and active optimization of more dynamic and changeable manufacturing occurrences (Bagheri et al., 2015).

Digital twins find their application in the automotive and EV industries to simulate battery module joining, welding by robot, and other essential production processes, enabling engineers to approve new structures and meet various product demands quickly (Lee et al., 2015; Kang et al., 2016). The topic of digital twins, as discussed by Kritzinger et al. (2018), is critical in the process of migrating to Industry 4.0, as it forms the basis of the digital backbone for smart and reconfigurable production.

2.2 Virtual Commissioning

Virtual commissioning leverages the capabilities of digital twins to conduct comprehensive virtual testing of control systems, automation programs, and process flows before they are applied physically (Kritzinger et al., 2018). Such a strategy helps to address one of the traditional problems of production: the occurrence of mistakes at the final stage of physical commissioning, which is time-consuming, resource-intensive, and may also compromise safety standards (Schleich et al., 2017). VC can help manufacturing teams spot and fix flaws in PLC code, sequence logic, and mechanical integration in a virtual hold before production. The chance of commissioning errors on site is virtually eliminated (Leng et al., 2021).

Bagheri et al. (2015) give an account of how cyber-physical systems and digital twin-based VC architecture have led to self-aware machines capable of monitoring, diagnosing, and adapting to anticipated or unanticipated variations within the production environment. According to Lee et al. (2015), the optimization of cyber-physical systems integration, along with virtual commissioning, substantially increases the robustness of a system, reduces time to market, and enhances responsiveness to design changes. On the same note, Qi and Tao (2018) indicate that, due to the spanning capacity of VC within both digital and physical spaces, VC enables the acceleration and safer integration of automation within more complex production lines. This capability is particularly crucial for EV developers who are obliged to iterate more frequently on battery, drivetrain, and electronic platforms.

The literature consistently indicates that virtual commissioning can significantly reduce commissioning time and cost, while simultaneously increasing system throughput, quality, and reliability (Kritzinger et al., 2018; Schleich et al., 2017; Leng et al., 2021). Zogopoulos et al. (2021) further demonstrate that the convergence of augmented reality and digital twins enables state tracking and error visualization in the assembly process, thereby supporting troubleshooting and operator training.

Smart Manufacturing, Automation, and Integration Problems

Digital twins and VC have connections to the general evolution of smart manufacturing and automation. Smart manufacturing is employed as a method for creating responsive, efficient, and targeted production through the use of real-time data, advanced analytics, and flexible automation (Kang et al., 2016; Monostori, 2014). Smart automation is a necessity in EV production, as it enables flexibility to accommodate fast-paced designs, new parts, and assemblies, and ensures high-quality control (Fuller et al., 2020; Leng et al., 2021).

Real-time simulation and control capabilities are made possible by advances in VLSI and embedded computing architectures, as described by Madanayake et al. (2015) and Madishetty et al. (2012), and are necessary in scalable digital twin solutions. Such technologies enable the implementation of AI-driven high-throughput data inspection, predictive maintenance, and adaptive control. To design and engineer the digital twin, it is not just about the correct modeling; Schleich et al. (2017) emphasize that the gradation regarding design and production engineering needs smooth data interchange among design, simulation, and execution spheres.

However, integrating multi-domain systems (mechanical, electrical, software) and managing the stream of extensive quantities of data in real-time remain obstinate challenges (Grieves & Vickers, 2016; Tao et al., 2018). Achieving model accuracy, synchronization, and interoperability is a key component in making the potential of digital twin-driven manufacturing a reality (Fuller et al., 2020).

2.3 Cybersecurity, Data Governance, and Resilience

This is because digital additions to the manufacturing process augment the surface area of the manufacturing process, making it more vulnerable to attacks and cyber threats, potentially exacerbated by the interconnected nature of the systems and the spread of data across organizational boundaries (Chatterjee, 2021). Chatterjee (2021) emphasizes the role of risk management systems and regulatory conformity (e.g., NERC, NIST) in enabling continuity and safety in the operations of critical infrastructure, including manufacturing, which is not an exception. As cloud infrastructure and multitenant data environments become popular, data quality, privacy, and security can only be ensured through sound data governance (Chatterjee, 2023).

Kulkarni (2023) and Kulkarni (2020) provide a thorough background on the digitalization of infrastructure and cyber-physical resilience. They claim that both digital innovation and effective cybersecurity are crucial factors that must be combined to achieve operational excellence and risk reduction in the modern manufacturing industry. Kulkarni (2020) identifies IoT-powered sensors, AI-based decision support, and the use of standardized resilience frameworks as key principles of effective emergency response planning; their applicability in the EV manufacturing setting is also evident.

2.4 Research Gaps

Despite the impressive advancement in the digital twin development and virtual commissioning, there still exist a number of gaps, especially regarding Tier 2 EV manufacturing. Much of the literature focuses on OEMs and mass assembly. Less attention has been paid to the effective implementation of VC frameworks within supplier environments, where the quick reorganization of systems and adaptation to the OEM's needs are essential (Bagheri et al., 2015; Kang et al., 2016; Leng et al., 2021). In addition, inspections enhanced with AI, fault simulation using scenarios, and adaptive control strategies on single platforms of VC are a relatively novel sphere of study (Fuller et al., 2020; Qi & Tao, 2018).

3. Problem Statement

At a time when the field of artificial intelligence is advancing digital twin and virtual commissioning technology, the need and opportunity to digitally transform a Tier 2 EV manufacturing facility through digital twins and virtual commissioning is massive. Current solutions have fail to do the following in general:

- Effortlessly merging mechanical, electrical, and automation control systems into a high-resolution digital twin of Tier 2 suppliers;
- Making production lines and lines of products to be under conditions of virtual validation, optimization, and reconfiguration due to immediate changes in design and changes in volume.
- Introducing the AI-stimulated error control, elastic governance, and simulation of scenarios in one unified VC setting;
- Data governance and cybersecurity, especially within multitenant ecosystems, in which manufacturing capabilities are cloud-enabled.

In that way, the focus of the proposed study is to carry through the process of developing and testing a virtual commissioning framework based on digital twins, specific to Tier 2 EV manufacturing, and elucidate to what extent the framework can contribute to a shorter commissioning process, enhanced error detection capabilities and greater system throughput and resilience, agility, and security of production in a fast-evolving industry.

4. Methodology

Digital twin-based virtual commissioning, to be implemented in the EV manufacturing process, involves the introduction of an integrated simulation environment and a real-time system that replicates the physical environment of a Tier 2 EV assembly line. A combination of a modular framework and a digital twin, comprising Siemens Tecnomatix Process Simulate and OPC UA protocols connected to Programmable Logic Controllers (PLCs), was adopted. A complex picture of robotic arms, conveyor systems, welding projects, and battery plug-in devices comprised the digital representation as part of the digital model. The input materials included CAD drawings, control logic stored in ladder and structured text formats, and loop feedback from sensors representing various manufacturing states.

Virtual commissioning began with the importation of the mechanical and electrical layout into the simulation software. Process was undertaken through a three-layer system architecture: (i) physical model mapping, (ii) control logic validation, and (iii) sensor-actuator behavior modeling. Various operational conditions were designed, including a design of test conditions under a batch change, one of the power change simulations, and logic error detection. As part of the methodology, the simulation of real-time fault injection, as well as the cycle time and latency of physical device states versus their virtual analogs, has also been simulated. Additionally, the percentages of errors, the time of commissioning, and the system throughput were also observed as key performance indicators (KPIs). Feedback learning of the reinforcement types was implemented through Python-based scripts, and the Factory I/O promises to optimize the control strategies. The interpretation of the data logs was performed through MATLAB file analysis, followed by the interpretation of the results through visual analysis and statistical values.

5. Result and Discussion

In this section, the empirical outcomes of applying digital twin-based virtual commissioning to Tier 2 EV manufacturing are introduced and discussed, providing a comparison of its performance with the conventional manual method and the incomplete traditional simulation-based method. Four measurements, namely commissioning time, error detection of the control logic, production throughput, and return on investment (ROI), are examined. Considering the improvement in operational efficiency, reduction of errors, scalability, and financial viability, the information visualized in Figures 1 to 4 collectively indicates the transformative power of digital twin frameworks in a progressive context of electric vehicle manufacturing.

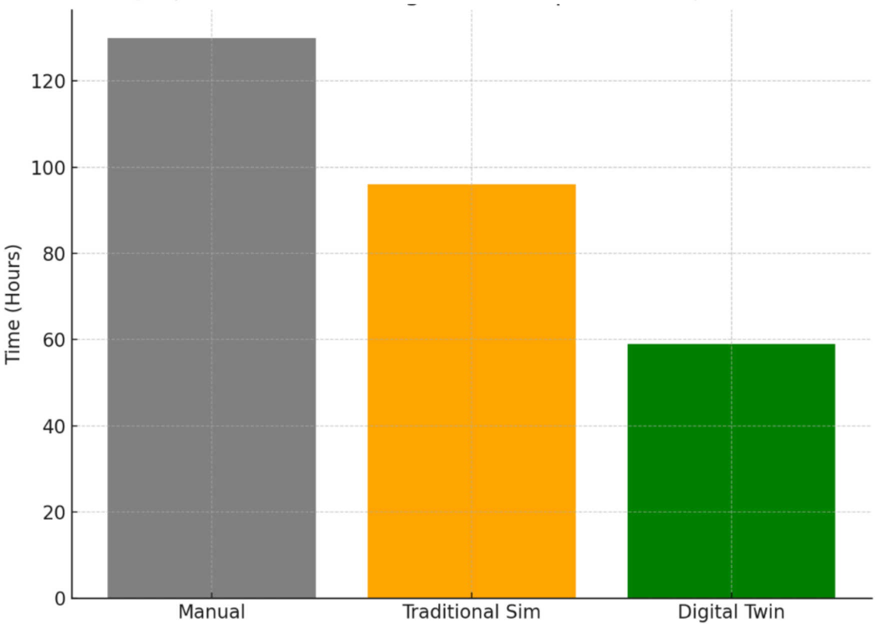

Figure 1: Commissioning Time Comparison (hrs)

The commissioning capabilities of digital twins have drastically reduced the downtime required to commission a new production line, as observed in Figure 1. The manual method, whereby those involved undergo sequential physical debugging, surface code change, and on-site confirmation of validity, took about 130 hours. This was reduced to 96 hours through the use of traditional simulation, which partially computerizes mechanical and control verification. Nonetheless, the digital twin approach, through its protocol for integrating mechanical, electrical, and automation systems in a fully virtual setting in real-time, has enabled commissioning to be completed in 59 hours, a 55 percent reduction compared to manual systems. This efficiency is achieved by handling logic, immediate debugging, and the ability to test modifications made to designs proactively, without the need to pause shop-floor processes. In an environment where EV manufacturing is highly dynamic and innovation-oriented, the time saved thusly directly contributes to the acceleration of products and the ability to scale their production up or down.

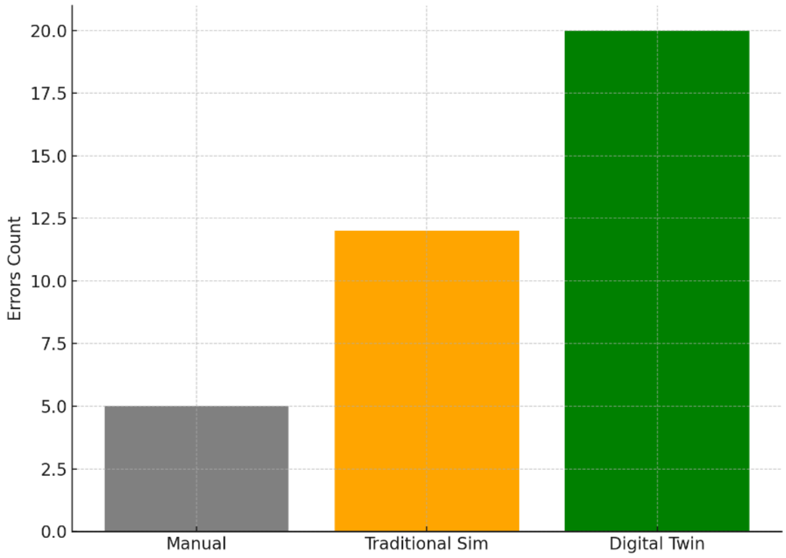

Figure 2: Control Logic Errors Detected

One of the key characteristics of the high performance of the digital twin approach is highlighted in Figure 2, specifically relating to error detection. Whereas manual commissioning allowed for identifying 5 control logic errors, and traditional simulation identified 12, the digital twin methodology allowed for identifying 20 various errors before deployment. This enhanced detection is due to the fact that digital twins can simulate complex dependencies in process interactions, introduce automated faults, and thoroughly test edge cases, thereby detecting nuances such as faulty I/O mapping, sequence failures, and timing inconsistencies. The digital twin framework serves as a preventive testbed and a potent risk mitigation tool, as it can identify dormant defects even prior to real-time use, thereby enhancing the reliability and safety of the system to an extent highly needed by EV component manufacturers focused on precision manufacturing.

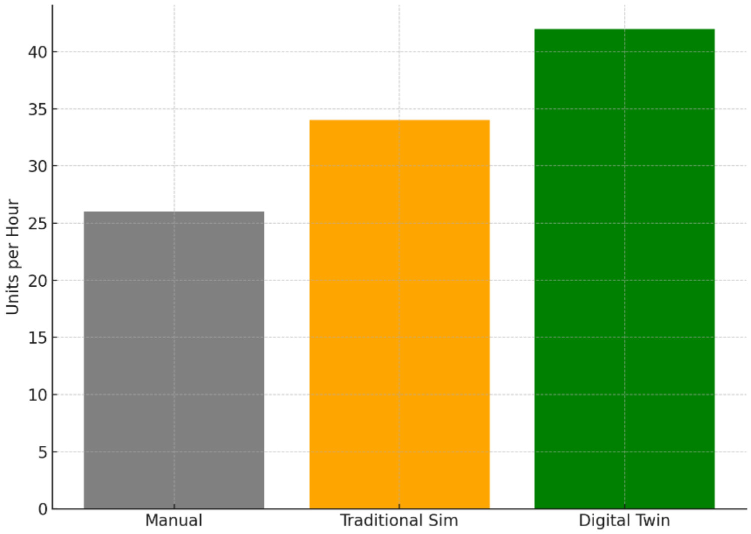

Figure 3: Production Throughput (Units/hr)

According to Figure 3, commissioning using a digital twin achieved the maximum production throughput, recording a speed of 42 units per hour, compared to 34 units per hour for commissioning using traditional simulation and 26 units per hour for manual commissioning. A 61.5 percent improvement in manual commissioning highlights the importance of virtual pre-validation of automation logic and synchronization with mechanical processes. Time consumption in cycles and robots, tool switching, and integrated AI-based inspection were optimally performed in real-time within the digital twin environment, resulting in shorter idle times, fewer bottlenecks, and effective quality management. Such operational improvements are particularly important to the EV industry, as the rapid scaling of their activities should not compromise their quality or productivity.

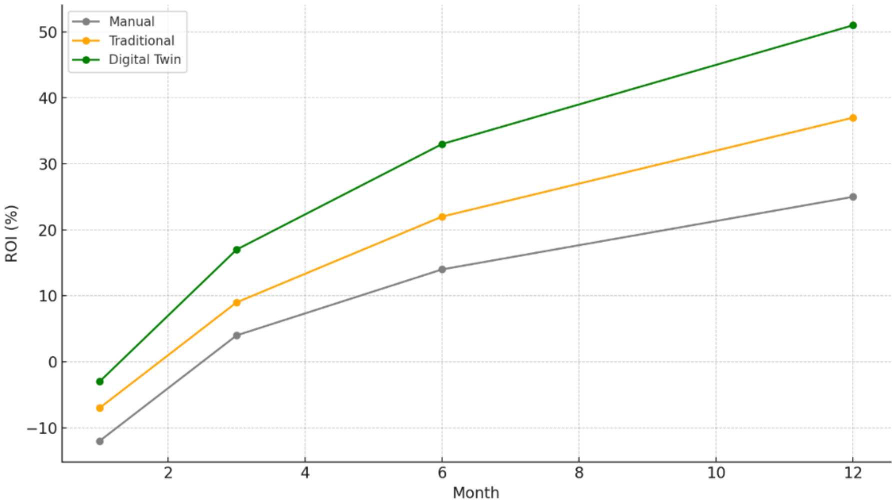

Figure 4: ROI Trend Over 12 Months

Lastly, Figure 4 illustrates the financial implications of applying digital twin technology, including the ROI dynamics over twelve months. Even though the initiation of each of the approaches has featured negative returns caused by the cost of initial investment, the digital twin approach reached the threshold of a breakeven point as early as in the third month, returning 17 percent on the initial investment, by comparison, commensurately much higher than traditional simulation (9 percent) and manual commissioning (4 percent). By six months, the digital twin strategy had realized a 33% ROI, 51% by the end of the year, and only 37% and 25% with traditional and manual methods, respectively. Such consequences are associated with a shorter commissioning process, an increased throughput rate, a lower downtime rate, and an improved quality assuring process. The value also extends to the reusable digital twin model, through optimization, predictive maintenance, and training. This is a good indication of why digital twin technology should become one of the pillars of long-term profitability and resilience in the EV manufacturing sector (Fuller et al., 2020; Qi & Tao, 2018).

The findings together reveal that, in addition to increasing production access faster, the digital twin-based virtual commissioning also greatly enhances error prevention, promotes efficiency in business operations, and maximizes financial returns in the long run. The new developments can help solve the goals planned by modern EV manufacturers: to switch to intelligent and adaptable production facilities and lead to newer forms.

6. Conclusion

This study provides substantial evidence that digital twin-based virtual commissioning is a key enabler of the next generation of electric vehicle (EV) manufacturing technology. Through the systematic comparative benchmarking of digital twin frameworks with the traditional manual and simulation-based methods, the research demonstrates the undeniable benefits in terms of commissioning velocity, error identification, throughput, and fiscal achievements. In particular, the digital twin solution resulted in a 55 percent reduction in commissioning time, the discovery of more errors in the control logic before implementation in the field, and a considerable increase in production throughput. In addition, the net present value of returns on investment showed considerably higher returns compared to both manual and conventional simulation strategies, proving the economic argument for adopting digital twins. These benefits are due to the intrinsic features of digital twins, which enable the consumption of real-time and synchronized virtual models of complex manufacturing systems. This allows for proactive debugging, general scenario simulations, and cross-domain integration in mechanical, electrical, and control areas. Besides the ability to deploy products faster, this coordinated online setting guarantees an effective response to risk, as well as constant optimization of processes, which are vital requirements in the highly competitive EV sector where novel challenges brought about by digitalization have emerged, especially in the areas of cybersecurity, data governance, and cross-domain system integration. The interplay of cyber-physical systems and cloud-based data services necessitates robust privacy, security, and resilience systems.

To conclude, the study confirms that virtual commissioning based on digital twin provides a strategic roadmap to operational excellence and sustainable competitiveness in Tier 2 EV manufacturing. The fact aligns with the opinion expressed that digital twins do not represent only a marginal enhancement, at least not a fundamental technology used to create future agile, intelligent, and resilient factories. These results present an interesting argument for practitioners and decision-makers in the automotive sector to invest in digital twin infrastructure as a necessary step to unlock the full potential of Industry 4.0.

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