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Mixed reality towards environmentally sustainable manufacturing – overview, barriers and design recommendations

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Abstract

Mixed reality (MR) stands for the seamless combination of the physical world and virtual objects, e.g. in form of augmented reality (AR) on head mounted displays or on smartphones. The underlying technologies are more and more mature and various use cases in and beyond manufacturing can be found in industry and research. Typical applications deal with e.g. support of maintenance, quality management, assembly operations or training. However, the question arises how promising MR potentials can also be tapped towards environmental sustainability in manufacturing. Against this background, this paper identifies and analyses existing MR approaches with direct or indirect contributions, but also analyses related efforts and barriers. Based on this, feasible design strategies are suggested to support the development of future environmentally sustainability oriented MR solutions for manufacturing.

Keywords: sustainable manufacturing; mixed reality, augmented reality, smart manufacturing

1. Introduction

As clearly pointed out by the IPCC report in context of climate change, environmental sustainability is and will be a major global challenge in the following decades. Industry is the largest driver here with being responsible for about a third of the global GHG emissions [1]. Given that, all measures that lead to a substantial improvement of environmental impacts from industrial processes are of strong concern.

Besides sustainability, ongoing digitalisation is still an accelerating megatrend in industry and beyond. Often linked to terms like Industry 4.0, smart industry or industrial internet of things (IoT), significant technological advancements in information and communication technologies (ICT) could be observed over the last decades [2][3]. This also includes the area of mixed reality (MR). MR stands for the seamless combination of the physical world and virtual objects and information, e.g. in the form of virtual (VR) or augmented reality (AR) on head mounted displays or on smartphones [4]. Related technologies and methods became significantly more performant, accessible, user friendly and cheaper over the last years. Studies point out an increase of the global VR/AR market size from around 30 billion in 2021 to almost 300 billion just until 2024 [5]. This includes a broad range of application fields e.g. in retail (e.g. sales, product demonstration, virtual tours), healthcare (e.g. training, support for treatments), military (e.g. training, support in operation), consumer electronics (e.g. video games, movies, virtual events), education in schools/universities [5] but of course also engineering and manufacturing in particular (e.g. design, maintenance, work instructions) [6].

All those applications fields already utilise the potentials of mixed reality around the intuitive and context specific visualization and interaction with data and digital models [4]. Also for the field of environmental sustainability in manufacturing, the general starting point is promising: given

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the advances in sensoring, data processing and storage, necessary data for energy and material flows is often available nowadays. Also, knowledge on general technologies and methods to improve sustainable manufacturing is existing [7]. With all that background, MR should have a promising potential to provide decision support for different stakeholders while bringing data, available knowledge and the current real world situation together through context-specific and insightful visualisation.
However, the question is how MR can be utilised best to support to explicitly improve the environmental sustainability of the manufacturing industry. Against this background, in a first step this paper aims at identifying and structuring existing MR solutions with relation to environmental sustainability in manufacturing. Based on current research gaps and barriers, design recommendations towards MR based decision support for industrial sustainability are derived.

2. Technical Background

2.1. System perspective on Sustainable Manufacturing

Mixed reality solutions can be found for different applications over the entire life cycle of products, some examples are mentioned in section 3. As indicated in Figure 1, this paper focuses on the manufacturing phase and its environmental sustainability. Manufacturing typically involves several process steps which form manufacturing system and factories. Understanding and improving the environmental impact of factories calls for a holistic factory perspective [8]: three different factory subsystems (production machines, technical building services/TBS, building shell) with the related specific objects can be distinguished. Those subsystems are connected through a diversity of energy and resource flows. This includes different externally acquired but also internal energy carriers (e.g. electricity, gas, compressed air, heat) as well as material flows (primary materials for products but also auxiliaries). Both are converted into valuable products but also result in different types of waste and emissions. All factory objects and the connected flows cause environmental impacts. For the manufacturing of products, different materials are obviously inherently needed which bring in a strong environmental backpack through their mining and preparation (e.g. in process industry). Studies show that around 70-80% of the energy demand of industry can be related to those material related processes [9] [10]. Also, all technical infrastructure in factories brings in an environmental backpack based on included materials and related production processes for their embodiment. Additionally, energy is normally required for their operation and direct emission may occur. Recent studies for the example of an automotive factory (without considering the product related material) underline that over the lifetime of a factory, energy demand of both production and TBS dominates its carbon footprint [11]. The embodied environmental impact of the technical infrastructure is still relevant but far less compared to the energy demand.
With that in mind, three major fields of action towards environmentally sustainable manufacturing can be identified [1][7][8]:

- Improving the *energy efficiency* (ratio of product output and energy input), e.g., through selection of energy efficient technologies, utilizing waste energy flows, proper dimensioning or more advanced process/factory control, e.g., for avoiding idle losses.
- Improving *material efficiency and circularity* - e.g., avoiding waste e.g. through better utilization of raw materials, increased quality rate (less rejects) as well as recycling of materials.
- Enabling *Substitution* (or effectiveness) strategy for energy sources (towards switching to renewable resources) but also materials (which cause less environmental impact in the upstream value chain).

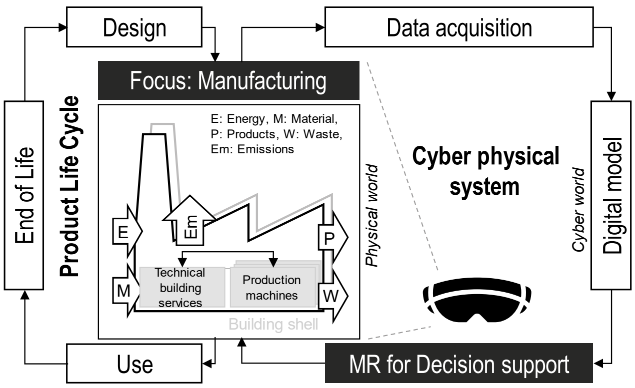

Figure 1: focus and scope of the paper - MR in context of sustainable manufacturing systems and as part of cyber physical (production) systems (factory and CPS definition based e.g. on [8][12]).

2.2. Mixed reality

Mixed Reality (MR) stands for the blended combination of real world objects and virtual objects [4]. The term is strongly connected to Augmented Reality (AR) and Virtual Reality (VR) but even broader brings together the variety of possible approaches along the reality–virtuality continuum (Figure 2) [4]. Depending on the focus and type of blending, various specific solutions are possible between the real physical (without digital objects) and pure virtual environments (e.g. showing software/results on conventional screen). This includes e.g. projections on and direct interactions with real objects, the augmentation of data/holograms in combination with smartphones or head mounted displays (see-through HMD) or also immersive virtual reality where real objects/users become part of virtual worlds through HMD or in VR rooms [4][13].

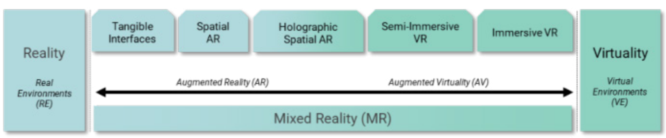

Figure 2: Extended reality–virtuality continuum, [13] based on [4].

2.3. MR as part of CPS

It is important to realize that the visible and tangible MR visualization is not an isolated element. MR solutions are a system with different components that can be understood as cyber physical (production) system (CPS/CPPS, Figure 1 right,

related to [12]). Cyber physical (production) systems are considered as a core element of Industry 4.0 and describe the connection of the real (physical) world with up-to-date digital (cyber) representatives (e.g. [2][3]). Often connected to the term digital twin, CPS are therewith necessarily based on acquisition of real world data and their embedment into digital models as base for decision support or autonomous control [12]. Over different maturity levels, CPS based solutions aim at creating visibility (visualizing data), over transparency (analyzing root causes) up to prediction (considering future scenarios) and ultimately autonomous adaption functionalities [14]. Within this framework, MR can be seen as an interface to different human stakeholders. It translates the potentially complex results of the background models into understandable and contextualized information and therewith facilitates decision making.
Due to the strong technological and methodological advancements in data acquisition, storage and analysis, the availability of data is not necessarily the critical bottleneck anymore. In modern factories, increased connectivity of machines, the integration of more and innovative sensors as well as sophisticated overarching IT systems (e.g. ERP, MES, building management systems) provide detailed data regarding the production related activities. This is also true for environmentally related data, e.g. regarding energy or material demand. As an example, studies showed already some years ago that there are over 90 energy monitoring solutions on the market [15]. The visualization of energy demands and related key performance indicators typically takes place through dashboards on conventional screens/tablets. While the data is there, the question remains whether and how MR capabilities can be used to further improve decision support and ultimately help to improve the environmental impact of factories.

3. MR in context of sustainable manufacturing

3.1. MR in life cycle context

As indicated in the introduction mixed reality applications gained increasing public attention over the last decades years due to advancing technological capabilities connected with cheaper hardware [5]. Also in the engineering domain different applications can be found that actually relate to different life cycle phases of products [6]. While various objectives are addressed, sustainability related aspects are partially reflected as well already. Examples are the utilization of MR approaches in (cooperative) product design, e.g. for development and assessment of digital prototypes, the remote collaboration of designers [16]. Other applications address consumers and create awareness and provide decision support for purchasing e.g. through AR visualization of product carbon footprints [17] or circularity aspects [18].

3.2. MR in Manufacturing context

As introduced before, this paper focuses on manufacturing. Therewith, a more detailed overview should be given for manufacturing related MR use cases and their connection to sustainability related aspects. Based on the analysis of related literature and the manufacturing understanding as introduced before, Figure 3 gives an structured overview of identified use cases to the factory subsystems and sustainability related factory flows (as defined in section 2). In general, numerous MR applications for manufacturing can be found in research and industrial practice – the question is whether those explicitly/directly or rather indirect focus sustainability related aspects already (indicated through the Harvey balls).

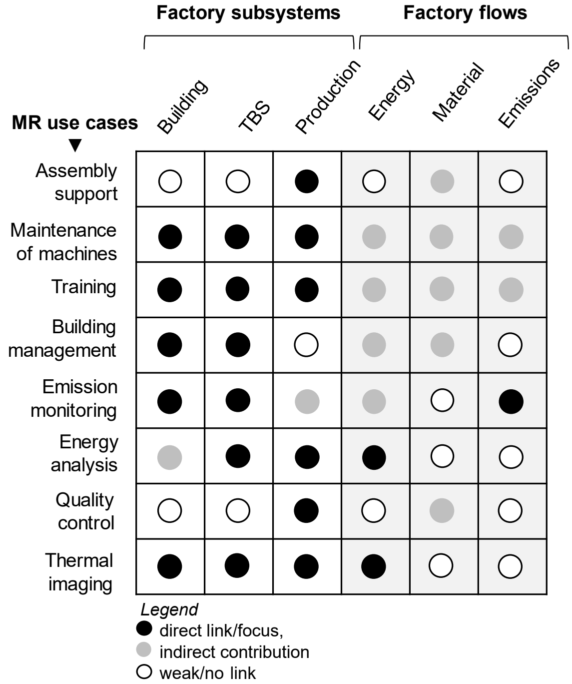

Figure 3: allocation of MR use case to factory subsystems and flows.

Providing working instruction for e.g. executing assembly tasks, support for maintenance activities and providing training can certainly be seen as major MR application fields in manufacturing. Various examples can be found from rather prototypical and research oriented approaches to commercially available solutions [19][20]. MR can enfold full potential here to provide context and user specific support (e.g. through digital expert systems or remote collaboration) in the planning phase or even more within the actual operation. These types of MR solutions aim at operational excellence, avoidance of unplanned errors, efficiency ramp up as well as the integration of new products and/or workers. Those objectives are of primary concern in those applications but there is certainly also an indirect influence on environmental sustainability. This includes the avoidance of quality rejects and related waste of energy and resources as well as keeping up the intended efficient performance of equipment. This is also true for the broad field of building construction and management. Nowadays, building information modelling (BIM) covers data from the whole building life cycle. Diverse MR approaches are available to use this data e.g. for ensuring correct execution of building construction or support of improvement measures [21]. With more focus on the production related equipment, similar MR solutions are available to support factory planning, e.g. through combination of planning data with actual factory environments [22]. Further development directions can be seen in the field of MR supported manufacturing quality control, e.g. to avoid and document quality errors with their spatial distribution in products [23]. Again, there is at least an indirect contribution to environmental sustainability.

However, there are also some MR approaches with more direct focus to energy, resource and emission flows in manufacturing systems. Some approaches deal with the MR based visualization of the energy demand of technical equipment. This ranges from first concepts for augmenting current energy demand values while looking at a certain machine [24] to more detailed breakdown into the spatial distribution of energy flows within machines in both AR or VR [25]. Other MR approaches take into account thermal emissions and their distribution in a (factory) building [26][27]. Typically a combination of measured data and CFD modelling is used here as base for the spatially related MR visualization. The spatial distribution of e.g. temperatures and airflows in a factory is interesting to ensure the required ambient conditions while avoiding unwanted over-dimensioning or control that lead to higher energy demand. This is even more relevant for potentially toxic gaseous emissions [28][29]. A specific role in context of MR and sustainability plays thermography. Thermography captures the surface temperature of objects based on infrared radiation and immediately displays that on screen with direct relation to the considered object [30]. But thermography can also be understood as MR since new data based insight is given through augmentation with the real world situation. It is actually very relevant from manufacturing and sustainability side: thermal imaging of e.g. buildings or machines is very established in manufacturing and beyond. It allows to identify unwanted heat sources or leakages and can make a significant contribution towards energy efficiency.

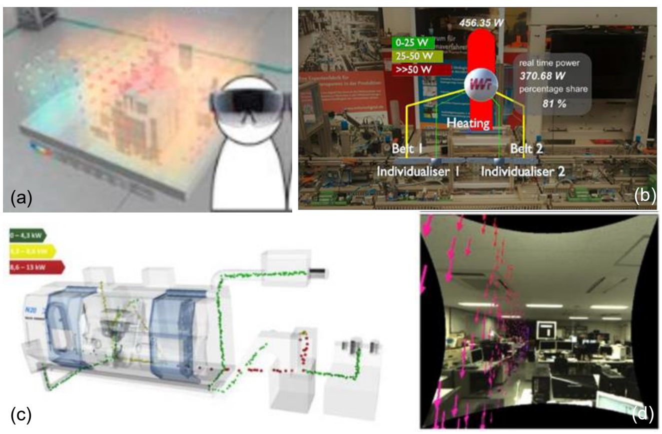

Figure 4: Exemplary MR solutions with link to energy and resource flows, a) thermal flows in factory [26] and d) in offices [27], b) spatial breakdown of energy demand [13] and c) energy flow visualisation for machine [25].

4. Towards MR supported SM

4.1. Observations and barriers

Based on the state of the art on sustainability related MR applications, several observations can be made. In general, quite some interesting MR based approaches are available in manufacturing context and beyond. Important fields of action like work instructions, maintenance support, quality management or training are addressed which certainly have at least an indirect influence on sustainability as well. Those examples underline what is possible with MR and show interesting directions for further improving decision support also towards environmental sustainability. While necessary data and partially even models in this context are often even available nowadays, current solutions have certainly not reached their full potential yet. Compared to other application fields, there are significantly less public available approaches with very direct link to energy demand, emissions and especially material demand in manufacturing. Additionally, those approaches tend to have a lower technology readiness level (TRL). Functionalities typically also just focus on the visualization of the current situation – there is limited consideration of potential improvement measures and future scenarios through predictive capabilities.

4.2. Design recommendations

While necessary data and general architectures are available nowadays, there are still barriers towards specific applications for industrial sustainability. Based on guiding principles for decision support systems and digital solutions, potential MR capabilities as well as identified barriers, some design recommendations can be derived [4][8]. In general, MR solutions should facilitate decision making while providing the right information (type and form) to the right user given the right timing and spatial context (Figure 5).

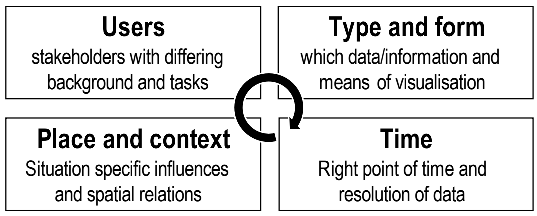

Figure 5: General fields of action of systematic MR design.

MR can provide different types of information (also related to Industry 4.0 maturity levels, [14]) to facilitate decision making. It can play an important to visualise relevant data closely connected to the specific context (e.g. in terms of the spatial situation and in timely manner). The combination of real and digital content in principle enables innovative, more intuitive and user centred ways of visualisation. With that, MR supports a better understanding towards what and why things are happening in manufacturing situations. Last but not least, MR also allows to directly incorporate future, predictive scenarios. Based on those opportunities and the identified state of current approaches, some design recommendations can be identified towards MR solutions for environmental sustainability:

1) Utilisation of **MR capabilities**: an added value should be created through using specific MR capabilities. For showing KPI values a screen-based dashboard (full virtual environment according to reality–virtuality continuum) is a valid and sufficient approach. Moving left along the reality–virtuality continuum leads to further capabilities in combination of physical and virtual contents. Promising examples could be the use of augmented visualisation of spatially distributed data (like distributions of energy flows or emissions) or virtual objects (e.g. placement of machines or piping, making invisible flows visible) on the real factory environment as well as the utilisation of sensory capabilities (e.g. spatial mapping).

2) **Influenceability**: MR solutions shall show aspects that can actually be influenced as result of the visualisation. Means for improving the situation and also the potential impact could be provided. Potentially, even an interaction can directly take place through the MR solution itself. However, this is case specific and careful design is necessary incorporating potential use case limitations (e.g. too narrow perspective through MR solution), technical boundary conditions (e.g. reliable, real time connection to machines) but also aspects like safety and security.
3) Definition of **relevant use case scope**: to ensure economic and environmental feasibility, a careful selection and definition of use cases is necessary. For the environmental sustainability this should explicitly include energy, material and/or emission flows. But it is crucial to address flows with high relevance so that sufficient added value can potentially be tapped through the MR solution. From the perspective of an implementation company (as owner of a MR solution), the continuity of potential improvements needs to be given in order to pay off continuing operational efforts. This is less critical with alternative business models, e.g. for companies that provide MR solutions as service for different customers.
4) Consideration of **future scenarios/alternative realities**: MR is connected to digital models based on up-to-date data. Promising solutions should also take into account the potential of the simulation of scenarios and visualisation of impacts in relation to the current real world situation.
5) **Synergies to other areas/multi-use of MR applications**: as pointed out before, numerous MR solutions are available that aim at diverse aspects in manufacturing. Solutions just dedicated to sustainability might not sufficiently pay off so interfaces and synergies to existing approaches should be utilized. There are e.g. strong links to production data (e.g. order tracking, throughput times, machine status) that is gathered anyway so integrated solutions are promising. But there are also synergies with areas like quality management, building management, cost calculations or occupational health and safety.

4.3. Considering effort and setup

As indicated above, ensuring the economic but also the environmental feasibility of MR solutions is an important point. Setting up a MR based decision support system requires efforts for set up and operation - in strong relation with the necessary and already existing ICT infrastructure. From an environmental perspective this involves the environmental backpack of all required components as well as the energy demand in operation. Obviously, the potential improvements triggered by the solution should be high enough to overcompensate those efforts. For assessing the necessary savings, feasibility diagrams as shown in Figure 6 can be used. The example (from [12]) illustrates the case of a dedicated continuous energy monitoring system: it consists of energy sensors, computer/server for data processing and visualization devices that are all just used for this application. The diagram gives an indication of minimum savings that should be achieved for an (environmental) breakeven in the addressed use case. In this case of a small machine workshop (approx. 50.000 kWh energy demand per year), 10-18% of energy need to be saved each year. Given the cost structure for energy and MR components this will even be more challenging from economic side. Obviously those considerations are highly case specific but underline the necessity of careful use case scoping. It is also important to take into that MR solutions are not isolated systems – in many cases, those solutions will actually built up on existing ICT infrastructures and make use of gathered data. In this context, MR is often an additional layer on existing architectures with few additional efforts so strong synergies in terms of the efforts can be used here.

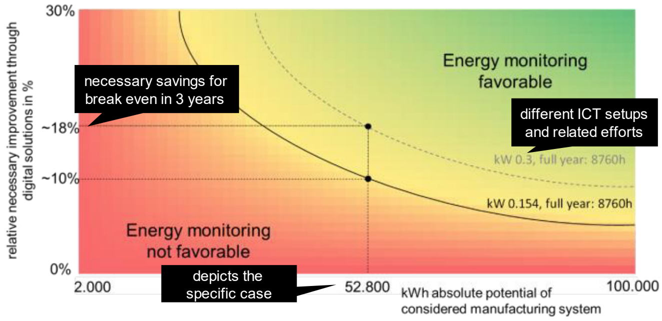

Figure 6: exemplary feasibility diagram for energy monitoring system [12].

4.4. Deriving promising MR application fields

As introduced, MR in general offers some promising potentials in context of sustainable manufacturing through providing more tangibility and transparency of energy, material and emission flows. But current solutions have certainly not reached their full potential yet and can profit from the design recommendations as introduced in section 4.2. Again it needs to be pointed out that data and necessary ICT infrastructures are often there nowadays, even MR solutions with focus on other objectives might be in place already. It is of highest interest to look for the synergies here and maybe extend/adapt current solutions towards sustainability. There are also interesting approaches outside of manufacturing which have interesting transfer potential, e.g. from the field of office or residential buildings. Scoping the specific MR use cases is a crucial point. Two general perspectives can be distinguished here: on the one hand, a MR solution can be developed by a manufacturing company for dedicated use in own facilities. Obviously, most promising application fields need to be identified and specific approaches will be established here. On the other hand, technology or consultancy companies could offer MR solutions with broader scope and high transferability. For this case, most urgent application fields from overall perspective need to be identified and transferable architectures and models are necessary. Looking at relevance of flows for environmental sustainability, current MR approaches as well as on the design recommendations reveals some interesting directions for further application fields. Two examples shall be introduced here:

Complex and dynamic energy flows
Input energy demand data of e.g. machines is often available nowadays and their visualization certainly relatively straight forward. While there are also some first examples available,

there is still improvement potential when it comes to the more complex perspective on energetical connections and distribution, conversion into other energy carriers as well as the related losses in a factory. This includes areas like process heating and cooling (e.g. waste heat), HVAC systems (e.g. distribution of heat, air flows, emissions) and compressed air (e.g. leakages) which are highly relevant for improving the sustainability [11][8]. The inherent complexity and spatial dimension as well as the invisibility of flows calls for MR solutions. Not all flows can be directly measured so digital models are necessary which also allow the simulation of alternative scenarios to give clear indications where and how to act. In terms of necessary background data and synergies to other applications (e.g. building management) are given.

Sustainability of material flows

There are few approaches in manufacturing yet with direct link to the environmental perspective of material flows. Since material efficiency has a major leverage on sustainability, aspects like the analysis of the embodied energy of materials or circularity options are of strong concern. Potential MR applications can profit from strong links to existing ERP and MES systems to gather the relevant background information and/or position of materials and orders. This could support on the shopfloor e.g. to find the right material/orders but also waste streams (maybe in connection with e.g. real time locating systems or image recognition), provide sustainability related information and decision support how to deal with that. Spatial analysis and visualization of products can also play an important in quality management and avoid quality rejects.

5. Summary and outlook

This paper addresses the question whether but even more how mixed reality approaches can improve the environmental sustainability of manufacturing. Various existing MR solutions with direct and indirect contribution were identified. Quite clearly MR is a topic of rising interest and further applications can built up and use synergies of existing architectures and solutions. However, still there is further research demand to more explicitly include environmentally related questions along energy, material and emission flows over all factory subsystems. The paper derives design recommendations that support the process of developing new or extended MR solutions. Based on that, some promising fields of action are introduced. Along those recommendations and in strong alignment with existing ICT solutions, next steps will focus on the development of new MR approaches. Important emphasis will be on the testing in industrial cases to ensure validity, practicability, feasibility and potential benefits.

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