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A Digital Twin Reference for Mass Personalization in Industry 4.0

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Abstract

The Fourth Industrial Revolution (Industry 4.0) leads to an age of extraordinary changes through digital transformation. High customer demands and market competitions drive almost all business sectors to meet individuals' requirements with a cost close to mass production. This paper aims to get the best out of Digital Twin capabilities for meeting mass personalization. A cross-sectional study was undertaken to explore the potential relationship between Industry 4.0, Information and communication technologies (ICT), and Digital Twin towards mass personalization. This study identifies cutting-edge technologies for building a Digital Twin reference model. The results reveal that Digital Twin fulfils mass personalization under Industry 4.0. The findings can contribute to a better understanding of new industrial applications for a wide range of Digital Twin integration levels.

Keywords: Industry 4.0; Digital Twin; Mass Personalization; Internet of Things; Augmented Reality; Reference Model;

1. Introduction

Industry 4.0 holds the promise of increased flexibility in manufacturing with improved quality and productivity [1]. The Fourth Industrial Revolution is a vision of smart factories built with intelligent objects to sense, act, and behave within intelligent cyber-physical systems (CPS). It enables the manufacturing ecosystem driven by smart systems together with self-configuration, self-monitoring, self-healing, and autonomy for achieving exceptional levels of efficiencies and growth in productivity [2]. In an increasingly global competitive market, businesses must rapidly build interactions with customers to meet an individual's expectations. Offering affordable personalization is one of the most wanted in the era of Industry 4.0 [3,4]. Affordability of personalization is a severe challenge due to being dependent on several factors and continuous changes [5,6]. Therefore, Mass Personalization Manufacturing (MPM) is recognized as the most exclusive manufacturing paradigm due to the highest Degree of Mass Personalization (DoMP). While industries are heavily investing in additive manufacturing for personalization, customers do not have instant interaction during the design process and transparency in MPM. Many disruptive technologies, such as Internet of Things (IoT), big data, Artificial Intelligence (AI), Augmented Reality (AR), Additive Manufacturing (AM), and Digital Twin have emerged. These technologies enable the

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manufacturing industry to satisfy dynamic changes worldwide and reduce time to market [7].

Implementation of Mass Customization Manufacturing (MCM) benefits pre-defined and limited needs [2]. Nevertheless, the ultimate goal is to meet the highest level of customer satisfaction, which gradually shifts MCM to MPM for recognizing requirements individually and attempt to satisfy their needs with 'tailor-made' features. Mass personalization in ICT has achieved far beyond manufacturing due to the flexibility and accessibility of cyberspace. Digital Twin is a suitable technology to fill the gap between the digital and physical world.

This paper describes how Digital Twin enables MPM via a proposed reference model. Section 2 presents an overview of Digital Twin followed by mass personalization and Industry 4.0 technology. Section 3 discusses manufacturing paradigms, including craft, mass production, mass customization, and mass personalization. Moreover, this section suggests critical technologies to build Digital Twin. Section 4 proposes a Digital Twin reference model. Section 5 discusses some Digital Twin solution providers. Section 6 highlights some research and development challenges. Section 7 concludes and point outs the future works.

2. Overview

Technology has evolved to the point where advancements in the Industry 4.0 era do not depend on any one-size-fits. Therefore, manufacturers are expected to offer the most suitable products and services based on individuals' requirements. This section gives an overview of Digital Twin, mass personalization, and Industry 4.0, which creates a high-value proposition for both customers and providers.

2.1. Digital Twin overview

Digital Twin is a significant area of interest, from manufacturing, product design, to service and operations. Digital Twin is disrupting the entire product lifecycle management, including mass personalization product development. This section gives an overview of some Digital Twin definitions, including the International Organization for Standardization (ISO) and researchers at the National Institute of Standards and Technology (NIST).

Digital Twin concept introduced by David Gelernter in his widely acknowledged 1991 book "Mirror Worlds". However, Digital Twin firstly applied in manufacturing by Michael Grieves in the Florida Institute of Technology. Consequently, he proposed the Digital Twin as the theoretical model underlying product lifecycle management (PLM) at the Society of Manufacturing conference in 2002. Up to now, as everything is changing in time, more advanced Digital Twin definitions have been proposed by both academia and industry.

Digital Twin is leading the ways digital and physical interactions. A Digital Twin is a digital replica of a physical entity [8]. Digital Twin is a highly dynamic concept growing in complexity along the product life cycle, which is more than a pool of digital artifacts; Digital Twin has a structure consist of connected elements and meta-information as well as semantics [9]. ISO 23247 series defines a framework for Digital Twin manufacturing as "virtual representations of physical manufacturing elements such as personnel, products, assets, and process definitions. Digital Twin manufacturing is defined as the detailed modeling of physical configurations and the dynamic modeling of product, process, and resource changes during manufacturing". Also, NIST has introduced an IEEE 1451 smart sensor Digital Twin federation and defined "The digital twin is a digital simulator or digital replica of a real IEEE 1451 smart sensor" [10].

Digital Twin can play an essential role in addressing the issue of mass personalization. Recently, researchers have shown an increased interest in Digital Twin. In light of the new industrial applications of Digital Twin, it is becoming tough to ignore the value of Digital Twin. Like most technologies, Digital Twin will only have a prolonged life when practical implementations and value-added services are seen in the industry. Therefore, discussions of Digital Twin definitions perhaps may not have significant value while it helps to understand how Digital Twin advanced.

2.2. Mass Personalization overview

Offering affordable and personalized products has a crucial position in customer satisfaction. In the new global economy, mass personalization has become a concern for SMEs [4]. Recent developments in Industry 4.0 have heightened the need for mass personalization in a wide range of industries including healthcare, telecommunication, and consumer goods.

Fig. 1 displays the differences between mass production, mass customization, and mass personalization [11]. The latter demonstrates that mass personalization is provisioned by key technologies, including Cloud, IoT, AR, and AM, through an iterative, incremental process, while the first two are making pre-defined products available for customers to purchase. Mass customization and mass personalization are often thought to be synonymous.

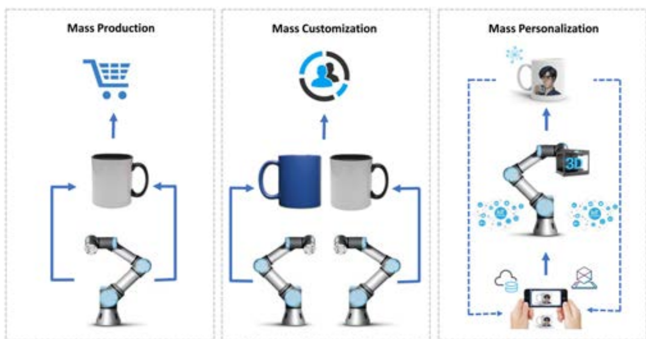

Fig. 1. Mass Production, Mass Customization, and Mass Personalization Manufacturing (MPM) Paradigms.

Utilizing the most suitable technologies for mass personalization has remained the main challenge. It is now well established from a variety of studies that Industry 4.0 has the potential for meeting personalization at scale [4]. However, affordable personalization has not developed adequately.

Unlike mass personalization, mass customization is limited to product segmentation, modular, and product family [12]. In mass customization, customers have the opportunity to choose from affordable but limited to a range of clustered products. Although mass customization has become a trend by maintaining mass production efficiency, there are some limitations due to product variety and lack of customer involvement to meet individuals' expectations. Fig. 2 Illustrates the position of different manufacturing paradigms.

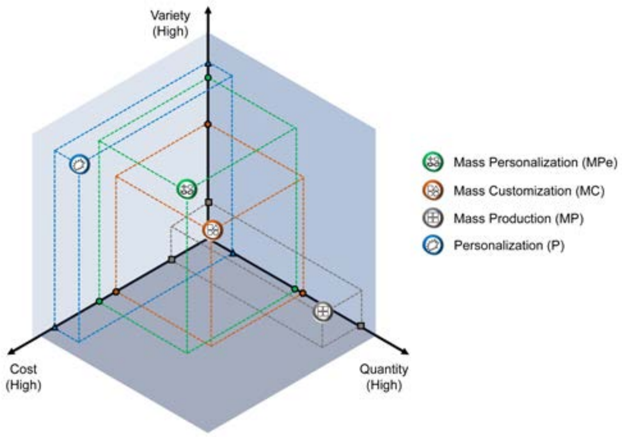

Fig. 2. The relationship between different manufacturing paradigms.

Equation (1) shows that Mass Personalization (MP_e) tend to meet a tradeoff among cost, variety, and quantity in comparison to mass production (MP), Mass Customization (MC), and Personalization (P).

$$\begin{aligned} &\textit{Cost:} && MP < MC \leq MP_e < P \\ &\textit{Variety (DoMP):} && MP < MC \leq MP_e \leq P \\ &\textit{Quantity (Mass):} && P < MC \leq MP_e \leq MP \end{aligned} \quad (1)$$

As a result, business sectors are keen to move beyond mass customization for meeting affordable personalization. Therefore, mass personalization will go beyond today's mass customization as personalized products can satisfy customers' needs and hold high sustainability [13,14]. MPM is a data-driven manufacturing paradigm with a combination of distinct features and the value proposition of mass production.

2.3. Industry 4.0 overview

The Fourth Industrial Revolution, a subset of cutting-edge technologies, has identified a transformation from mass production to mass personalization under the high flexibility and scalability, along with virtualized resources to perform autonomously [14]. The manufacturing industry is undergoing a significant digital transformation enabled by Industry 4.0 to provide on-demand services with high reliability, scalability, and availability in a distributed environment [15].

I4.0-components defined an industrial standardization to represent a physical or digital asset. The definition makes it possible to classify assets if a digital representation of an asset is accessible on a separate computer. Thereby production machines can be upgraded to I4.0-components with minimal expenses. The main feature of I4.0-components is an Asset Administration Shell (AAS), which manages between an asset and other systems. Therefore, the concept of AAS is highly suitable for standardization without interfering with the functionality of an asset [16,17].

Industry 4.0 is converging advanced hardware and software capabilities along with changes, and new features such as Digital Twin enabled individual vehicles' sensor data, which allows efficient resource allocation and personalized user experience. So, when a business experiences an ultimate variation, the related methodologies and processes must also adapt [18]. To this end, the conjunction between Industry 4.0, Lean 4.0, and Cloud Manufacturing (CMfg) paradigms are adding suitable capabilities to MPM [19]. Industry 4.0 puts forward a value proposition by mass personalization to meet longevity and higher customer satisfaction [20]. As Heiner and Hans-Georg [21] states, "The vision of future production contains modular and efficient manufacturing systems and characterizes scenarios in which products control their manufacturing process. This is supposed to realize the manufacturing of individual products in a batch size of one while maintaining the economic conditions of mass production".

3. Digital Twin enabled Mass Personalization

Digital Twin converges Industry 4.0 technologies to meet MP while trends may not be directly related to each other. Digital Twin has the potential to make a digital replica of wanted characteristics, appearances, and functionalities, along with processes and systems. Firstly, Digital Twin can represent a large number of things by utilizing Industry 4.0. Therefore, Digital Twin is suitable for a mass number of twins. This characteristic needs IoT, Cloud, and big data as the three vital Industry 4.0 technologies. Secondly, a digital version of a physical thing has enough precision to distinguish a tangible difference in regards to observable characteristics of a product that are relevant to customers' preferences and features. As a result, the Digital Twin is suitable for a high degree of personalization, which needs IoT, AI, AR, and AM technologies. Fig. 3 illustrates the required technologies for efficient MPM.

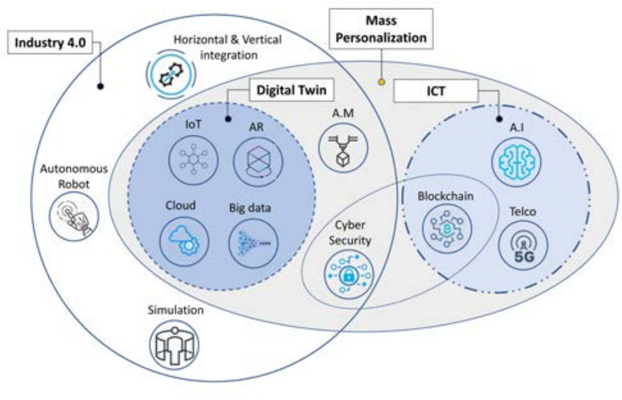

Fig. 3. Key technologies enabled Mass Personalization.

The fifth-generation for digital cellular networks (5G) and AI, along with crucial Industry 4.0 technologies, can offer feature extraction and prediction based on customers' historical data. Unlike conventional machining, casting and forging processes, AM (3D printing farms) is leading to strictly personalized product from a digital file. While mentioned technologies have a unique value proposition in MPM, Digital Twin makes the best use of integration toward ICT and Industry 4.0. Finally, yet importantly, Digital Twin builds a bridge between personalized design and manufacturing.

3.1 Industry 4.0: The Backbone for Digital Twin

Industry 4.0 and Digital Twin are closing the gap between digital and physical by providing instant access to digital models that virtually represent their physical complements. Industry 4.0 empowers the key features of a Digital Twin. First, integrate a tailored digital model with an expected physical product. Secondly, instant communication between digital and physical counterparts. Thirdly, Industry 4.0 supports Digital Twin to expand the volume and level of variations for mass personalization. Fourthly offers visibility into the entire personalized product life cycle. Finally, yet importantly, the full fidelity of a Digital Twin comes to be feasible as Industry 4.0 used by three 'P's' – Products, Processes, and People in MPM. The 'historical and live' data will serve the next Digital Twin generation industrial applications as Digital Twin provides essential information to make real-time decisions.

3.2 ICT: Shaping the future of Digital Twin

Digital Twin is one of the most superior technologies that allows customers not only to see virtual objects overlaid in the real world but also to experience real-time tailored features and appearances. Fig. 4 shows the current and future of the product personalization models. While AM is suitable for prototyping, advanced 3D printing farms and CMfg have made significant resource utilization that can be used in MPM. Digital Twin and AI can take customers to a new journey that is personalized in nature. Besides, predictive personalization would be more feasible than ever by using Digital Twin enabled AI.

Digital Twin is bridging the gap between design and manufacturing due to the mirroring capability of the real and virtual worlds. Gartner survey in February 2019 reveals that 75 presents of the organization implementing IoT already uses Digital Twin or plan within a year. However, adopting big data and AI technologies comprising Machine Learning (ML) and Deep Learning (DL) will move Digital Twin beyond monitoring and controlling toward predictive as a service, which is suitable for mass personalization. Also, Digital Twin and CMfg are converged in the form of services [22]. Digital Twin enabled equipment can self-heal by adding new features via software updates, which represents Digital Twin as a Service (DTaaS).

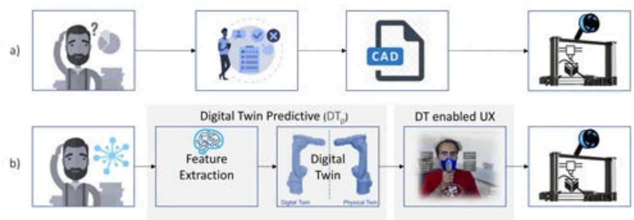

Fig. 4. (a) Personalization using conventional personalization; (b) Predictive personalization using Digital Twin Predictive (DT_p).

4. Digital Twin Reference Model

A reference model is a framework to represent comprehensive system components to meet business functions. Xun et al. have introduced a Digital Twin reference model consist of three crucial components that must work together for constructing a Digital Twin [23]. Guinard et al. [24] proposed a Digital Twin architecture reference model and discussed how an active twin feedback loop could improve the quality of physical systems and becomes more scalable. However, there is a need to make sure a Digital Twin reference model can fulfill the ultimate manufacturing paradigm. Industry 4.0, as an interdisciplinary revolution, integrate cutting edge technologies for the highest value based on the reference architecture model Industry 4.0 (RAMI) [25]. Fig. 5 suggests an adapted version of this 3D layered architecture as a Digital Twin reference model for mass personalization.

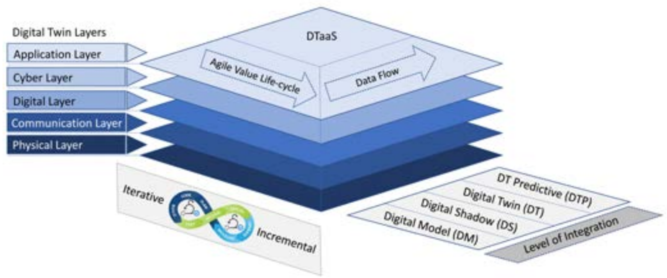

Fig. 5. A Digital Twin reference model.

This concept has comprised of three dimensions, including five-layered architecture, agile value life cycle [11], and a Digital Twin integration hierarchy. The left horizontal axis represents an iterative, incremental product development. The right horizontal axis characterizes the different Digital Twin integration level [26]. The vertical axis serves to describe the five Digital Twin layers from Physical to Application. Although the Digital and Cyber are synonymous terms, the difference comes in how we perceive each; The Digital layer can exist in digital form on various electronic, magnetic, or optical disks while the Cyber layer is using scalable and distributed computing technologies such as Cloud technology. The digital layer has to do with an imitated digital copy of physical things, including geometric data, while the Cyber layer is in the effect of big data analytics [26], algorithms, AI, ML, and DL technologies for advanced applications including Digital Twin predictive (DT_p).

Meeting a high number of diverse and affordable personalization needs interactive, incremental product development with a range of integration. The proposed Digital Twin reference model is an abstract framework consisting of an interlinked set of defined concepts including physical, communication, digital, cyber, and application. 1) This reference model can help those who need to develop from simple to the most complex Digital Twin applications. 2) It can help break down a substantial challenge into smaller that can be understood, tackled, and refined. 3) Also shows roles, responsibilities, and relationships for functionality and performance measurement through agile product development [27]. 4) Last but not least, this reference model allows the comparison of different Digital Twin integration levels. This reference model is validated through a DT-enabled solution for managing over five hundred unique wetlands in a large area in Auckland, New Zealand, which represents an industry-led mass personalization. Fig. 6. Displays a Digital Twin solution that uses Industry 4.0 technologies including IoT, AR, Cloud, and big data analytics to address prioritization, schedule maintenance, prediction, and real-time monitoring and controlling along with an augmented user interface for a high number of distinct infrastructure [28].

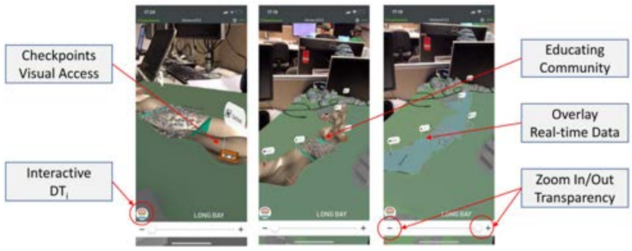

Fig. 6. A Digital Twin enabled Mass Personalization – A case study of a smart wetland maintenance system.

This project is based on the proposed reference model. It provisioned up to Digital Twin integration level through an iterative, incremental process. The Digital Twin prediction has been identified as future work.

5. Providers of Digital Twin Solutions

Digital Twin solutions can add significant value as manufacturing processes become increasingly digital. Companies can provide digital footprint through both product development and product life cycle to detect physical issues sooner, predict outcomes more accurately, and build better products. A Digital Twin is often at the very heart of the business transformation, which can influence the industrial organization and product's performance. Different understandings of Digital Twin can be observed in industrial practices. In this regard, Table 1. points to the leading companies that are using Digital Twin to solve different industrial challenges. Surprisingly, the effects of Digital Twin for MPM have not been closely examined.

Table 1. Digital Twin observations by different companies and industries.

Company	Main Digital Twin Solution
Ansys	Simulation combined with analytics to make predictions.
Dassault Systemes	Virtual factory replication, twins for design and simulation.
Bosch	Analyze production processes in the virtual world.
GE	Digitize assets and processes for forecasting performance.
IBM	Modeling to predict equipment failure, optimize maintenance schedules, and make better decisions.
Microsoft	Model the interactions between people, places, and devices.
PTC	Increasing the manufacturing flexibility & competitiveness.
SIEMENS	Planning & designing products, machines, plants, and production systems.
TESLA	Synchronous data between every Vehicle Identification Number (VIN) and the factory.

Digital Twin is often used to monitor and evaluate wear and tear for a stress test, which could affect design and process. Industries implement Digital Twin for aggregating real-time data from physical sensors and use analytics in cyberspace to manage actuators in an interactive incremental process through the physical-digital-physical loop. Digital Twin is made possible by utilizing Industry 4.0 and enabled by IoT for collecting real-time data from the physical world. Digital Twin can visualize the data for integration between the physical and virtual parts as a success factor for smart manufacturing [29]. Gartner expects half of all major industrial companies to be using digital Twin by 2021 and increasing their effectiveness by ten percent.

6. Research and Development Demand and Challenges

Based on a search among academic journals, articles, and books, the frequency of results from a search with the keyword "personalization" in the abstract, title, and keywords obtained from the Scopus database is depicted in Fig. 7. This figure visualizes the increase of interest on this topic by the scientific community.

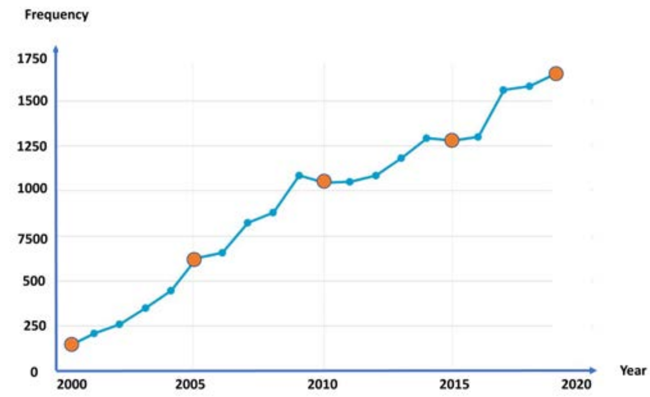

Fig. 7. Frequency of appearance of "personalization" keyword.

While Industry 4.0 has the potential to address MPM challenges, business sectors are looking for Digital Twin to realize the full potential of these three 'P's' – Products, Processes, and Personalization at scale. Michael and John [26] recognized three main obstacles that need to be addressed. "These obstacles are organizational siloing, knowledge of the physical world, and the number of possible states that systems can take." However, there is a trade-off between the business value and impact of creating Digital Twin. The three 'I's' – Intricacy, Integration, and Interval should be considered before undertaking a Digital Twin.

- **I**ntricacy: How much effort (time and cost) required for creating a Digital Twin?
- **I**ntegration level: How specific will the Digital Twin integration (DM, DS, DT, and DT_P) be?
- **I**nterval: What is the essential communication rate, and how detail and accurate the Digital Twin should be?

It is likely to use Digital Twin to unleash the full potential due to the trade-offs and value of Digital Twin for addressing different needs, as implemented by companies in Table 1.

7. Conclusion

The main goal of this study was to determine vital Industry 4.0 technologies for building Digital Twin. The second aim was to investigate a Digital Twin reference model to provision mass personalization, as the most complicated manufacturing paradigm. This research set out to gain a better understanding of mass personalization in comparison with mass customization. The findings of this investigation complement those of earlier studies that Digital Twin is the most suitable technology to close the gap between the physical and digital world and provide insights for meeting mass personalization. This study contributes to existing knowledge of Digital Twin and has been one of the first attempts to investigate the utilization of Digital Twin for mass personalization. Moreover, it provides an empirical confirmation by an industry-led mass personalization with significant value, including real-time monitoring, remote controlling, predicting, scheduling and maintenance functionalities. AI and Blockchain technologies could be further investigated in the near future.

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