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A framework for enabling metaverse for sustainable manufacturing

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Abstract

Newly introduced technologies often require time for adoption and integration into manufacturing environments, for several reasons including technological maturity, adoption costs, and skills gaps. The inclusion of sustainability as a new requirement for both customers and producers adds further complexity to the equation. As metaverse technology became available, it became logical to establish a set of requirements to harness its new potential and create a sustainability-oriented framework for seamless integration into modern smart manufacturing environments. Against this background, the current work introduces a framework aimed at harnessing the potential of the metaverse to enhance manufacturing sustainability. As a case study, an industrial workshop was analysed and evaluated using the proposed framework. The findings help create a future plan for leveraging the use of the metaverse and prioritising its requirements.

Keywords: Metaverse; Sustainable Manufacturing; Sustainability; Technology Adoption;

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1. Introduction

Technology acceleration has been impressive over the last century. Introducing new technologies triggers the enhancement of already available products/services or the invention of new ones. According to the "Consumer Trends 2022: A Statista Trend Report on the Future of Consumption", six pillars that drive the emergence of new customer trends are Sustainability, Governance, Health, Gamification and Shoppertainment, Digitalisation and Personalisation [1]. The dramatic procedures to tackle the Covid-19 pandemic influenced users' experience and the fulfilment of their existential needs. Thus, companies' investment policies took a different direction as major market players such as Meta and Amazon are allocating more funds for the development of virtual and augmented reality (VR and AR respectively), artificial intelligence (AI), and digital assets metaverse [1].

On the manufacturing systems side, the most technologically advanced manufacturing paradigms as discussed in both the industry and academia are Industry 4.0 and Industry 5.0. The former focuses on the realisation of the cyber-physical system (CPS), whereas the latter further considers the social dimension, thus, it aims to create the socio-cyber-physical system (SCPS) [2]. The research community realises the metaverse as a technology that supports both of the paradigms. On the one hand, CPS are known for their 5C: connection, conversion, cyber, cognition and configuration, where the metaverse can improve their interaction and visualisation [3]. On the other hand, the metaverse is listed as an enabler of Industry 5.0 (in addition to big data and digital twin (DT)) and a prerequisite of Society 5.0 [4]. Following the rise of the Internet of Things (IoT) and its integration into manufacturing, the term "Industrial IoT" was coined as IIoT. Similarly, the metaverse is anticipated to evolve into "Industrial Metaverse", which acts as a platform that allows IoT, Internet of People (IoP), Internet of Services (IoS) and Internet of Contents and Knowledge (IoCK) to collaborate together in both the virtual and real worlds [2]. Looking at the industrial practice, a recent study conducted by Deloitte and the Manufacturing Leadership Council (MLC) in 2023 [5] attempted to shed light on the current uses of the industrial metaverse and the obstacles that hinder it. The respondents, who are mainly executives, believe that the potential benefits of the industrial metaverse can be:

- Production efficacy: in relation to new production introduction rate and speed to market.

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- Business outcomes: increased competitiveness and revenue and less cost.
- Supply chain: in terms of improved performance.
- Customer management: enhancing customer experience, demand and aftermarket services
- Employee engagement: training, engagement and upskilling.

As it can be noticed, with the industrial metaverse being in its infancy, its influence on sustainability and sustainable manufacturing is not yet realised by practitioners, whereas it is regarded as an integral element of advanced manufacturing paradigms. Therefore, as it has been regarded in the manufacturing paradigms, its potential for improving sustainability should be unlocked. Consequently, this work aims to logically analyse the mechanism by which the industrial metaverse's capability can be harnessed in a framework that helps manufacturers adopt it.

The remainder of this paper is structured as follows: Section 2 reviews the literature on industrial metaverse current uses and its influence on manufacturing sustainability. The methodology for creating a framework for sustainable manufacturing using the metaverse is introduced in 3. A case study is introduced in Section 4 and Section 5 concludes the paper.

2. Literature review

When studying the metaverse and its influence on sustainability, two types of metaverse exist: consumer metaverse and industrial metaverse. The former does not connect to the real (physical) world and focuses on entertainment and socialisation while providing some information. In contrast, the latter virtually mirrors the physical state of industrial assets (e.g., factories, machines and supply chains) and even may predict their behaviour [6]. To do so, a variety of digital technologies are connected/integrated with the metaverse such as cloud applications, AI, blockchain, etc.

Singh et al [7] refer to the smart system composed of the smart factory and smart energy system in which the metaverse can be an enabling technology that provides a virtual environment accessible by web technologies and extended reality. Also in the field of transport, Deveci et al [8] compared three freight fluidity measurement alternatives, of which one relied on integrating activities into metaverse to measure the fluidity. According to the criteria that involved sustainability, the option to use metaverse proved to be more advantageous. Pamucar et al [9] endeavoured to investigate how the metaverse affects sustainable transportation by constructing a multi-criteria decision-making problem taking into account the sustainability and efficiency criteria. Anshari et al [10] believe that the ethics of the business that invests in the metaverse affect on the business's sustainability, in addition to the way the business handles users' data. Park et al [11] state that the study of metaverse design for sustainable learning is crucial due to the need to include students experiences rather than relying on educators' experiences only. In the same vein, Lee and Hwang [12] addressed converting the education material made using virtual reality (VR) can be integrated to a metaverse platform for more sustainable education. Within smart cities, the metaverse is anticipated to reduce the emissions produced by the sectors of transportation, manufacturing and energy generation [13]. Furthermore, better resource management is envisioned due to the reduced need for travel, demand for infrastructure and waste. To control and manage energy systems in smart tech parks using metaverse, Pang et al [14] believe that the starting point is to collect real-time IoT data and transfer them into the digital twin. In their view of the industrial metaverse as an enabler of Industry 5.0, Yao et al [2] believe it contributes to synthesising sustainable human-centric solutions. Dolgui and Ivanov [15] constructed a framework for the metaverse of supply chain and operations management. Based on their research, enhancing sustainability can be achieved through increased transparency regarding carbon emissions and greater visibility into the complete product life cycle. Another research work on metaverse adoption in supply chains is presented by Chen et al [16] who analysed the adoption of metaverse taking into account the possibility of increasing efficiency and performance, especially when integrating metaverse with Artificial Intelligence (AI) and blockchain technology. Wang et al [17] suggested a metaverse-based parallel oil fields framework which is meant to achieve the 6s goal that includes sustainability. The digital layer of the framework has a variety of apps such as 'energy management' and 'production optimisation & prediction'. Also in the field of the process industry, Qian et al [18] share the same view of the industrial metaverse as an enabler of the cyber–physical–social systems (CPSS) and envision its potential contribution to oil refinement greenisation. From a product life cycle perspective, Brecher et al [19] believe that the industrial metaverse allows the generation of synthetic data so that production systems become error-free, thus, more sustainable from the moment they are started up. In terms of companies' adoption to the industrial metaverse technology, it is reported by Kshetri [6] that BMW Group in its iFactory initiative collaborated with Siemens and Nvidia where it is hoped that a variety of data-oriented applications will help reduce costs and machine downtime. Renault has started to invest in this technology with expectations of a substantial reduction of energy consumption [20]. Nvidia, which is a major provider of omniverse technology reported that PepsiCo looks to utilise this technology in its supply chain to increase its efficiency [21]. Nevertheless, no clear figures about the expected reduction of pollution across industries as products and production methods vary from one industry to another [20].

It can be observed by examining the aforementioned research works that the inclusion of metaverse for improving sustainability has been recently started. Apparently, a significant interest in the metaverse fields that the implementation has covered so far the areas of education and transport in addition to others. However, research into sustainable manufacturing by utilising the "industrial metaverse" has been limited despite the digitalisation wave that is changing the landscape of manufacturing systems. This is attributed to the fact that the roadmap of industrial metaverse to support sustainable manufacturing is vague in addition to the absence of technically-oriented implementation steps.

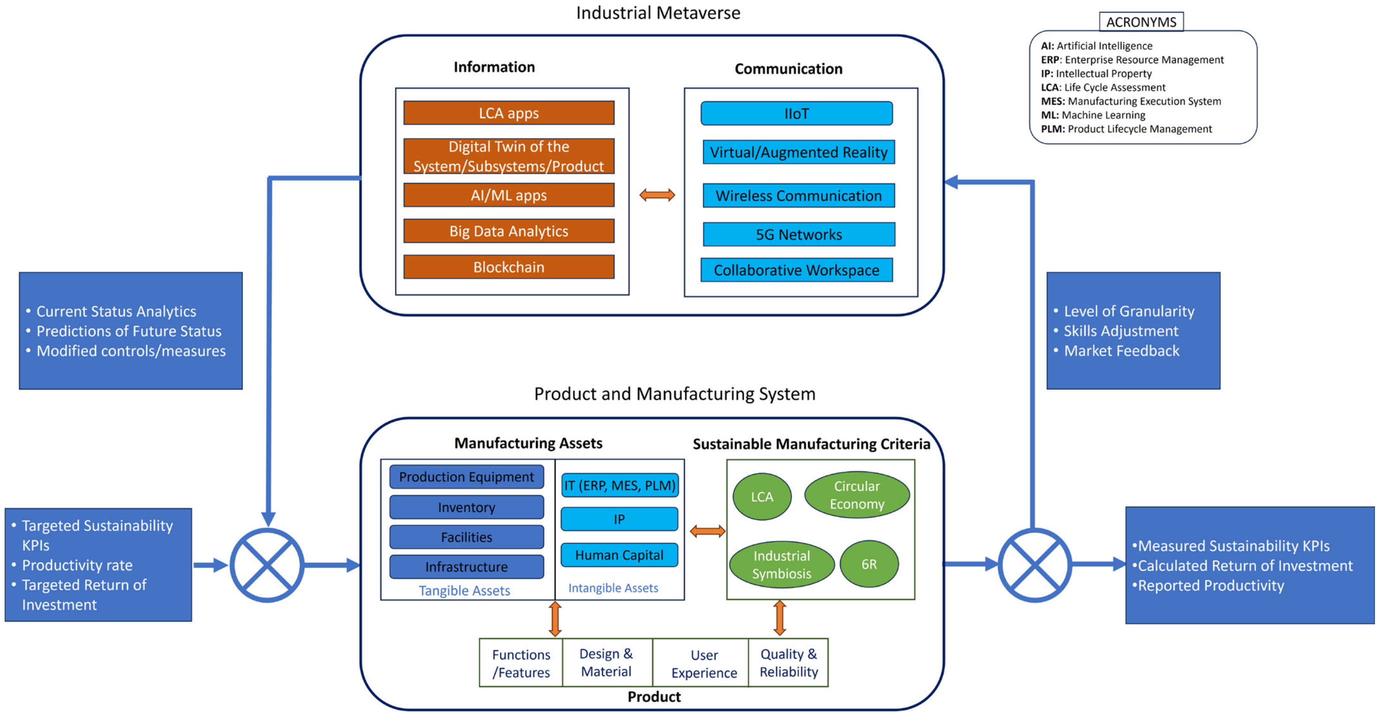

Fig. 1. Industrial Metaverse as part of the cyber-physical-social system

3. Methodology

3.1. Establishing the link of industrial metaverse with sustainable manufacturing

A typical challenge for sustainable manufacturing is balancing the profitability (out of a product or a service) with the environmental and social responsibilities. Profit is gained as a result of the sustainable use of resources and high productivity rates. Profit is also impacted by the innovation in processes or materials to introduce a desired product/service, along with the corresponding changes in production control and supply chain. An advantage gained by using the industrial metaverse is the possibility of industrial processes' configuration and control as well as visualising numerous real-time performance indicators. Thus once a change is decided in response to market needs or innovation requirements, the industrial metaverse which encompasses a variety of tools will assist in reflecting the change (and series of corresponding configurations) in the actual system, product and humans involved. This understanding is depicted in Figure 1 and be further explained with regard to the manufacturing system life cycle.

The current work proposes a framework based on the three pillars of sustainability to enable metaverse:

- Social: It has become widely acceptable that a skilled workforce can enable digital transformation. Through human interaction experience fed into industrial metaverse and processed/aggregated with previously stored data/information/knowledge, then using it to advance the sustainability of product/system, social sustainability in terms of labour's well-being and sufficient training can take its full advantage.
- Economic: A greater control over the manufacturing system's processes is enabled via the industrial metaverse. Consequently, processes' optimisation can take less time to be imposed, and meanwhile, the effect can be detected allowing better resource allocation and real-time decision-making.
- Environmental: DT technology has gained significant merit so far in preserving the environmental sustainability of the system. The industrial metaverse builds upon this merit and extends by including further resources, thus allowing for more environmental indicators to be captured and studied.

3.2. The integration of industrial metaverse with other technologies

By nature, the industrial metaverse refers to a digital, immersive, and interconnected environment that combines elements of the physical and virtual worlds. Among these are Industry 4.0 technologies such as IIoT, DT, Big Data, VR and AR among others. Therefore, in a consequential logic, building such an environment up to the level where the cyber-physical-socio system is created requires creating virtual models and developing them across the manufacturing system life cycle phases. A simplified view of these phases is depicted in Figure 2. Usually, the Planning Phase involves engineering requirements identification, where Computer-Aided Engineering (CAE) tools are used and VR models can be created [22]. These can be harnessed as building blocks for the industrial metaverse which

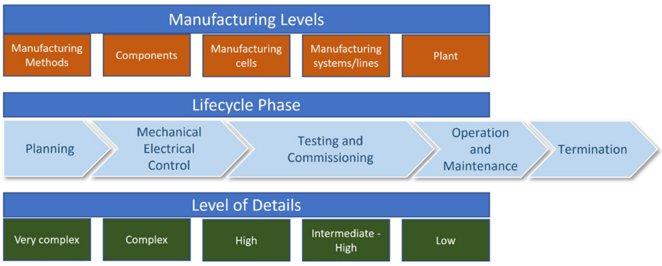

Fig. 2. A simplified view of manufacturing system life cycle [23]

continues to evolve over the following phases. In the vision illustrated in Figure 1, a sustainable manufacturing scheme or sustainability assessment tools can be used shoulder to shoulder with CAE and VR tools demonstrating a proactive approach to embedding sustainability in the life cycle. Noticeable contributions for the industrial metaverse here are the realisation of the layout, ergonomics design and human-machine user experience, which all support the "social" dimension of sustainable manufacturing.

Once more specifications are added and the physical build of the mechanical, electrical, control and IT systems is started new elements are added to the Industrial metaverse environment, especially with regard to information and communication aspects. Data transfer channels are established while moving to the "Testing and Commissioning" while updating the assets (virtual models) available in the industrial metaverse platform. Once virtual and physical commissioning takes place, the digital twin and digital shadow should have reached an acceptable level of maturity by which Sustainability Key Performance Indicators (KPIs) can be assessed such as machine idle/active time, energy consumption, material reuse and the percentage of waste. Besides, productivity rate adjustment can be implemented using predictions and recommendations coming from the industrial metaverse environment. Another advantage here is the possibility of planning sustainable supply chain practices using both sustainability and productivity indicators.

Over the "Operation and Maintenance" phase, the Return on Investment (ROI) should have reached its expectation and 'fine tuning' of manufacturing processes and product features is meant to take place unless a major change comes from the market (e.g, rapid changes in supply and demand, new sustainability regulation or inclusion of a new product feature). The industrial metaverse can remarkably support management by providing real-time analytics and predictions that allow them to leverage productivity and sustainability indicators. In the case of maintenance (whether periodic, preventive, etc.), the industrial metaverse should help reduce downtime and help establish a condition-based maintenance scheme where predictions of potential faults can be made.

3.3. Tailoring the level of detail

It can be noticed from both Figure 1 and 2 that the level of detail or the granularity changes depending on the changes in sustainability KPIs, ROI and productivity rate. The issue of granularity level affects the computational load as well as performance required by the industrial metaverse requirement when it comes to analytics/prediction provision and visualisation. Although the concern given to the granularity level has been prior to Industry 4.0, its importance has grown due to the increased connectivity and accessibility thanks to IIoT. With this in mind, reporting the system resource consumption status in terms of energy, water and heat might require rethinking the actual level of granularity so that the required accuracy and the timeliness of industrial metaverse's data remain achievable. Communication protocols also play an important role in deciding this as they are the medium used to transfer data and without them, the system's visualisation capability is eliminated.

4. Case study

4.1. Description

The case study introduced in this section and illustrated in Figure 3 is from a project work for an industrial collaborator. The product description and the assembly sequence in addition to other manufacturing details are anonymised due to confidentiality and non-disclosure reasons. The system is composed of the following areas:

- Area A: There are two variants of the product to be assembled in this area. This area comprises the following stations: 'body input', 'laser marking', 'assembly' and 'final product collection'.
- Area B: Products are transferred from Area A to Area B for testing via a secondary conveyor.
- Area C: Engineers and technicians attempt to repair the products that are rejected as a result of the testing in this area.

As explained earlier in 3.2, for the industrial metaverse to reach its full potential, digital twins that are detail-tailored to the current time purpose have to be created. The strategic vision is to satisfy both productivity and sustainability criteria starting with achieving

In the first stage of the development of the Industrial Metaverse for the aforementioned manufacturing system (Figure 3), an initial model is built. There are two representations of the system in the physical world and the virtual world (at the left and right-hand sides of the picture respectively). The virtual world represents a Discrete Event Simulation (DES) model built using Anylogic software tool[1]. This model allows the simulation of the production processes, analysis, optimisation and prediction of the key data needed to build a physical system. It can be connected to a physical machine using OPC-UA client-server communication using Prosys OPC UA (Open Platform Communications Unified Architecture) Java SDK[2] and to external applications for analytics and control.

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[1] `https://www.anylogic.com/`

[2] `https://forum.prosysopc.com/forum/opc-ua-client/communication-anylogic-opc-ua-server/`

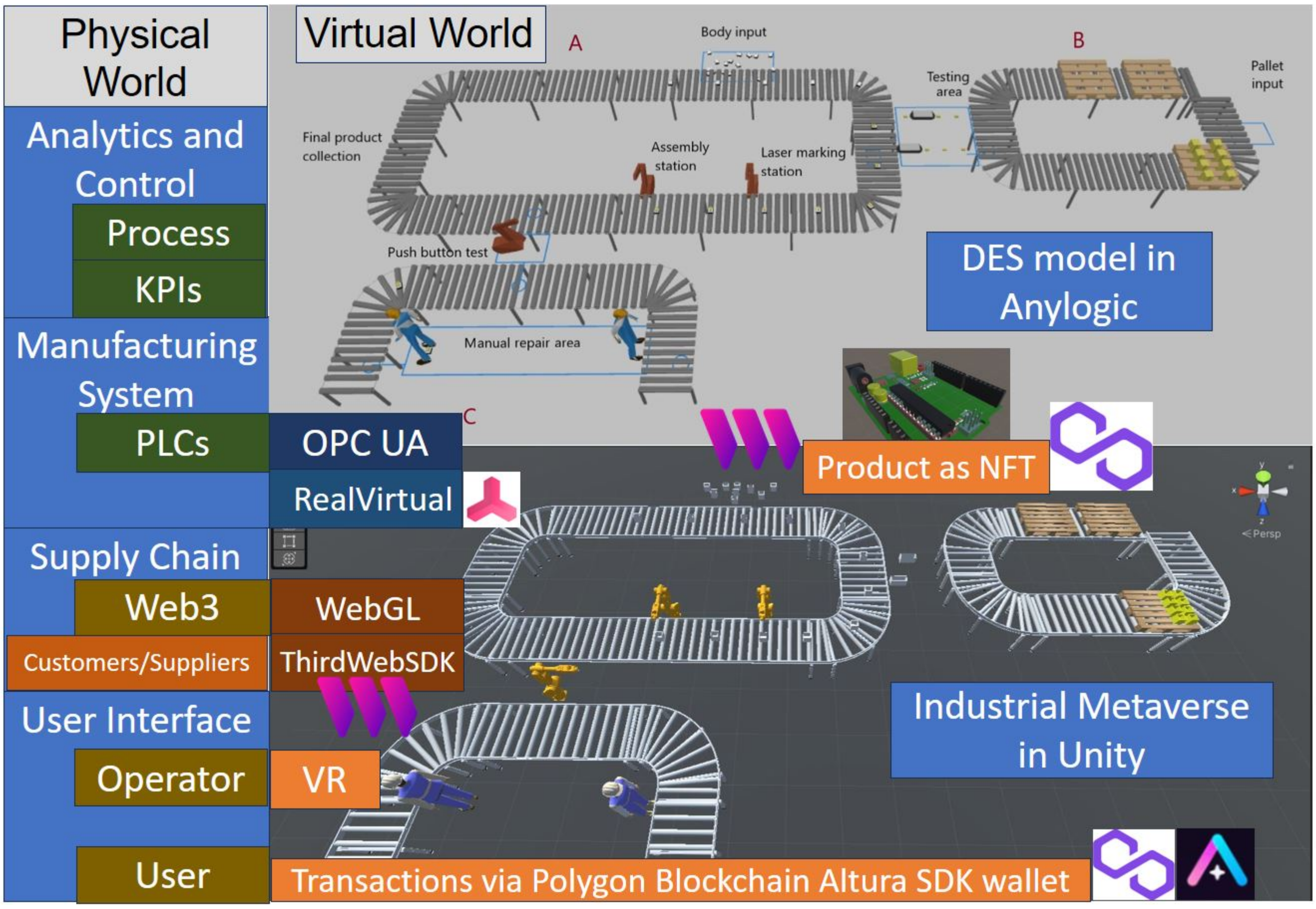

Fig. 3. The virtual model of the studied manufacturing facility on the way to building its industrial metaverse

The DES model can be also connected to a Unity application using OPC UA (see Figure 3), where Realvirtual Unity asset[3] provides OPC UA client and kinematics for the 3D simulation, virtual commissioning and validation and digital twin integration. Each product can be represented as a Non-Fungible Token (NFT) using ThirdWeb Unity SDK[4] and Polygon network[5], so it can be a unique product both in the physical and virtual worlds. Polygon can also be used for transactions within the supply chain for traceability as well as a payment method.

The Operator/user can interact with the Industrial metaverse via WebGL interface over a web browser, Unity application and over a VR asset. The operator training can be done via VR before the physical system has been built.

4.2. Initial results

Referring to the vision this work puts forward (as illustrated in Figure 1), productivity rate and sustainability KPIs govern the behaviour of the system with the aid of the industrial metaverse. For productivity, the DES model developed in AnyLogic was used to assess a variety of scenarios such as evaluating the use of two different robots for assembly (Figure 4) by comparing simulation results to the actual production. Using the NFT technology, products are traced to provide feedback on the Return on Investment.

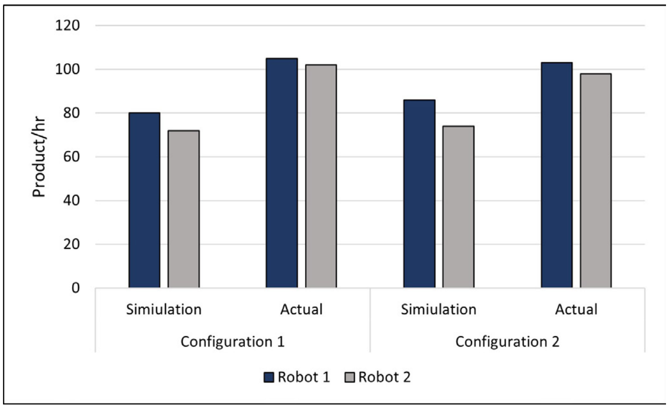

Fig. 4. Hourly production simulation results vs. actual

An example of the sustainability measures targeted by this study is to find the most efficient scheduling sequence of the repair task, where the setup involves a cobot to assist the engineer/technician. Energy consumption was measured to compare the difference, as illustrated in Figure 5.

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[3] https://realvirtual.io/
[4] https://thirdweb.com/
[5] https://polygon.technology/

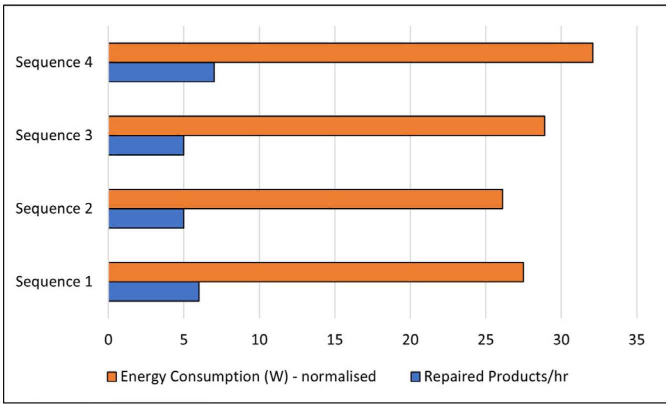

Fig. 5. Energy consumption and productivity for a number of sequences

Thanks to the developed industrial metaverse model, further training on collaborative work with cobots will be provided later, leading to a more socially sustainable work environment.

5. Conclusion

Following the rise of the industrial internet and cyber-physical systems technologies, socio-cyber-physical systems are changing the manufacturing landscape as the industrial metaverse promises added benefits. However, its advantage has not been fully taken as it is still in its infancy. The current work presented a framework for utilising the industrial metaverse to support sustainable manufacturing. As an application, a case study is presented, in which, a variety of scenarios were examined to evaluate their sustainability potential.

The current work did not discuss the computational power and the digital infrastructure that guarantee the full functionality of the proposed framework. Besides, there are some security concerns and data privacy issues that arise when humans are involved and their behaviour is modelled, which are not discussed either. Therefore, future work will take these matters into account.

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References

1. Statista, . Consumer Trends 2022: A Statista Trend Report on the Future of Consumption. Available: https://www.statista.com/study/48106/consumer-trends-2022/; 2022. Accessed: 24/10/2023.
2. Yao, X., Ma, N., Zhang, J., Wang, K., Yang, E., Faccio, M.. Enhancing wisdom manufacturing as industrial metaverse for industry and society 5.0. *Journal of Intelligent Manufacturing* 2022;:1–21doi:10.1007/s10845-022-02027-7.
3. Lee, J., Kundu, P.. Integrated cyber-physical systems and industrial metaverse for remote manufacturing. *Manufacturing Letters* 2022;34:12–15. doi:10.1016/j.mfglet.2022.08.0121.
4. Leng, J., Sha, W., Wang, B., Zheng, P., Zhuang, C., Liu, Q., Wuest, T., Mourtzis, D., Wang, L.. Industry 5.0: Prospect and retrospect. *Journal of Manufacturing Systems* 2022;65:279–295. doi:10.1016/j.jmsy.2022.09.017.
5. Deloitte, . Exploring the Industrial Metaverse. Available: https://www2.deloitte.com/us/en/insights/industry/manufacturing/industrial-metaverse-applications-smart-factory.html; 2023. Accessed: 30/10/2023.
6. Kshetri, N.. The economics of the industrial metaverse. *IT Professional* 2023;25(1):84–88. doi:10.1109/MITP.2023.3236494.
7. Singh, R., Akram, S.V., Gehlot, A., Buddhi, D., Priyadarshi, N., Twala, B.. Energy system 4.0: Digitalization of the energy sector with inclination towards sustainability. *Sensors* 2022;22(17):6619. doi:10.3390/s22176619.
8. Deveci, M., Gokasar, I., Castillo, O., Daim, T.. Evaluation of metaverse integration of freight fluidity measurement alternatives using fuzzy dombi edas model. *Computers & Industrial Engineering* 2022;174:108773. doi:10.1016/j.cie.2022.108773.
9. Pamucar, D., Deveci, M., Gokasar, I., Tavana, M., Köppen, M.. A metaverse assessment model for sustainable transportation using ordinal priority approach and aczel-alsina norms. *Technological Forecasting and Social Change* 2022;182:121778. doi:10.1016/j.techfore.2022.121778.
10. Anshari, M., Syafrudin, M., Fitriyani, N.L., Razzaq, A.. Ethical responsibility and sustainability (ers) development in a metaverse business model. *Sustainability* 2022;14(23):15805. doi:10.3390/su142315805.
11. Park, S., Kim, S.. Identifying world types to deliver gameful experiences for sustainable learning in the metaverse. *Sustainability* 2022;14(3):1361. doi:10.3390/su14031361.
12. Lee, H., Hwang, Y.. Technology-enhanced education through vr-making and metaverse-linking to foster teacher readiness and sustainable learning. *Sustainability* 2022;14(8):4786. doi:10.3390/su14084786.
13. Allam, Z., Sharifi, A., Bibri, S.E., Jones, D.S., Krogstie, J.. The metaverse as a virtual form of smart cities: Opportunities and challenges for environmental, economic, and social sustainability in urban futures. *Smart Cities* 2022;5(3):771–801. doi:10.3390/smartcities5030040.
14. Pang, X., Fan, X., Lu, X., Li, Y., Han, J.. Carbon neutrality in smart tech-parks: Leveraging metaverse and energy management application. In: *International Conference on Metaverse*. Springer; 2023:55–70. doi:10.1007/978-3-031-44754-9_5.
15. Dolgui, A., Ivanov, D.. Metaverse supply chain and operations management. *International Journal of Production Research* 2023;0(0):1–13. doi:10.1080/00207543.2023.2240900.
16. Chen, P.K., Ye, Y., Huang, X.. The metaverse in supply chain knowledge sharing and resilience contexts: An empirical investigation of factors affecting adoption and acceptance. *Journal of Innovation & Knowledge* 2023;8(4):100446. doi:10.1016/j.jik.2023.100446.
17. Wang, X., Cheng, X., Lu, J., Kwan, O., Li, S., Ping, Z.. Metaverses-based parallel oil fields in cpss: A framework and methodology. *IEEE Transactions on Systems, Man, and Cybernetics: Systems* 2022;53(4):2138–2147. doi:10.1109/TSMC.2022.3228934.
18. Qian, F., Tang, Y., Yu, X.. The future of process industry: A cyber–physical–social system perspective. *IEEE Transactions on Cybernetics* 2023;doi:10.1109/TCYB.2023.3298838.
19. Brecher, C., Petrovic, O., Dassen, Y., Blanke, P., Trinh, M., Wurm, S.. Sustainable production-as-a-service. 2023. URL: https://doi.org/10.24406/publica-949. doi:10.24406/publica-949.
20. Kshetri, N., Dwivedi, Y.K.. Pollution-reducing and pollution-generating effects of the metaverse. *International Journal of Information Management* 2023;69:102620. doi:10.1016/j.ijinfomgt.2023.102620.
21. NVIDIA, . NVIDIA Omniverse Ecosystem Expands 10x, Amid New Features and Services for Developers, Enterprises and Creators. Available: https://blogs.nvidia.com/blog/2022/03/22/omniverse-ecosystem-expands/; 2022. Accessed: 06/11/2023.
22. Assad, F., Konstantinov, S., Rushforth, E.J., Vera, D.A., Harrison, R.. Virtual engineering in the support of sustainable assembly systems. *Procedia CIRP* 2021;97:367–372. doi:10.1016/j.procir.2020.05.252.
23. Konstantinov, S., Assad, F., Ahmad, B., Vera, D.A., Harrison, R.. Virtual engineering and commissioning to support the lifecycle of a manufacturing assembly system. *Machines* 2022;10(10):939. doi:10.3390/machines10100939.

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