SPS2022
A.H.C. Ng et al. (Eds.)

doi:10.3233/ATDE220168

Enabling Industrial Mixed Reality Using Digital Continuity: An Experiment Within Remanufacturing

Víctor IGELMO [1], Anna SYBERFELDT , Jörgen HANSSON and Tehseen ASLAM
University of Skövde, Sweden

Abstract. In the digitalisation era, overlaying digital, contextualised information on top of the physical world is essential for an efficient operation. Mixed reality (MR) is a technology designed for this purpose, and it is considered one of the critical drivers of Industry 4.0. This technology has proven to have multiple benefits in the manufacturing area, including improving flexibility, efficacy, and efficiency. Among the challenges that prevent the big-scale implementation of this technology, there is the authoring challenge, which we address by answering the following research questions: (1) “how can we fasten MR authoring in a manufacturing context?” and (2) “how can we reduce the deployment time of industrial MR experiences?”. This paper presents an experiment performed in collaboration with Volvo within the remanufacturing of truck engines. MR seems to be more valuable for remanufacturing than for many other applications in the manufacturing industry, and the authoring challenge appears to be accentuated. In this experiment, product lifecycle management (PLM) tools are used along with internet of things (IoT) platforms and MR devices. This joint system is designed to keep the information up-to-date and ready to be used when needed. Having all the necessary data cascading from the PLM platform to the MR device using IoT prevents information silos and improves the system’s overall reliability. Results from the experiment show how the interconnection of information systems can significantly reduce development and deployment time. Experiment findings include a considerable increment in the complexity of the overall IT system, the need for substantial investment in it, and the necessity of having highly qualified IT staff. The main contribution of this paper is a systematic approach to the design of industrial MR experiences.

Keywords. Mixed reality, Digital Continuity, Product Lifecycle Management, Remanufacturing, Industry 4.0.

1. Introduction

Many observers in academia and the private sector agree that the world is going through its fourth industrial revolution, so-called Industry 4.0. This term encompasses multiple technologies and techniques working together towards digital manufacturing, thus the well-known term *digitalisation*. Widely speaking, Industry 4.0 is characterised by an increment in mechanisation and automation, digitalisation and networking, and miniaturisation. These concepts are born to cover a modern need for short development periods, individualisation on demand, flexibility, decentralisation, and resource

---

[1] Corresponding Author; Email: victor.igelmo.garcia@his.se

efficiency [1]. In the past years, the industrial sector started transitioning towards Industry 4.0. Many have labelled this movement as *digital transformation*. One of the most common results of this transition is an exponential growth in collected and stored data. However, data itself is meaningless. The power of data lies within the human capacity to understand it, learn from it, make decisions based on it, and design artefacts that can use this data. The ability to display contextualised data at the right place at the right time can increase human understanding of information, hence exploiting the core value of data. In the digitalisation era, the capability to overlay and interact with digital information on top of the physical world becomes essential. Immersive technologies, such as mixed reality (MR), are designed to enhance this capability, and they are considered a key driver of Industry 4.0 [2].

From a manufacturing point of view, it is essential to keep high efficiency and low error rate with high product quality on the shop floor. Furthermore, the trend towards mass customisation, and relentless growth in product complexity, have pushed manufacturers to surge the operational flexibility degree within this area [3]. Changing the current linear models is imperative to making companies more sustainable [4]. These requirements have led the discussion for numerous topics regarding improving the current operations within manufacturing. The most relevant topics include improvements in operator training and support to cope with the desired flexibility, the investigation of new information displaying techniques, and the necessity for revising the ongoing design and use of information systems in manufacturing.

Some of the solutions developed within academia use information systems to solve real-time communication between devices, among other issues. However, only a fraction of these studies take advantage of these systems to reduce the development time associated with MR apps (MR-experiences). A lack of solutions that coordinate MR technologies with information systems can cause a setback on the big-scale implementation of MR technologies in the industry. This study aims to complement the existing MR literature by providing a framework to systematically approach assembly and disassembly tasks, leveraging information systems to optimise the process of creating MR applications. While this study has been developed within a remanufacturing process, the framework can be applied to other assembly and disassembly tasks.

2. Background

Complex products, such as combustion engines, have multiple components which have a longer individual lifespan than the product as a whole. Circular economy (CE) refers to the notion of "promoting the retention of the economic and environmental value of material, by keeping products in productive use or by recapturing the materials in loops (providing new lifecycles) and seeing them as a resource and a source of value" [4]. CE's primary focus is on the products' end-of-life (EOL) tasks such as reuse or recycling. Remanufacturing is an essential component of CE, which consists of shaping and rebuilding a product that has reached its EOL into a new one, with at least equivalent performance and warranty. Remanufacturing is a highly manual, rather complicated process. Consequently, the need for operator support is higher than in many other industrial applications. Industry 4.0 technologies have established their value within operator support in many areas. However, they have hardly been implemented and proven in remanufacturing [5].

MR is one of the technologies critical for enabling operator support within Industry 4.0 and remanufacturing [5]. The concept of MR was presented along with the reality-virtuality framework in 1994 [6]. While the original framework referred to MR as the "combination of real and virtual objects in a single display", a revisited version of it defines MR as the combination of physical and virtual objects presented in a fashion that can be simultaneously perceived [7]. This reviewed definition is the one considered in this paper. Within the research community, there is still a meaningful discussion on where to draw the line between MR, augmented reality (AR) and virtual reality (VR). The term extended reality (XR) has also been proposed [8] for the sake of differentiation. For this publication, articles using the terms AR, XR, and MR, are reviewed as belonging to MR (and referred to as such) as long as they fulfil three conditions: (1) the natural environment is presented in combination with the virtual objects/environment, (2) virtual objects appear in a 3D space, and (3) there is a minimum degree of interaction with the virtual objects. The first two constraints depend neither on the perception technology (e.g., see-through and 2D perception of the real world are both valid) nor on the form of interaction (e.g., voice, or hand-based interaction are equally valid). MR has been proven useful in several tasks within manufacturing, including but not limited to assembly, maintenance, quality, and logistics [9].

MR devices' practical contribution is outstandingly higher when connected to a network. Internet of things (IoT) is a technology that aims to add connectivity capabilities to different devices using embedded electronics and communication protocols. These devices (named 'things') are provided with "unique identifiers, physical attributes, and virtual personalities, and seamlessly integrate them into an information network" [10]. IoT plays a key role within Industry 4.0 by enabling techniques such as mobile and cloud computing, big data analytics, real-time machine-to-machine communication, or predictive maintenance [11]. Devices provided with IoT capabilities are usually tagged as 'smart' devices. IoT is also considered one of the key technological enablers within remanufacturing [5,12]. IoT provides MR with the capability to access real-time and stored digital information, promoting digital continuity. This concept refers to making the latest version of any piece of digital information available wherever and whenever needed, in the required shape. Digital continuity is imperative to preventing information silos and improving data management interoperability and efficiency. Storage (including properly structuring information and adequate input/updating protocols) and connectivity are central to achieving digital continuity. It is essential to mention that both the storing and connectivity platforms must have specific characteristics concerning reliability, robustness, and security. In an industrial context, storage is performed using specialised information management tools, such as product lifecycle management (PLM). Success will depend on the system architecture and the devices' nature regarding connectivity.

3. Previous work

AR and MR are still relatively underdeveloped technologies in manufacturing contexts, although they are topics that have been studied for some time. While literature is moderately abundant, research efforts are scattered. When reviewing the literature, two main inclusion factors were used: (1) authors developed an AR/MR-based framework or system, and (2) developed artefact uses information systems, cloud technologies, or a combination of both. Publications within manufacturing contexts, specifically in assembly and disassembly processes (often referred to as operator support), are prioritised. Some papers within building information modelling (BIM) have been included, given their intimate relation with research addressing AR/MR-based communication with information systems. Following the abovementioned inclusion criteria, the most common topics include AR/MR-based collaboration and telepresence [13–15], monitoring, control, machinery programming, assembly, maintenance, logistics, quality control and training [16–18]. Learning, including cognitive ergonomics, in manufacturing and non-manufacturing contexts, is a recurrent topic in the AR/MR field [19,20]. Among these topics, we found that monitoring, control and machinery programming often fall out of the scope of this paper, as they primarily focus on parts of the system which are irrelevant for this work. As a final point, acknowledging the limited scope of the literature review performed for this paper, a few review studies have been included to support the taken assumptions and premises [2,5,16,17].

Many studies include a methodology section in which authors explain the setup process and the software involved. Some studies highlight the need for 3D CAD objects, even "realistic models of the product to be operated" [21]. There is, however, little to no information about the origin of these 3D objects. Most of the developed systems include manually created or manually imported CAD models. It is possible to find some exceptions, where authors define third-party systems as the origin for these models [18,22,23] and other manufacturing information [18,24–26]. These papers are explicit about the importance of using cloud-based technologies to store and deploy information. The process of manually creating or manually importing assets (3D objects and information to be used in AR/MR) is feasible for proof of concepts and for industries with a minimal number of products that are not modified over time (e.g., the construction industry [22]). An essential assumption within this work is that this developing strategy AR/MR is not feasible to reach scalable development and deployment. In line with this, another crucial premise is that this lack of feasibility and the number of product variants and their modifications over time are directly proportional. In conclusion, we noticed that functional, operational, and fully integrated AR-PLM connections are yet to be realised.

4. Research methodology

Considering the advantages of MR and its extended capabilities when connected to information systems, a pilot program was launched at Volvo remanufacturing. Volvo had different objectives, including solving some of their specific remanufacturing issues (not fully disclosed in this publication), exploring implementation challenges, and investigating this technology's viability in practice. There are many barriers to the practical implementation of MR solutions within the current state of this technology. In an initial case of study within CE, implementation challenges arose [4]. These challenges include authoring, deployment, comfort, technology limitations, user acceptance, change in the procedure, a trade-off between user knowledge and constraints imposed by the MR system, and cognitive load among experienced workers. Some of those mentioned above are intrinsic to MR technologies, and others are particularly enlarged in remanufacturing. Among the many variables under review in the pilot, challenges related to the authoring of industrial MR experiences are considered particularly important by the practitioner. This prioritisation is mainly associated with the number of product variants in remanufacturing and the operational differences from product to product within the same station. This work aims to suggest a solution for authoring-related challenges. More specifically, we aim to address two questions: (1) how can we reduce development time for industrial MR experiences, and (2) how can we reduce deployment time for industrial MR experiences?

Direct experimentation in manufacturing environments is a complicated process. Experiments within manufacturing environments will inevitably be constrained by many factors such as privacy and security policies, downtime-related restrictions, and industrial readiness of the solutions to be implemented, to name a few. Constraints are vast when management systems or information systems are involved. While direct experimentation would have been ideal, our approach to the problem was to observe the system and mirror it in a controlled environment, where a solution that applies to the actual environment is developed. This solution uses the concept of digital continuity, which has not been found explicitly mentioned in the MR literature. Finally, the solution will aid in the building of a framework within the development and deployment processes of MR solutions, which is the main contribution of this paper.

5. Results

As mentioned above, the remanufacturing operation taken as a reference is the one performed at Volvo, particularly on the remanufacturing process of trucks engines. This operation consists of three main steps: disassembling, machining (reconditioning), and assembling. In the disassembling step, wires, harnesses, sensors, and camshaft are removed and systematically discarded. The rest of the main parts go through washing stations. Subsequently, different components are inspected, discarded if necessary, and sent to either assembly (when fully operational in their current state) or machining. Product parts that go through the machining step need to fulfil specific requirements, mostly related to tolerances, in order to meet quality standards. Washed, machined, and new parts reach the assembly, or so-called reassembly, step. Afterwards, engines are submitted to a quality inspection before their delivery [4].

While disassembling can be a significant source of value for MR implementation, it carries a more significant operational error margin than assembly. On the other hand, the machining stage is much more standardised than the other two processes, considerably reducing the need for operator support. Therefore, it was determined that assembly is the most valuable process for the task at hand. Some of the implementation expectations of MR-based operator support include: increment in standardisation of the assembly process in remanufacturing, decrement of the procedural deviations, increment in the quality standard (given by the previous two points), expected decreased assembly time, knowledge storage, and knowledge transformation (from tacit to explicit), enabling less-experienced workers.

The authoring of industrial MR experiences is still not yet adequately defined, and it is currently an important research topic in the field. Nowadays, MR experiences are manually created, and there is one experience per product, constraining the application of MR to those uses in which it is limited to a few products (e.g., construction industry) or to proofs of concept. In this experiment, following the idea of digital continuity, we explore how implementing PLM systems to the MR experiences creation workflow affects MR developing times. Knowing that (re)manufacturing processes have a frequent pattern, consisting of receiving the product in a station and performing some task on it, it is possible to use information systems to reduce the number of experiences created massively. Subsequently, the overall development time required to build these experiences would also be reduced. Moreover, when using only a few experiences, instead of one per product, deployment is limited to changes on the experience itself (e.g., functionality), making it independent of product data changes.

The experimental setting consisted of a valve hood assembly task, which was performed in collaboration with a cobot (a robotic arm designed explicitly for collaborative tasks). In this task, the worker is required to follow a specific procedure: wait until the robot has picked the valve hood, manually move the valve hood, which is held by the robot, to the top part of the engine, align the valve hood for screwing, and screw in a specified order. This setting is used considering that, given the flexibility of the cobot, this station can be used to perform top-side screwing operations in various products, which could have different screwing procedures (therefore different instructions) and even tasks pre-processing or preparation of the workstation.

By implementing PLM information into MR experiences, we reduced the number of built experiences to one. This experience displays a virtual *panel*, common to all different products, with its origin (spatial placement reference) on the edge of the product. Next to the panels, virtual buttons allow the worker to change the instructions steps, back and forward. The product and working station are recognised using a QR-code, and the program enters the recognition stage once the experience is started and when an assembly task has been completed. Once the product is identified, its information is retrieved from the PLM platform and displayed, using the IoT platform as a medium. Retrieved data contains the number of steps, assembly pictures/drawings, and instructions in the form of text (Figure 1). If this information is updated or modified, all deployed experiences will update accordingly. For the experiment, MR experiences are prototyped in mobile devices due to the simplicity of deployment compared with head-mounted devices. The latter is used at the deployment stage since one initial requirement from the practitioner is that the operators should have both hands free. The final software is developed using Unity 3D ® and deployed in a Microsoft Hololens 2 ® headset.

Step 2

Robot in collaborative mode

- Pick valve cover with your rigth hand and the robot's tool with your left hand.
- Move valve cover to its position on the engine.

Step 3

- Fix blue and black cables to lower part of robot's arm with fastener.

Figure 1: Example steps

In this experiment, the measured time to create each experience was, on average, one working day without following the suggested approach. Overall development time is increased according to the number of products and stations. The time to modify the data on the experience, such as reference pictures, was on average one hour, including deployment. It is imperative to mention that the MR equipment was idle during this time. Once following the presented approach, the developing time of the first MR experience increased as expected. This increment was caused by the need to implement product identifiers and their logic for information retrieval. Total developing time was approximately one week. Time to modify the experience content, including deployment, was reduced to zero. This sole experience was tested in a few hypothetical working stations in the controlled environment, without the need to modify it, adapting the product information correspondingly. A need to create more experiences in the future was therefore not present. While the many-to-one reduction is generalisable, it would be unrealistic to suggest that the absolute developing times would be the same since it greatly depends on the desired functionalities and the designer's knowledge about particular PLM and IoT systems.

When executing the experiment with company data, a significant setback arose: in practice, PLM information might be well shaped, structured, and up to date in the initial phases of the product lifecycle, but it is somewhat neglected at its EOL [4]. Because of that, a workflow to improve the system's overall feasibility is designed (Figure 2), and primary information sources are defined. These are product information and production data. On the one hand, product information is stored in the PLM system, containing all the necessary details on how to (re)assemble the product. If PLM information does not exist, experienced assembly operators should generate it, storing their knowledge in the system. In contrast, production data is essential since it includes information about the process that one particular product went through within the factory, for instance, pieces that have been discarded or machined. Production data is made available on an IoT platform to enable digital continuity and improve scalability. This approach eases the use of MR technologies in remanufacturing and can enhance the business circularity by improving information management and usage at the product's EOL.

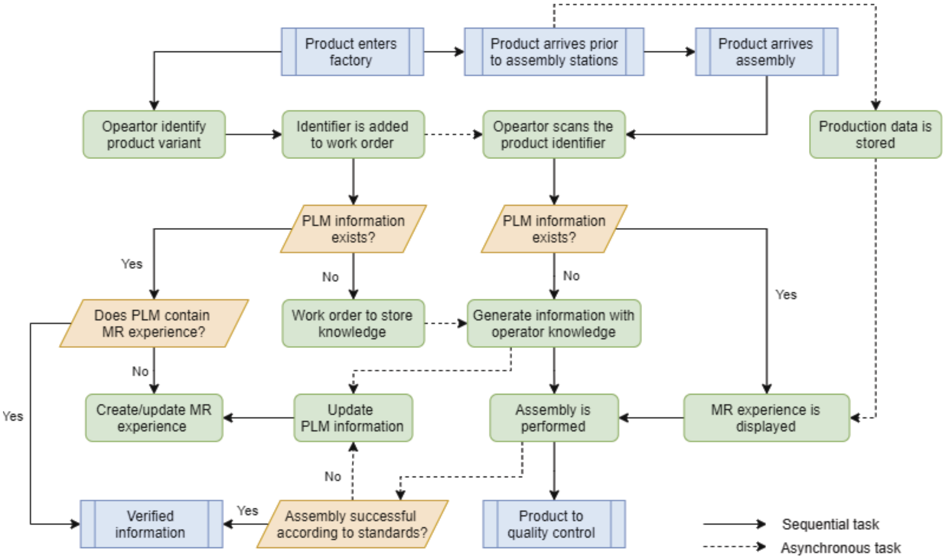

Figure 2: Suggested approach

The leading enabler for this approach (and for this experiment in general) is the information systems, which must contain all the product data required. These systems must include connectivity capabilities and information retrieval protocols/procedures. To correctly retrieve product information, an identification protocol should exist, in which the information is linked with a particular product variant and its identifier. The identifier itself can take many shapes, such as barcodes, QR-codes, proprietary identifiers, or even a number or text string. The latter would require manual input from the worker at least once. Object recognition is discarded as a viable identification method in remanufacturing given low accuracy caused by similarities among product variants and the different states a product might have at its EOL.

6. Discussion

While the scope of the study was one single experiment, based on one case of study, there is a certain degree of generalizability. The framework presented can be used in virtually any assembly and disassembly task in need of operator support, for which an MR implementation has been planned, and there are existing industrial information systems. We believe that embracing this framework is complementary to other approaches in the literature, as they have different approaches to MR technologies (presented in the previous work section). The suitability of the MR implementation itself is not covered by this framework, leaving that to the practitioners. On the other hand, the developed approach builds on PLM systems, but it is acknowledged that not all practitioners use these particular systems, especially when it comes to small and medium enterprises. However, even though this approach has been developed for PLM systems, it could be extended to other information systems as long as they have the capability of exchanging information with third-party MR software. The presented approach is limited to assembly and disassembly tasks. Predictably, other fields, such as maintenance, could greatly benefit from this framework. On a final note, this study has explored the inclusion of instructions in the shape of images, videos and text, not exploring the possibility of appending other types of MR-specific instructions, such as overlayed 3D animations or remotely drawn annotations.

Multiple advantages arise from the practical use of PLM in MR industrial experiences combined with the presented approach in remanufacturing. From a knowledge perspective, most of the knowledge in remanufacturing is tacit, i.e., each worker's gained knowledge through professional experience. Some disadvantages of depending on this type of knowledge in the shopfloor include lack of standardisation, highly variable performance, and overly sensitivity to personnel rotation/absence. Among other advantages, digital tools such as PLM allow storing the workers' knowledge. By doing this, this knowledge is transformed into implicit, which is, from an epistemological perspective, more efficient and meaningful when it comes to analysis and evaluation [27]. From a CE perspective, having more standardised operations and more information about the product variants at its EOL makes the overall remanufacturing process more effective and, potentially, more profitable. From a social perspective, using implicit knowledge in remanufacturing would enable less-skilled workers to go into production. Lastly, from an operational perspective, the tasks are performed more efficiently, information silos are prevented, and the system's overall reliability is increased.

There are several shortcomings in the system presented in this experiment. Firstly, it dramatically increases the complexity of the overall IT system. PLM and IoT systems are not easy to set up, maintain or manage, and they are not extended enough in practice to have homogeneous design rules to follow. Secondly, caused by the increment in the system's complexity, the system requires upskilling of the IT personnel or even a multidisciplinary team to manage it properly. Thirdly, the required initial investment is high, making the adoption of this method difficult for small enterprises. Lastly, the efficiency of the approach is proportional to the initial number of different MR experiences. In other words, if the number of MR experiences is low, the total developing time would probably increase. On a special note, the MR experiences depend entirely on the information retrieval, downloading the information when required, rather than having this information stored on the experience files. Depending on the working environment, these connectivity requirements could become inconvenient. One of the ongoing improvements of the system includes managing local copies of the product information.

7. Conclusion

We present an approach to using MR technologies along with PLM systems in remanufacturing processes. The proposed solution dramatically reduces the developing and deploying times of MR technologies. The more MR experiences are to be implemented, the higher the time reduction. This reduction is achieved by limiting the number of MR experiences to one and building the content by retrieving information from PLM systems. It is essential to have accurate, up-to-date information at the EOL to increase the circularity of our processes. This approach provides a way to use product information more systematically. Among others, the proper use of information prevents information silos and improves the system's overall reliability. Furthermore, this method aids with converting the process knowledge from tacit to explicit, impacting production-related metrics such as the degree of standardisation.

Research following this work could focus on several things. One of the most significant internal points of discussion during the execution of the experiment has been how many product variants are necessary to justify the use of this approach. We encourage the academic community to extend this study, using the presented approach, with mentioned scope. To further cover the gaps present in this study, we suggest replicating this study in other experiments and extending this study to other industries and application fields, such as maintenance. Other research areas include automatic content generation [28], MR-based input systems to feed PLM platforms, or user adaptability (adapt the MR experience to particular needs, such as preferred information displaying method). Mentioned topics can make extensive use of information systems.

Predictably, MR will become a standard in manufacturing operations, coexisting with traditional WIMP (windows, icons, menus, and pointer) systems. The question surrounding MR technologies is not *if* but rather *when*. MR technologies are an indispensable part of our advances within *the virtual*. That said, from a business and engineering perspective, the question is *how*. Howbeit it is acknowledgeable that efforts have been put into answering the latter question, they are not enough to keep up with the upcoming paradigm swift that MR will cause in manufacturing. Adding up, much of MR literature focuses on the experience itself, which is necessary but insufficient. It is essential to expand our knowledge regarding topics adjacent to MR, such as scalability, security, privacy, or connectivity, to name a few.

Acknowledgement

The authors wish to thank the Swedish innovation agency Vinnova and the Strategic Innovation Programme Produktion2030 (funding number 2019-00787). Likewise, the authors

References

[1] Lasi H, Fettke P, Kemper HG, Feld T, Hoffmann M. Industry 4.0. Bus Inf Syst Eng 2014;6:239–42. https://doi.org/10.1007/s12599-014-0334-4.
[2] Masood T, Egger J. Augmented reality in support of Industry 4.0—Implementation challenges and success factors. Robot Comput Integr Manuf 2019;58:181–95. https://doi.org/10.1016/j.rcim.2019.02.003.
[3] Zhong RY, Xu X, Klotz E, Newman ST. Intelligent Manufacturing in the Context of Industry 4.0: A Review. Engineering 2017;3:616–30. https://doi.org/10.1016/J.ENG.2017.05.015.
[4] Despeisse M, Chari A, González Chávez CA, Chen X, Johansson B, Igelmo Garcia V, et al. Achieving Circular and Efficient Production Systems: Emerging Challenges from Industrial Cases. vol. 633 IFIP. 2021. https://doi.org/10.1007/978-3-030-85910-7_55.
[5] Kerin M, Pham DT. A review of emerging industry 4.0 technologies in remanufacturing. J Clean Prod 2019;237:117805. https://doi.org/10.1016/j.jclepro.2019.117805.
[6] Milgram Paul, Kishino Fumio. A Taxonomy of Mixed Reality Visual Displays (Special Issue on Networked Reality). IEICE Trans Inf Syst 1994;77:1321–9.
[7] Skarbez R, Smith M, Whitton MC. Revisiting Milgram and Kishino's Reality-Virtuality Continuum. Front Virtual Real 2021;2:1–8. https://doi.org/10.3389/frvir.2021.647997.
[8] Fast-Berglund Å, Gong L, Li D. Testing and validating Extended Reality (xR) technologies in manufacturing. Procedia Manuf 2018;25:31–8. https://doi.org/10.1016/j.promfg.2018.06.054.
[9] Egger J, Masood T. Augmented reality in support of intelligent manufacturing – A systematic literature review. Comput Ind Eng 2020;140:106195. https://doi.org/10.1016/j.cie.2019.106195.
[10] Xu L Da, He W, Li S. Internet of things in industries: A survey. IEEE Trans Ind Informatics 2014;10:2233–43. https://doi.org/10.1109/TII.2014.2300753.
[11] Lu Y. Industry 4.0: A survey on technologies, applications and open research issues. J Ind Inf Integr 2017;6:1–10. https://doi.org/10.1016/j.jii.2017.04.005.
[12] Chang MML, Ong SK, Nee AYC. Approaches and Challenges in Product Disassembly Planning for Sustainability. Procedia CIRP 2017;60:506–11. https://doi.org/10.1016/j.procir.2017.01.013.
[13] Ens B, Lanir J, Tang A, Bateman S, Lee G, Piumsomboon T, et al. Revisiting collaboration through mixed reality: The evolution of groupware. Int J Hum Comput Stud 2019;131:81–98. https://doi.org/10.1016/j.ijhcs.2019.05.011.
[14] Piumsomboon T, Lee GA, Hart JD, Ens B, Lindeman RW, Thomas BH, et al. Mini-me: An adaptive avatar for Mixed Reality remote collaboration. Conf Hum Factors Comput Syst - Proc 2018;2018-April:1–13. https://doi.org/10.1145/3173574.3173620.
[15] Mourtzis D, Siatras V, Angelopoulos J, Panopoulos N. An augmented reality collaborative product design cloud-based platform in the context of learning factory. Procedia Manuf 2020;45:546–51. https://doi.org/10.1016/j.promfg.2020.04.076.
[16] Baroroh DK, Chu CH, Wang L. Systematic literature review on augmented reality in smart manufacturing: Collaboration between human and computational intelligence. J Manuf Syst 2021;61:696–711. https://doi.org/10.1016/j.jmsy.2020.10.017.
[17] Egger J, Masood T. Augmented reality in support of intelligent manufacturing – A systematic literature review. Comput Ind Eng 2020;140:106195. https://doi.org/10.1016/j.cie.2019.106195.
[18] Fraga-Lamas P, Fernández-Caramés TM, Blanco-Novoa Ó, Vilar-Montesinos MA. A Review on Industrial Augmented Reality Systems for the Industry 4.0 Shipyard. IEEE Access 2018;6:13358–75. https://doi.org/10.1109/ACCESS.2018.2808326.
[19] Siatras V, Athanasopoulou L, Alexopoulos K, Stavropoulos P, Mourtzis D. Applying the Teaching Factory Paradigm and Augmented Reality Technology for Operator Training in Assembly Operations. SSRN Electron J 2021. https://doi.org/10.2139/ssrn.3859475.
[20] Werrlich S, Daniel A, Ginger A, Nguyen PA, Notni G. Comparing HMD-Based and Paper-Based Training. Proc 2018 IEEE Int Symp Mix Augment Reality, ISMAR 2018 2019:134–42. https://doi.org/10.1109/ISMAR.2018.00046.
[21] Blaga A, Tamas L. Augmented Reality for Digital Manufacturing. MED 2018 - 26th Mediterr Conf

Control Autom 2018:173–8. https://doi.org/10.1109/MED.2018.8443028.

[22] Schweigkofler A, Monizza GP, Domi E, Popescu A, Ratajczak J, Marcher C, et al. Development of a digital platform based on the integration of augmented reality and BIM for the management of information in construction processes. IFIP Adv. Inf. Commun. Technol., vol. 540, 2018, p. 46–55. https://doi.org/10.1007/978-3-030-01614-2_5.

[23] Michalos G, Kousi N, Karagiannis P, Gkournelos C, Dimoulas K, Koukas S, et al. Seamless human robot collaborative assembly – An automotive case study. Mechatronics 2018;55:194–211. https://doi.org/10.1016/j.mechatronics.2018.08.006.

[24] Mourtzis D, Siatras V, Angelopoulos J. Real-time remote maintenance support based on augmented reality (AR). Appl Sci 2020;10. https://doi.org/10.3390/app10051855.

[25] Makolkina M, Pham VD, Kirichek R, Gogol A, Koucheryavy A. Interaction of AR and IoT Applications on the Basis of Hierarchical Cloud Services. In: Galinina O, Andreev S, Balandin S, Koucheryavy Y, editors. Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics), vol. 11118 LNCS, Cham: Springer International Publishing; 2018, p. 547–59. https://doi.org/10.1007/978-3-030-01168-0_49.

[26] Romero D, Stahre J, Wuest T, Noran O, Bernus P, Fast-Berglund Å, et al. Towards an operator 4.0 typology: A human-centric perspective on the fourth industrial revolution technologies. CIE 2016 46th Int Conf Comput Ind Eng 2016:0–11.

[27] Johannesson P, Perjons E. An introduction to design science. vol. 9783319106. Springer Publishing Company, Incorporated; 2014. https://doi.org/10.1007/978-3-319-10632-8.

[28] Chang MML, Ong SK, Nee AYC. AR-guided Product Disassembly for Maintenance and Remanufacturing. Procedia CIRP 2017;61:299–304. https://doi.org/10.1016/j.procir.2016.11.194.