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Proliferation of Digital Twins: Towards new horizons of Digital Twin-technology

Jari Kaivo-oja[1,2], Mikkel Stein Knudsen[1] and Theresa Lauraeus[1]

[1] Finland Futures Research Centre, Turku School of Economics, University of Turku, Turku, Finland
jari.kaivo-oja@utu.fi, mikkel.knudsen@utu.fi, Theresa.lauraeus@utu.fi

[2] Kazimieras Simonavicius University, Vilnius, Lithuania

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ABSTRACT

Digital Twin (DT) technology is at the forefront of the manufacturing integration of informatization and industrialization, pairing the datafied virtual world with the physical world of advanced manufacturing. It is a digital representation mirroring real-life objects, processes or systems, and as such DT is the spearhead of rapidly developing virtual simulation technology. While the concept of Digital Twins is relatively new, attention to the technology has exploded in recent years both in academia and among businesses. This is e.g. reflected by the placement of Digital Twin at the very peak of the Gartner Hype Cycle for 2019. Grasping the opportunities provided by Digital Twin-technology is therefore paramount in order to assess the current state-of-the-art of intelligent manufacturing, but also in order to fully exploit the potential benefits of intelligent manufacturing in an Industry 4.0-society.

This paper first assesses the historical development of the Digital Twin-concept from the first proposition of the concept around 2002, through the incubation stage to the current growth stage. The paper then briefly examines the current state-of-the-art of Digital Twin in manufacturing through design, manufacturing, the use phase, and on to maintenance, repair and operation (MRO). After this, the remarkable current proliferation of the Digital Twin-concept is discussed. Now the concept is not only gradually expanding into more and more areas of the operating environment of the manufacturing industry, Digital Twin is also put to use in radically different contexts. There are increasingly Digital Twins of physical places, and DT is becoming an important tool for town planning and urban development. Smart City Digital Twins (SCDT) illuminates cities' human-infrastructure-technology interactions, enables informed urban development choices and rapid responses to emergency situations. In 2019, the new Indian state capital Amaravanti, is thought to be the first ever city born with a Digital Twin approach. DTs are also used to simulate processes, and the idea of modelling complete operational environments for Digital Twin of an Organisation (DTO) is emerging. Also Personal Digital Twins (PDT) are appearing on the horizon as intelligent decision-assistance systems based on data algorithms and machine learning, aiding individuals in navigating through data-rich communication with machines, systems and other PDTs. Integrating digital, physical and social realms through PDTs can create superior customer experiences in both business-to-business and business-to-consumer markets and indeed fundamentally alter these markets. We can

also expect that in the future novel products and services are innovated to Digital Twins, which is a novel challenge for companies and corporations.

While digital twin in manufacturing and digital twins of smart cities has received significant academic attention in recent years, literature on DTOs and PDTs are hitherto very sparse. With the introduction and discussion of these concepts, the article therefore provides a significant contribution to the academic literature on digital twins.

1 INTRODUCTION

Digital Twin (DT) technology is at the forefront of the manufacturing integration of informatization and industrialization, pairing the datafied virtual world with the physical world of advanced manufacturing [1]. It is a digital representation mirroring real-life objects, processes or systems [2], and as such DT is the spearhead of rapidly developing virtual simulation technology [3]. The digital twin is composed of three basic components, which is i. physical entities in the physical world, ii. virtual models in the virtual world, and iii. the connected data between these two worlds [4].

While the concept of Digital Twins is relatively new, attention to the technology has exploded in recent years both in academia and among businesses. As a good illustration of this, the Gartner Hype Cycle for 2019 places Digital Twin at the very peak [5]. We can note that there is much hype in this technological R&D field, but applications in real-life are also increasingly appearing. A 2018 Gartner study claimed that 48 percent of organizations implementing IoT were already using Digital Twin or planning to use it that same year [6].

Most considerations of Digital Twin-technology have been related to ‘shopfloor digital twins’, ie. applications in manufacturing [3, 7, 8]. Now, however, the concept of Digital Twin is witnessing a proliferation. DTs are apperaring in a wide range of different contexts. This paper examines trends within this proliferation from Shopfloor Digital Twins (SDT) to Smart City Digital Twin (SCDT), Digital Twin of an Organisation (DTO), and Personal Digital Twin (PDT).

2 ORIGIN OF DIGITAL TWIN

The origin of the concept of Digital Twins comes from the world of simulation, and it builds on the ideas of the NASA Apollo program, in which twin copies were constructed in order to use it for reasoning about other instances of the same parts or products [9, 10]. Instead of creating two physical copies of the same space shuttles, a physical system could be twinned with a virtual copy – ie. its digital twin. Beyond the space industry, many manufacturing industries have needs to provide “safe environment” for piloting and testing new ways of production proving a fertile ground for the development of DT.

Grieves and Vickers (2017) provide fruitful input on the development of a vision for Digital Twin: “*The idea of the Digital Twin is to be able to design, test, manufacture, and use the virtual version of the systems. We need to understand whether our designs are actually manufacturable. We need to determine the modes of failure when the system is in use. We need all this information before the physical system is actually produced. This will reduce failures of the physical system when it is deployed and in use, reducing expenses, time, and most importantly harm to its users.*” [11].

They also provide a useful attempt of a definition : (…) ”*We would propose the following: Digital Twin (DT) – the Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin.*” [11].

We can note that all key definitions of the Digital Twin are linking the Digital Twin to Industry 4.0 developments. An obvious benefit of the Digital Twin approach is that it can reduce risks of innovation activities of organizations. In a way the Digital Twin approach can lead us to the development of a Supermind. Current discussion about the Supermind evolution underlines that distribution of benefits of depends on types of Supermind. Thomas W. Malone (2018) has reported the following table of relevant comparisons [12].

Table 1. Costs of group decision making, benefits of group decision making and distribution of costs ([12]).

Type of Supermind	**Costs of Group Decision Making**	**Benefits of Group Decision Making**	**Distribution of Costs**
Hierarchy	Medium	High	Low
Democracy	High	High	Medium
Market	Medium +/-	Medium	High
Community	Medium	Medium	Medium
Ecosystem	Low	Low	Low

All these comparisons depend on utilitarian philosophy. It is relevant to note that democracy provides highest costs and benefits of group decision making and distribution of costs provides medium level of distribution of costs. In the market case costs of group decision making can be both positive or negative and benefits of group decision making are medium. Distribution of costs is high in the market case. In the ecosystem case costs of group decision making, benefits of group decision making and distribution of costs are low in all cases, but in the community case they are medium. In the hierarchy case costs of group decision making are medium, benefits of group decision making are high and distribution of costs are low.

If we want to have low costs of group decision making, we should prefer ecosystems. If we like to want to have high benefits of group decision making, we should prefer hierarchy or democracy. Market provides high distribution of costs. We can conclude that we should pay attention to the type of the Supermind. Very uniform supermind strategy probably leads to problems in balancing costs and benefits of Supermind solution. This critical observation is relevant also in the Digital Twin strategy of companies.

We can expect that traditional business models (B-C and B-to-B) must somehow re-organized creating B-DT models and DT-DT models. Innovative orchestration of ecosystems, hierarchies and markets will be needed.

2.1 PLM

In its origin, Digital Twin was very closely linked with developments of Product Lifecycle Management (PLM) [11]. The 2002 conceptual PLM-model of Michael Grieves built on all the elements of Digital Twin: A physical space, a virtual space, and a flow of dynamic information linking the spaces. Links between DT and PLM can also be found in [13] which stresses how the Digital Twin is a vision referring to a comprehensive physical and functional description of a component, product or system, which includes more or less all information which could be useful in all – the current and subsequent – lifecycle phases.

2.2 Virtual simulation

Simulation is a core functionality of systems by means of seamless assistance along the entire life cycle, e.g. supporting operation and service with direct linkage to operation data."

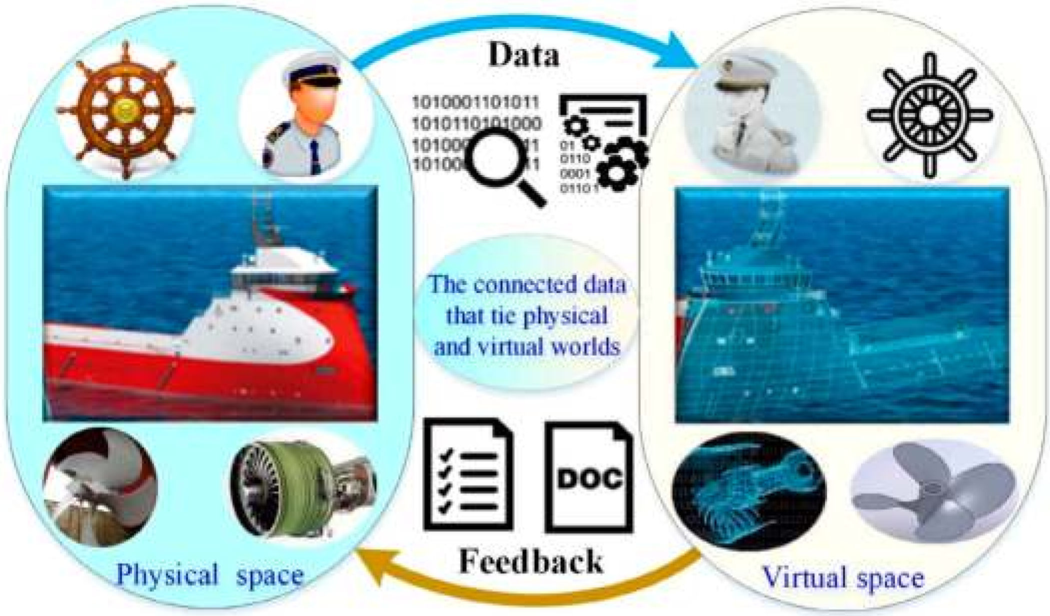

Figure 1. General digital twin mode for a product [8]

Simulations are often having similar advantages and disadvantages what scenarios have. Typically, simulations reveal risks and uncertainties of dynamic processes. The use of scenario and simulation techniques has several strengths (see e.g. [14]):

- The strength of scenarios and simulations is that they do not describe just one future, but that several realisable or desirable futures are placed side by side (multiple simulated futures).
- Scenarios and simulations open up the mind to hitherto unimaginable possibilities and challenge long-held internal beliefs of an organisation; moreover, the use of scenarios can change the corporate culture, compelling its managers to rethink radically the hypotheses on which they have grounded their strategy.
- Scenarios and simulations are an appropriate way to recognise 'weak signals', technological and economic discontinuities or disruptive events and include them into long-range planning. As a consequence, the organisation is better prepared to handle new situations as they arise and to promote proactive leadership initiatives.
- One beneficial function of scenarios and simulations beyond the planning aspect is improving communication and knowledge sharing. Scenarios can lead to the creation of a common language for dealing with strategic issues by opening a strategic conversation within an organisation. This communication aspect is emphasised especially by van der Heijden (1996) [15].
- Another function beyond the planning aspect is the coordinating function. During the scenario or simulation process the aims, opportunities, risks, and strategies are shared between the participants which supports the coordination and implementation of actions. In fact, the organisational learning and the decision-making process can be improved.
- The large number of different scenario/simulation techniques points out that the ways of building a scenario/a simulation are very flexible and can be adjusted to the specific task or situation.

In contrast to these mentioned strengths, scenario and simulation techniques have also some weaknesses ([14], p. 236):

• The practice of scenario or simulation modelling can be very time and financial resource consuming. Therefore, there could be a wish to condense scenario building and simulation runs to a half-day or one day activity. However, this may not give participants enough time to analyse cases.
• A more qualitative approaches have to put a strong emphasis on the selection of suitable participants/experts, and in practice this could not be an easy task to fulfil.
• It should not be overlooked that a deep understanding and knowledge of the field under investigation is absolutely necessary. Data and information from different sources have to be collected and interpreted which makes scenario building and simulation runs even more time-consuming.
• It could be difficult not to focus on black and white scenarios or the most likely scenario (too wishful thinking) during the scenario-building process. That is why many simulations are normally needed.

3 DIGITAL TWIN TODAY: NEW ARENAS AND OPPORTUNITIES

3.1 Digital Twin in manufacturing

3.1.1 Digital Twin in Product Design

Today, manufacturers' success in product design is closely linked to the capability of the manufacturer to handle data [8]. Modern product design also sets the customers at the centre and includes cocreation and participation of customers [8]. The product design is becoming more and more virtualization, networking, and visualizing. Against this backdrop, Digital Twin offers a multitude of new opportunities during the design phases. For the conceptual design, designers can integrate physical properties of the product as well as the historical data of users. When designing a new bike, knowledge of intended customer's bike habits and physical traits can be important qualifiers. In the detailed design phase dynamic feedback from the shopfloor or from customers can in incorporated. And in a virtual verification stage, tests can be made of the final product against key parameters, allowing for rapid design changes prior to mass manufacturing.

3.1.2 Digital Twin in other Product Manufacturing lifecycles

Tao et al. also shows how Digital Twins can be used in Product Manufacturing as well as for Maintenance, Repair and Operation (MRO). The vision of including all current and future lifecycle phases [13] is slowly being realised in the manufacturing industry. Lu et al. [16] differentiates between four distinct types of Smart Manufacturing Digital Twins: i. Digital Twin for Manufacturing Assets, ii. Digital Twin for people, iii. Digital Twin for Factories, and iv. Digital Twin for Production Networks. More than 85 % of currently identified Smart Manufacturing Digital Twin-applications relate to DT for Manufacturing Assets.

3.2 Smart City Digital Twins

Digital Twin is becoming an important tool for town planning and urban development. Digital Twins are tightly connected to Building Information Modeling (BIM), which is becoming standard in the construction industry [17]. For larger areas, Smart City Digital Twins (SCDT) illuminates cities' human-infrastructure-technology interactions [18], and enables informed urban development choices and rapid responses to emergency situations [19]. Large visual 3D models are being deployed in Smart Cities around the world [19], but the level of ambition and technical ability is constantly rising. In 2019, the new Indian state capital Amaravanti, is thought to be the first ever city born with a Digital Twin [19].

3.3 Digital Twin of an Organization

The concept of 'Digital Twin of an Organisation' has started to take hold in corporate and consulting contexts. By the end 2018, Gartner pronounced it as one of the top 10 Strategic Technology Trends for 2019 [21]. A DTO enables the dynamic virtual representation of an organization in its full operational context. Tools are now on the market to support this concept, noting that every asset that falls within the context of an organisation (processes, technology architecture, infrastructure, customer interactions, business capabilities, strategies, roles, responsibilities, products, services, distribution channels) can be connected, reported upon and visualized [22].

In order to make successful use of a DTO, even for simple organisations large amount of unstructured data related to complex operational and surrounding environments must be captured with sufficient quality, and the model must be dynamic and highly adaptive to the constant changes. Overall, it presents a major emerging application area for DT requiring quite different elements than the classical Shopfloor Digital Twin, but also an area in rapid development.

3.4 Personal Digital Twins

As the world moves towards data-rich markets, intelligent decision-assistance systems based on data and machine learning are needed to help humans navigate [23]. The intelligent decision-assistance systems help identify optimal matches in these big data markets, but humans will retain the ultimate decision-making power and decide how little or how much to delegate as they transact. These future intelligent decision-assistance systems, which allows individualisation of markets not only based on algorithms of the sellers and marketing departments, but also on behalf of the customer, expressing and acting on behalf of the genuine interest of the user, will be much more intelligent than current companion devices. We can think of these new systems as Personal Digital Twins [24], and these new PDTs are likely to have a very sizable impact on future consumer markets.

4 SCENARIOS FOR THE FUTURE OF MANUFACTURING AND DIGITAL TWINS

In this section we discuss shortly about the future of manufacturing and digital twins.

To clarify product development decisions, we can describe the key attributes of a product from a manufacturability standpoint as volume, customization and complexity [25]. Our assumption here is that the future of manufacturing is organized on the basis of these three pillars: Production volume, customization and complexity. Production volume simply refers to the number of parts made in a given timeframe such as a lot size or quantity. Complexity refers to the number of features a product contains, the geometry and location of the parts. Naturally, the more complex a part of product is, the more difficult it is to manufacture. Customization is the rate of uniqueness. Customization ranges from the mere monogram to an implant that is tailored to a specific person. These three attributes represent three axis scenario model of manufacturing.

We can identify 8 relevant scenarios of manufacturing: (1) Mass Manufacturing, (2) Manufacturing of the Few, (3) Complexity Advantage Manufacturing, (4) Mass Complexity Manufacturing, (5) Customized for an Individual Manufacturing, (6) Mass Customization Manufacturing, (7) Artisan Product Manufacturing and (8) Complete Manufacturing Freedom Manufacturing.

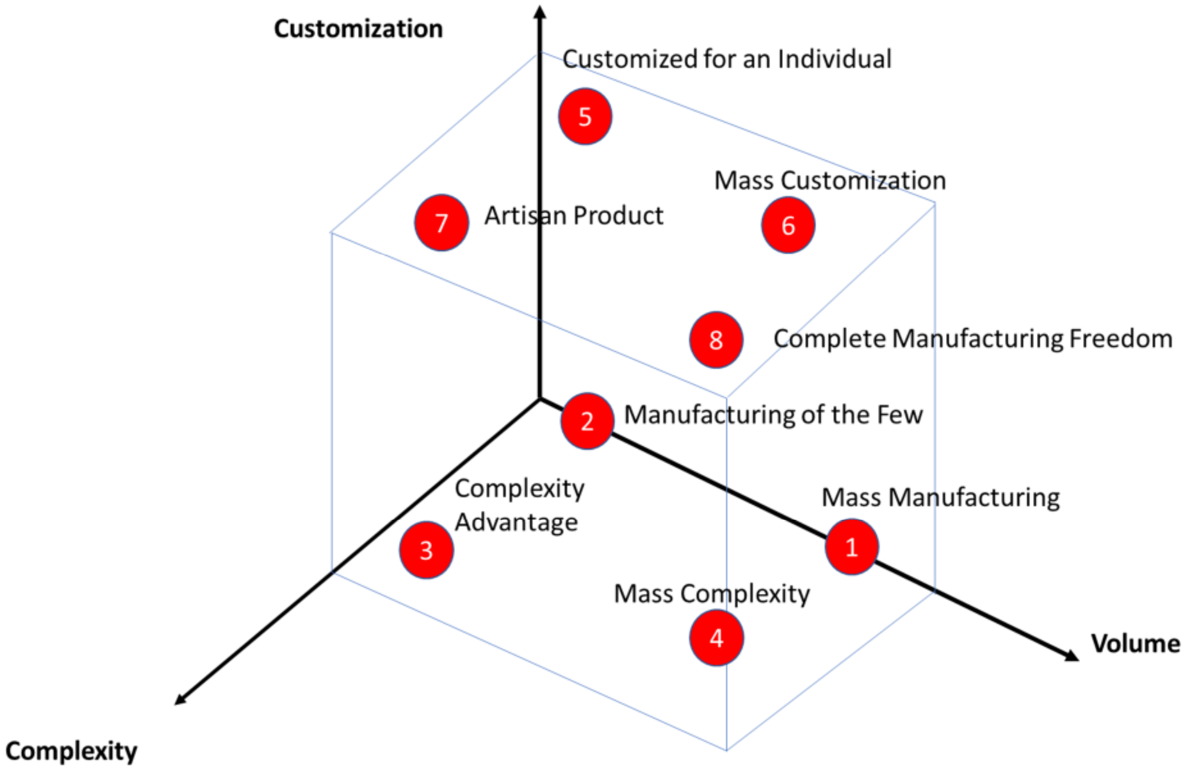

Figure 2. Three Axis Scenario Model of Manufacturing [23].

(1) *Mass Manufacturing.* Conventional manufacturing is primarily focused on mass manufacturing. Normally, the mass manufactured products have a single or several simple parts. There is no customization to be able to produce large amount of parts with low costs and high productivity. The business model for mass manufacturing is not value driven and primarily cost driven to lower the unit cost of each part [24]. We suppose that digital twin approach can create less comparative advantages in mass manufacturing than the other manufacturing scenarios..

(2) *Manufacturing of the Few.* This scenario of manufacturing includes products or parts with limited complexity and customization but also in low production volumes. Good examples of "manufacturing in few" is high value parts for low volume such as parts of ships or satellites (Conner et al. 2014).. We suggest that probably digital twin approach has high relevance in the manufacturing of the few.

(3) *Complexity Advantage Manufacturing.* This scenario of manufacturing includes products or parts with increased complexity which leads to increased multiple operations, longer production times and therefore lower production rates [25]. We believe that digital twin approach has a very special role complexity advantage manufacturing

(4) *Mass Complexity Manufacturing.* In this manufacturing scenario products are not customized, but they are complex, and the volumes are greater than in the "complexity advance manufacturing". We suppose that digital twin approach can create less comparative advantages in mass complexity manufacturing than the other manufacturing scenarios.

(5) *Customized for an Individual Manufacturing.* In this scenario of manufacturing includes low volume products with low complexity but high customization. There are no two exact repairs and the products are essentially customized [25]. We believe that digital twin approach has a very special role in customized for an individual manufacturing.

(6) *Mass Customization Manufacturing.* In this scenario of manufacturing the concept of mass customization is a daunting task with conventional manufacturing processes [25]. We suppose that digital twin approach can create less comparative advantages in mass customization manufacturing than the other manufacturing scenarios.

(7) *Artisan Product Manufacturing.* In conventional artisan manufacturing, simplicity and symmetry in part design is important because of processing capabilities. This artisan scenario of manufacturing means to produce unique artwork with design attributes which is labour-intensive and costly and time consuming [25]. We suggest that probably digital twin approach has high relevance in artisan product manufacturing.

(8) *Complete Freedom Manufacturing.* In this scenario of complete freedom manufacturing the ultimate objective is to respect three attributes of ability to produce highly complex and highly customized products without limitations to product volume [25]. We propose that probably digital twin approach has high relevance in complete freedom manufacturing.

We can expect that Digital Twin Approach will be extremely beneficial when complexity and customization dimensions will be taken into consideration. This imply that Digital Twin Approach has a very special role in (3) Complexity Advantage Manufacturing and (5) Customized for an Individual Manufacturing. This does not mean that it does not have any relevance in other manufacturing scenarios. Probably it has high relevance in (7) Artisan Product Manufacturing, (2) Manufacturing of the Few and (8) Complete Freedom Manufacturing. Our scholarly guess is that Digital Twin Approach can create less comparative advantages in (1) Mass Manufacturing, (4) Mass Customization and (4) Mass Complexity. However Digital Twin Approach can be applied also in these manufacturing scenarios.

5 CONCLUSIONS

This paper first assessed the historical development of the Digital Twin-concept from the first proposition of the concept around 2002, through the incubation stage to the current rapid growth stage. We briefly examined the current state-of-the-art of Digital Twin in manufacturing through design, manufacturing, the use phase, and on to maintenance, repair and operation (MRO). After this, the remarkable current proliferation of the Digital Twin-concept was discussed. Now the concept is not only gradually expanding into more and more areas of the operating environment of the manufacturing industry, Digital Twin is also put to use in radically different manufacturing and production contexts. There are increasingly Digital Twins of physical places, and DT is becoming an important tool for town planning and urban development. Smart City Digital Twins (SCDT) illuminates cities' human-infrastructure-technology interactions, enables informed urban development choices and rapid responses to emergency situations. In 2019, the new Indian state capital Amaravanti, is thought to be the first ever city born with a Digital Twin approach. DTs are also used to simulate processes, and the idea of modelling complete operational environments for Digital Twin of an Organisation (DTO) is emerging.

Also Personal Digital Twins (PDT) are appearing on the horizon as intelligent decision-assistance systems based on data algorithms and machine learning, aiding individuals in navigating through data-rich communication with machines, systems and other PDTs. Integrating digital, physical and social realms through PDTs can create superior customer experiences in both business-to-business and business-to-consumer markets and indeed fundamentally alter these markets and business models. In our paper we emphasize alternative contexts of DT and Supermind applications. Optimal combination of benefit maximation and costs minimization can be a combination of ecosystems, markets and hierarchies.

We can also expect that in the future novel products and services are innovated to Digital Twins, which is a novel challenge for companies and corporations. This mean that traditional business models (B-C and B-to-B) must somehow re-organized creating B-DT models and DT-DT models. This reorganization process is linked to alternative manufacturing scenarios, which were elaborated in this paper. We identified eight alternative manufacturing scenarios: (1) Mass Manufacturing, (2) Manufacturing of the Few, (3) Complexity Advantage Manufacturing, (4) Mass Complexity Manufacturing, (5) Customized for an Individual Manufacturing, (6) Mass Customization

Manufacturing, (7) Artisan Product Manufacturing and (8) Complete Manufacturing Freedom Manufacturing. We discussed shortly about potential use of Digital Twin Approach concerning these alternatives emphasizing the challenges of complexity and customization.

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REFERENCES

[1] Y. Zheng, S. Yang, H. Cheng, An Application Framework of Digital Twn and Its Case Study, Journal of Ambient Intelligence and Humanized Computing. 10 (2019).

[2] R. N. Bolton, J. R. McColl-Kennedy, L. Cheung, A. Gallan, C. Orsingher, L. Witell, M. Zaki, Customer experience challenges: Bringing together digital, physical and social realms, Journal of Service Management. 29 (2018) 5.

[3] R. Rosen, G. von Wichert, G. Lo, K. Bettenhausen, About the Importance of Autonomy and Digital Twins for the Future of Manufacturing, IFAC-PapersOnLine. 48 (2015) 3.

[4] Q. Qi, F. Tao, Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison, IEEE Access. 6 (2018).

[5] K. Panetta, Gartner Top 10 Strategic Technology Trends for 2019, Smarter with Gartner, 2018.

[6] E. Quirk. Gartner Survey Reveals Increased IoT Implementations and Use of Digital Twins in 2018. Solutions Reviews, 2018.

[7] F. Tao, H. Zhang, A. Liu, A. Y. Nee, Digital Twin in Industry: State-of-the-Art. *IEEE Transactions on Industrial Informatics.* 15 (2019) 4.

[8] F. Tao, J. Cheng, Q. Qi, M. Zhang, H. Zhang, F. Sui, Digital twin-driven product design, manufacturing and service with big data, The International Journal of Advanced Manufacturing Technology. 94 (2018) 9-12.

[9] B. Schleich, N. Anwer, L. Mathieu, S. Wartzack, Shaping the digital twin for design and production engineering, CIRP Annals. 66 (2017) 1.

[10] E. H. Glaessgen, D. S. Stargel, The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles. 53rd Structures, Structural Dynamics, and Materials Conference (2012).

[11] M. Grieves, J. Vickers, in F-J Kahlen, S. Flumerfelt, A. Alves (eds), Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches. Springer International Publishing, 2017, Ch. 4.

[12] T. W. Malone, Superminds. The Surprising Power of People and Computers Thinking Together. Oneworld Publishers, London, 2018.

[13] S. Boschert, R. Rosen, in P. Hehenberger, D. Bradley (eds.), Megatronic Futures: Challenges and Solutions for Megatronic Systems and their Designers. Springer, Cham, 2016, Ch. 5.

[14] D. Mietzner,G. Reger, Advantages and disadvantages of scenario approaches for strategic foresight', International Journal of Technology Intelligence and Planning. 1 (2005) 2.

[15] K. van der Heijden, Scenarios: The Art of Strategic Conversation, Wiley, Chichester, 1996.

[16] Y. Lu, C. Liu, K. I-K. Wang, H. Huang, & X. Xu, Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues. Robotics and Computer Integrated Manufacturing, 2020.

[17] A. Borrman, M. König, C. Koch, & J. Beetz, in A. Borrman, M. König, C. Koch, & J. Beetz (Eds.), Building Information Modeling, Springer, Cham, 2018, Ch. 1.

[18] N. Mohammadi, J. E. Taylor, Smart City Digital Twins, 2017 IEEE Symposium Series on Computational Intelligence (SSCI), 2017.

[19] S. Weekes, The rise of digital twins in smart cities, Smart Cities World, 2019.

[20] T. Ruohomäki, E. Airaksinen, P. Huuska, O. Kesäniemi, M. Martikka, J. Suomisto, Smart City Platform Enabling Digital Twin, 2018 International Conference on Intelligent Systems (IS) (2018).

[21] D. Cearley, The Top 10 Strategic Technology Trends for 2019. Gartner (2018).

[22] Mavim, Digital Twin of an Organization, 2019.

[23] V. Mayer-Schönberger, T. Ramge, Reinventing Capitalism in the Age of Big Data. John Murray, London, 2018.

[24] J. Kaivo-oja, O. Kuusi, M. S. Knudsen, T. Lauraeus, in: L. Uden, I-H. Ting, J. M. Corchado (eds.), Knowledge Management in Organizations. Springer Nature Switzerland, Cham, 2019, Ch. 23.

[25] I. J. Petrick, T. W. Simpson, 3D Printing Disrupts Manufacturing. How Economies of One Create New Rules of Competition 3D printing may represent a disruption to the manufacturing industry as profound as the Industrial Revolution, Research-Technology Management (2013).