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DEVELOPMENT OF SMART FACTORY 4.0 USING CYBER-PHYSICAL SYSTEM-BASED WORKSHOP IN ROLLING STOCK INDUSTRY TO SUPPORT INDUSTRY 4.0

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ABSTRACT

Driven by the concept of mass customization, manufacturing enterprises are now required to transform their traditional workshops into smart workshops. The integration of cyber-physical systems (CPS), which serves as the core of Industry 4.0, is crucial in achieving smart manufacturing. By implementing CPS, the conventional workshop can transition into a new paradigm characterized by intelligence and flexibility. However, the implementation of CPS in workshops is a complex undertaking that is still in its early stages. Therefore, this research paper aims to provide a comprehensive perspective on CPS-based workshops, with the intention of facilitating their implementation in the industry. Initially, the paper identifies seven key features of CPS-based workshops, namely self-sensing, self-awareness, self-assessment, self-optimization, self-adjustment, self-configuration, and self-control. Subsequently, the paper proposes the architectural framework of CPS-based workshops from a technical standpoint. Furthermore, a conceptual model of CPS-based workshops is developed, which highlights the three fundamental elements and closed-loop mechanism of such workshops. Finally, a case study of a Rolling stock manufacturing company in Indonesia is presented to demonstrate the feasibility of implementing CPS-based workshops in the industry.

KEYWORDS *Digital Transformation, Industry 4.0, Manufacturing, Rolling Stock, Smart Factory*

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INTRODUCTION

Driven by a market that prioritizes customer satisfaction, mass customization has emerged as a crucial aspect of modern manufacturing [1]. The success of mass customization hinges on the ability of manufacturing companies to swiftly adapt to evolving customer demands [2]. However, traditional workshops are only equipped to produce standardized products in large quantities, lacking the capability to cater to small-batch customized orders. To address this limitation and meet the requirements of mass customization, the transformation from traditional workshops to smart workshops becomes imperative.

In recent years, the concept of cyber-physical systems (CPS) has garnered significant attention from both industry and academia. CPS is widely acknowledged as a pivotal factor in the future development of smart manufacturing [3]. Despite its potential, the implementation of CPS in industrial settings is still in its nascent stages. This is primarily due to the complex and systemic nature of integrating CPS into existing infrastructures, which necessitates a bottom-up approach. Consequently, research on the implementation of CPS at the workshop level remains limited.

To bridge this gap, this paper presents a comprehensive overview the development of Smart Factory 4.0 (SF4.0) using CPS-based workshop for smart manufacturing to be implemented on a traditional, labour – intensive industry, offering practical guidance for manufacturers. Firstly, the paper identifies seven key features of a CPS-based workshop, encompassing self-sensing, self-awareness, self-assessment, self-optimization, self-adjustment, self-configuration, and self-control. Secondly, it proposes an architectural framework for a CPS-based workshop from a technical standpoint. Thirdly, a conceptual model of a Smart Factory 4.0 using a CPS-based workshop is developed, highlighting the three fundamental elements and closed-loop mechanism that underpin its operation. Finally, a case study of a Rolling stock manufacturing company in Indonesia is presented to illustrate the feasibility of implementing a CPS-based workshop in an industrial context.

Literature Review

CPS integrates computation, communication, sensing, and actuation with physical systems to fulfil time-sensitive functions with varying degrees of interaction with the environment and human. Cyber-physical production system (CPPS), as a specific application of CPS in manufacturing, has been extensively studied in the literature. By implementing CPPS, autonomous and cooperative elements and subsystems within and across all levels of the production system are interconnected, from processes through machines up to production and logistic networks. Various researchers have identified different clusters of CPPS application fields, including manufacturing processes, logistics and supply chain management, as well as research and development. Methods and applications for the design, modelling, simulation, and integration of CPS have been discussed by researchers, showcasing the practicality of these methods with cyber-physical production systems (CPPS). Different architectures and frameworks have been developed for CPPS implementation, such as the 5C architecture proposed by Lee et al., which provides a step-by-step guideline for implementing CPS in a factory. Additionally, Jiang has added 3C facets into the 5C architecture of CPS, considering horizontal integration and presenting an example of implementing CPS in a factory for the production of wire electrical discharging machines based on the 8C architecture. Rojas et al. have presented a framework for connecting cyber-physical elements in a smart factory from a functional view. Liu and Jiang [13] put forward a CPS framework and pinpoint essential technologies that enable optimal process control and intelligent decision-making on the shop floor. Raharno et al [14] developed a configurable virtual workshop (CVW) concept on a labour – intensive industry enabling the labour – intensive industry to step into the digital transformation era.

Through a review of existing literature, it becomes evident that the implementation of CPS in actual production settings is still at a nascent stage. The workshop, positioned as an intermediate level within a factory, emerges as a suitable environment for the introduction of CPS in this context. Furthermore, only a limited number of frameworks have been utilized in practical manufacturing scenarios, underscoring the need for additional case studies on industrial applications.

RESEARCH METHOD

Features of CPS-based workshop

The CPS-based workshop (CPWS) is an intelligent and autonomous system that possesses various capabilities. These capabilities include self-sensing, self-awareness, self-assessment, self-optimization, self-adjustment, self-configuration, and self-control [9], [14], [15]. Self-sensing refers to the workshop's ability to perceive its physical environment by acquiring accurate and reliable data on equipment, tools, workers, workpieces, and the surrounding conditions. Self-awareness involves the workshop's capacity to derive meaningful information from the collected data, utilizing its knowledge about the production status and environment. Self-assessment is the process of evaluating the workshop's status and ensuring that all activities and events align with the production goal. Self-optimization entails the workshop's capability to coordinate and integrate production resources, aiming for continuous improvement in resource efficiency. Self-adjustment refers to the workshop's ability to promptly respond to environmental disturbances or adapt itself to changing customer demands during the production process. Self-configuration involves the workshop's capacity to reconfigure production assets, such as machines, materials, and workers, in order to meet the demands of customization with small batch sizes. Lastly, self-control is the workshop's ability to precisely control the production process based on well-informed and rational decisions, rather than arbitrary choices.

Proposed architecture of SF4.0

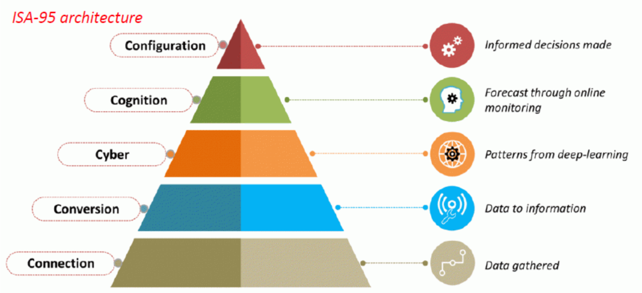

Fig. 1. 5C Architecture

As illustrated in Fig. 1, Smart Factory 4.0 is built upon the established 5C architecture. Connection layer, utilizes IoT technology to create a unified system that links various "things" within a workshop through standard communication protocols. This facilitates the real-time capture and exchange of information. A functional CPWS commences with self-sensing, where data is gathered from diverse sources within the workshop.

Conversion layer, the significance of vast amounts of data can be harnessed through sophisticated industrial big data analytics. This process enables the workshop to attain self-awareness. By analyzing the collected data using existing knowledge, valuable insights and information can be derived. A typical data process encompasses several stages, including data storage, data integration, data analysis, data mining, and data visualization. To ensure the accuracy and reliability of the data, it is essential to have data quality management throughout the entire process.

Cyber layer, the cyber layer plays a crucial role. The digital twin serves as the "heart" of this implementation, enabling interaction, communication, and collaboration between the physical workshop and the virtual workshop. By integrating with the virtual workshop, the physical shop gains self-awareness and self-assessment capabilities.

Cognition layer, the cognition layer addresses the challenges faced by workers in a traditional workshop. It provides them with access to valuable information through human-machine interfaces (HMI) and supports various applications. Tools such as mobile devices, computers, LED screens, artificial reality (AR), virtual reality (VR), and voice devices are commonly used to create HMIs. In the workplace scenario, functions such as information visualization, pre-warning, co-decision, task scheduling, performance evaluation, and operation guidance are particularly useful in enhancing workers' capabilities.

Configuration layer, at the configuration layer, the workshop achieves self-configuration and self-control. Based on feedback from the cyber world, the physical entity autonomously takes actions to achieve the desired results. Industrial Apps, a new form of industrial software, serve as carriers that encapsulate industrial knowledge and capabilities. They enable various functions of CPWS, such as process parameter optimization, defect recognition, fault diagnosis and prediction, energy optimization, and mis operation recognition.

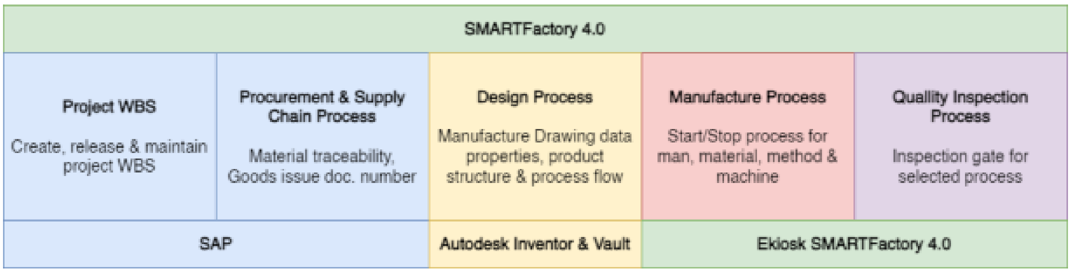

Fig. 2. SF4.0 Block Diagram

The Smart Factory 4.0 incorporates the SAP project systems, SAP procurement systems, Autodesk CAD & PDMC systems, and links them with production and quality assurance systems on the shopfloor level.

Proposed conceptual vertical-horizontal integration model of SF4.0

Illustrated in Figure 3, SF 4.0 seamlessly integrates the production section at the shop floor level all the way up to the enterprise resource planning system on the enterprise level, ensuring a vertical integration. Moreover, it horizontally integrates all the business processes within rolling stock companies, encompassing marketing division, projects system, procurement system, finance and even after-sales service to customers. This comprehensive integration is a result of the development based on the CPS approach. The Cyber-Physical System (CPS)-based workshop comprises three essential components: physical space, cyber space, and human involvement.

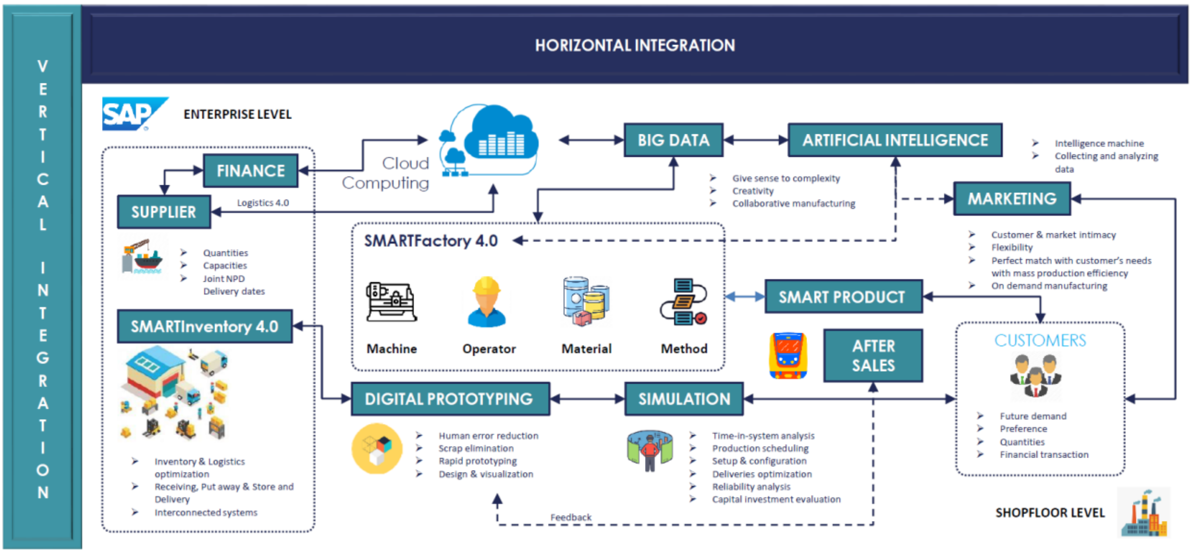

Fig. 3. SF4.0 vertical-horizontal integration model

The physical space of a CPS-based workshop encompasses a variety of physical entities, such as machines, robots, tools, materials, and products. Each physical entity functions as a manufacturing unit, interacting and communicating with one another to coordinate production activities. Throughout the production process, a significant amount of information is generated, including process parameters, equipment status, workpiece quality, energy consumption, and operational procedures. This information is then transformed into data through digitalization tools, serving as the "fuel" for driving the cyber space. Within the cyber realm, a virtual workshop is established, consisting of interconnected cyber replicas of physical entities. Fuelled by real-time data collected from the physical world, the virtual workshop can synchronize with its physical counterpart. Moreover, the virtual workshop facilitates the coordination and optimization of all assets and activities from a global perspective, enhancing production efficiency. Based on the optimized decisions, physical entities can be precisely controlled, ensuring that decision-making is rooted in knowledge extraction rather than arbitrary choices. Human involvement is also crucial in a CPS-based workshop, typically playing a role in the control loop. Leveraging advanced technologies like augmented reality (AR), virtual reality (VR), Radio Frequency Identification (RFID), mobile devices, and smart industrial wearables, humans become integral components of the CPS-based workshop. For workshop managers, these technologies enhance production management by providing information transparency and traceability throughout the production process. With a comprehensive view of production operations, managers can streamline the value stream more effectively and expediently.

Production managers now have the authority to participate in decision-making processes, no longer relying solely on intuition. Operators have the opportunity to engage in interactions involving humans, machines, and the environment, aiming to enhance production efficiency by taking into account the ever-changing surroundings. The utilization of cutting-edge technologies like RFID, AR, VR, and industrial wearables has transformed the approach to acquiring skills and training. Furthermore, ensuring safety and security in workshop management can be enhanced through real-time monitoring and proactive warnings. The Smart Factory 4.0 operates on a closed-loop mechanism, which encompasses seven distinct phases. Initially, production element data is collected from physical entities within the workshop. Subsequently, a virtual workshop is constructed using a vast amount of data and virtual models to accurately represent the production status. The third phase involves the integration, analysis, and visualization of data from various sources. Data integration aims to uncover relationships among different data sources, while advanced data analysis and mining tools are employed to extract valuable information that aids in decision-making. Data visualization is utilized to present information in a clear and explicit manner. The fourth phase entails the execution of synchronous actions in the cyber space based on real-time data. In the following two phases, the status and behaviours of physical entities are simulated and optimized using virtual models to support decision-making. Operators have the ability to directly interact with the virtual model in a simulated environment through the use of HMI technologies, enabling sophisticated human-machine-environment interaction. In accordance with recommendations provided by the virtual model, appropriate decisions can be made for individual tasks within the real workshop. Finally, in the last phase, the physical entities are precisely controlled based on feedback received from the cyber space, ensuring the desired behaviours are executed.

RESULT AND DISCUSSION

In this segment, we present a practical example of an implementation of SF4.0 based on Cyber-Physical Systems (CPS) established in a Rolling stock manufacturing industry in Indonesia. The company, referred to as INKA, is the largest rolling stock industry in Indonesia. INKA offers a wide range of railway products and components to various international railway operators and has been recognized as the best supplier by Bangladesh Railway and Philippines National Railway. Its primary product line includes locomotives, passenger car, wagon and special purpose vehicle. As the demand for customized products continues to rise, INKA is confronted with increasing challenges. The production of small batches of customized products results in higher costs for quality management, increased machine downtime, and process intricacies, ultimately leading to a significant decline in productivity. Consequently, INKA has initiated a trial initiative to establish a Smart Factory 4.0 in their air conditioner and bogie manufacturing workshop.

The traditional workshop for air conditioner and bogie manufacturing comprises various computer numerical control (CNC) machines, manually operated tools, and workers. Over the past few years, INKA has implemented several information systems, including ERP SAP, Autodesk Vault PDMC, and Barcoding system (a system for managing internal production monitoring), to gather production data. Initially, data on machinery workpieces, environment, CNC machines, material, and operators is collected from information systems, sensors, controllers called Ekiosk SF4.0. Subsequently, this data is transmitted through the use of internet protocol to a big data platform for processing.

Fig. 4. Operator using Ekiosk SF4.0

In Fig. 4, an operator register himself to the Smart factory 4.0 system. A virtual model or the digital twin of the workshop is constructed, which consists of production element data, man, machine, material and method. This digital twin of the workshop operates in sync with real-time data obtained from the physical workshop, showcasing its internal workings such as when the production is started and when it will be finished. Furthermore, in Fig. 5, demonstrate the display of Ekiosk SF4.0 HMI to simulate the production workflow. These virtual models are further combined to create a virtual workshop, which can be utilized for production simulation, optimization, and decision-making in workshop management. Additionally, a monitoring platform, mobile app and web app have been developed to facilitate interaction with the Production and Planning Control area. Finally, the workshop responsible for manufacturing air conditioner and bogie is effectively regulated by intelligent actuators that rely on feedback obtained from the virtual realm.

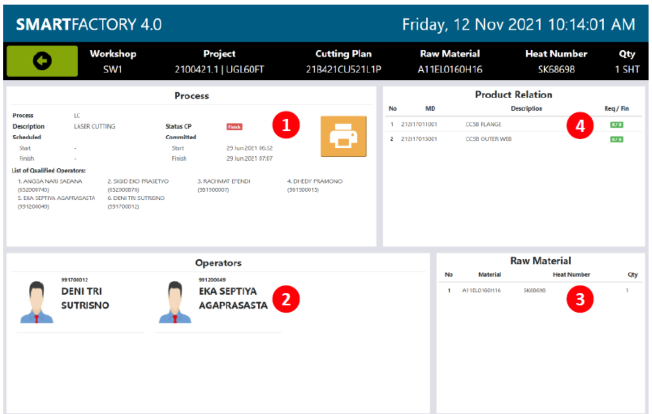

Fig. 5. SF4.0 display HMI

CONCLUSION

The rise in demand for mass customization poses numerous challenges for manufacturing enterprises, including increased costs, reduced efficiency, and compromised quality. To address these challenges, the transformation of traditional and labour-intensive workshops into smart workshops is necessary. Cyber-physical systems (CPS), which encompass a range of advanced capabilities and technologies, offer a viable solution for achieving smart workshops. Consequently, the implementation of CPS in traditional workshops has garnered significant attention in recent years. This paper aims to provide a comprehensive perspective on the technical architecture, fundamental elements, operation mechanism, and features of cyber-physical system-based workshops, with the goal of assisting manufacturing enterprises in adopting CPS-based workshops without the elimination of man-element in their production process. Furthermore, future research should focus on exploring the development of a factory-wide CPS-based system at the configuration level. This can be accomplished by employing pattern recognition techniques and conducting extensive of big data analysis resulting from the integration of multiple CPS-based workshops.

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