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Exploring the potentials of mixed reality for life cycle engineering

Max Juraschek [a,*], Lennart Büth [a], Felipe Cerdas [a], Alexander Kaluza [a], Sebastian Thiede [a], Christoph Herrmann [a]

[a] Chair of Sustainable Manufacturing and Life Cycle Engineering, Insitute of Machine Tools and Production Technology (IWF), Technische Universität Braunschweig, Germany

* Corresponding author. Tel.: +49-531-391-8752; fax: +49-531-391-5842. *E-mail address:* m.juraschek@tu-braunschweig.de

Abstract

Mixed Reality (MR) applications are currently finding their way into productive industrial activities due to recent technological developments. Promising fields of professional utilization for MR are information visualization, education and training, human machine interfaces, design tools and collaboration. In Life Cycle Engineering (LCE) great amounts of data are required to be synthetized and interpreted in order to gain the required insights that lead to consistent environmental strategies. LCE tools and methods such as Life Cycle Assessment (LCA) can profit from modern technology and interfaces for visualization. The utilization of MR offers advantages in this context. Based on an analysis of the key capabilities of MR, possible application scenarios in LCE are identified such as contribution analysis, design processes, information visualization and communication. A conceptual approach is proposed for mapping the possible application for mixed reality applications.

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Keywords: Mixed Reality; Augmented Reality; Life Cycle Assessment; Life Cycle Engineering; Visualization

1. Introduction

Mixed Reality (MR) technology is increasingly reaching a state of productiveness in many applications. Augmented Reality (AR) and the majority of Virtual Reality (VR) applications are part of the MR market. The main fields of application of MR today are entertainment and gaming, education, engineering, military, healthcare and retail. A study from 2016 suggests that by the year 2025 VR and AR technology will be used for these applications by 315 million persons and the revenue generated with software for these technology will be as high as USD 35bn [1].

Life Cycle Engineering (LCE) makes use of large amounts of data. This data needs to be synthetized and interpreted in order to gain the required insights and to support the development of consistent environmental strategies. LCE has been recently redefined as the set of activities within the scope of a product life cycle(s) aiming for sustainability [2] and has to cope with complex interdependent systems. Therefore, methods and tools are required supporting the decision making process. LCE is seen as the link between product and process planning, engineering activities and the impact caused by the production and consumption of these products [2].

Life Cycle Assessment (LCA) and LCA-based approaches are one of the main methodologies supporting life cycle engineers with respect to environmental sustainability. LCA enables a quantitative assessment of energy and resource flows along the product life cycle. Its results enable effective LCE support [2]. The application of LCA-based LCE in industry currently faces two main challenges. First, its application depends to a great extent on analyzing this mentioned amount of data, the collection processes of which are uncertain and require high labor effort [3]. Second, the results of LCA studies are rather difficult to understand for professionals outside the LCA world [4]. These two issues overshadow the effective implementation of LCA for product development and generally

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in engineering activities. As data automation in manufacturing (and in society in general) matures and becomes increasingly utilized, data use for LCA is expected not only to increase in the future, but also to become available after shorter intervals of time. In this regard, new visualization technologies and innovative automated product-environment-society interfaces can help to make the application of LCE more efficient [5]. As an example, using MR for LCE may lead to achieving a better and wider understanding of the environmental issues of product systems at different stages of their life cycle. However, there is a lack of methods for assessing the potential of MR in LCE and selecting suitable technology for applications. In other fields of engineering such as maintenance, selection processes for the application of MR can already be found [6].

1.1. Goal and scope

There is a high application potential for the utilization of MR technology to support LCE tasks through the visualization and interpretation of LCA data. MR may support the adoption of a life cycle thinking culture that leads to a better understanding of effects caused by product systems. With an easier evaluation of impacts of product systems, this can lead to consistent and faster improvements.

This paper explores the potential formats in which MR can be effectively implemented in research and industry in the context of LCE. The goal is to generate an approach that allows to classify possible MR applications for LCE within the reality-virtuality continuum. Based on the identification of key capabilities of MR for LCE an overview of the potential for utilizing MR technology in LCE tasks is proposed. This overview is intended as a starting point and not yet to provide an application procedure, which is subject to future discussion and research. It is not within the scope of this paper to provide a comprehensive survey of MR technologies or applications (this has been accomplished, e.g. by [7]–[10]).

2. Mixed Reality –Technology and capabilities

To explore the potential applications for beneficial implementation of MR in LCE it is important to understand the technological capabilities. “Mixed Reality” (MR) is often used interchangeably with the term “augmented reality” (AR) although technically AR is only a part of MR. A comprehensive framework for the mixing of reality and virtuality is the reality-virtuality-continuum that is shown in Figure 1. In this framework real environments (reality) and virtual environments (virtuality) are put on each side of the two dimensional continuum [7]. Between these two extremes, reality and virtuality are combined in different degrees resulting in a mixed reality environment. If the share of real objects is higher than that of virtual objects in an application, it can be classified as augmented reality (AR). If the virtual objects are predominant, an application can be classified as an augmented virtuality (AV) application. Based on *Milgram* [7] the following definitions for real and virtual objects are applied in this study:

- Real objects have an actual objective existence
- Virtual objects exist in essence or effect, but not formally or actually

In LCE both real and virtual objects are usually considered, thus there might be a high application potential for the utilization of MR technology. Virtual elements in LCE have always been present. For instance, in LCE the use of scenarios is a common procedure to describe possible changes in a system’s subsystem. A common task is to try to answer “what if” questions in order to get a more complete picture of the different product or process design alternatives. For instance, in the hypothetical question of what could happen if the weight of a vehicle’s component was reduced through the application of a lighter material, this lighter component mostly does not exist or is still under development at a laboratory level. In addition, while real, environmental impacts most of the time have a virtual character, as its significance tends to be abstract in other professional and academic circles outside the group of LCA enthusiasts.

To define what characterizes an application as an MR application a definition originally designed for AR is used in the context of this paper. *Azuma* defined in 1997 the three characteristics of augmented reality (AR) [8]:

- AR combines real and virtual content
- AR is interactive in real time
- AR is registered in three dimensions

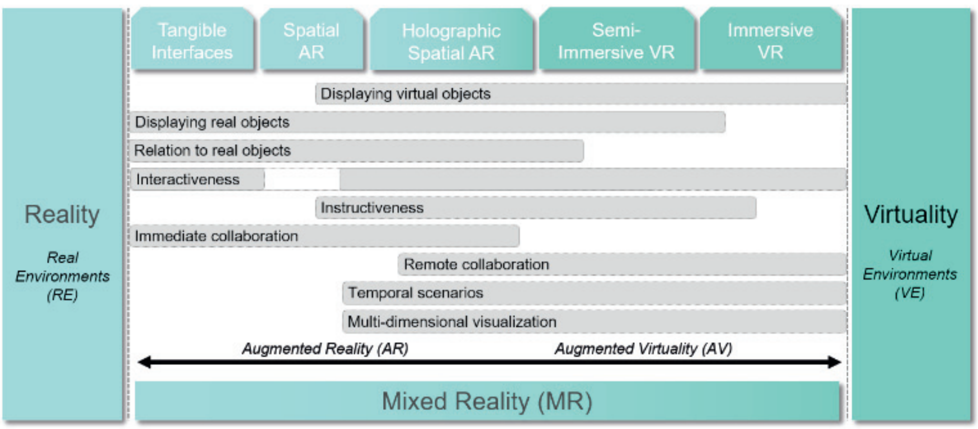

Fig. 1. The reality-virtuality continuum based on [7] mapping technological implementation concepts (top) and key mixed reality capabilities

These characteristics can also be applied to the whole reality-virtuality-continuum and thus define MR as well. In MR real objects and virtual objects can be found as defined in section 1. Real objects can be viewed either by direct observation or sampled, transferred into a digital model and resynthesized through a display device. Virtual objects do not exist in essence and thus cannot be directly observed but have to be simulated to create a viewable representation on a display device [11]. MR allows the interaction of real and virtual objects in the mixed reality environment. Different technological implementation concepts can be mapped on the reality-virtually-continuum. Tangible interfaces use physical objects to create virtual models. In Spatial AR, technology projects virtual objects into the user's environment, 2D and 3D projection mapping are examples. A higher degree of virtual immersion can be achieved with holographic spatial AR. More in the direction of the virtual side of the continuum, semi-immersive and immersive VR are located.

2.1. Identifying the key capabilities of MR utilization

To select meaningful MR applications in LCE, the key capabilities of MR need to be identified in the context of LCE. A summary and brief explanation of these identified main criteria is given in table 1. All these capabilities of MR have a different degree of occurrence along the continuum. This is illustrated in figure 1. Although several further capabilities of MR are present all along the continuum, only those are stated in detail that are relevant in the context of this paper. This provides the foundation for the relation of the MR capabilities to LCE tasks.

2.2. Examples of MR applications

There is a great number of very diverse MR applications that are in practical use in industry and education or have been demonstrated in the recent decades. To show the variety of applications, examples are given in this section, ranging from visualization of occluded parts to city planning with tangible interfaces.

- In car manufacturing the company Ford uses interactive see-through HMD to enable an independent and collaborative design process. The designer can change the outer appearance of a car making augmented drawings, a remote co-worker can later see them and comment [12].
- In the "CityScope" project, the augmentation of the results of a dynamic simulation is connected to the movement of physical objects. This tangible user interface is thus capable to interactively augment changes of city planning scenarios on a table [13].
- For the improvement of maintenance efficiency *Erkoyuncu* et al. developed a context aware AR environment, which

Table 1. Key capabilities of Mixed Reality for application in Life Cycle Engineering and their characteristics

Key capabilities of MR for LCE	Description and characteristics
Displaying virtual objects	Virtual objects require interfaces in order to be displayed and made visible for the human eye. Achieving convincing projections of virtual objects based on complex digital objects is very important for the immersion of the user. The physicality of the world surrounding us is based on three spatial dimensions. Thus for an immersive MR application three-dimensionality in displaying virtual objects is an important criterion.
Displaying real objects	Physical objects are displayed as they are in reality either directly or as a recreation. Directly displayed real objects are immediately visible for the human eye. This is the case e.g. for tangible interfaces. See-through head mounted devices (HMD) also allow to view real objects directly. Opaque HMD can have built-in cameras to enable displaying of real objects.
Relation to real objects	All along the continuum real and virtual objects are brought together. Digital data can be brought into relation to real objects and vice versa. This can be e.g. an augmentation of digital information on real objects or the use of real objects as input interfaces for the application. Data from physical objects is captured with sensors and transferred/utilized in the digital world, e.g. measurements and location. This is probably one of the most defining capabilities for MR applications and technologies, setting it apart from "solely" digital applications.
Interactiveness	It is possible for the user to interact with virtual and/or real objects as an interface for the application. Interacting with objects allows higher degrees of immersion and can support in gaining insights on hidden properties of real objects that are invisible to the human eye. To achieve a high degree of interactiveness an application is required to show a dynamic response to actions of the user in an adequate time period.
Instructiveness	A capability of MR applications is to convey information and skills with an instructive content. The dissemination can be fostered by combining real and virtual content to generate a personalized learning environment and lowering abstraction barriers.
Immediate collaboration	The capability for immediate collaboration on tasks with other persons depends on the ability to interact with each other. Eye contact, conversation and other forms of interaction, which can be obstructed by opaque HMD, support this.
Remote collaboration	Technical means need to be employed to enable the collaboration over distances that allow no direct interaction. One example is voice transmission or video conferencing. Both can be implemented as an integrated part of a MR experience. As the communication ways are based on a digital infrastructure, this is in most cases easier in virtual ways.
Temporal scenarios	Many tasks in engineering require the consideration of the temporal dimension. This is e.g. the case for the investigation of different scenarios or for understanding historical data. As time in the real world is a physical entity with a behavior that cannot be changed, the temporal dimension can be incorporated through virtual elements.
Multi-dimensional visualizations	Data visualization can be a very complex task especially when handling large datasets. For displaying a great amount of data, multidimensional presentations are often useful, illustrating interdependencies of parameters and values. The capability for multidimensionality is stronger on the virtual side of the continuum as is the case for data processing and interactive manipulation.

adapts to available data and the user's skill level. A novel authoring system was implemented that enables non-programmer maintenance technicians to change the content of the AR system to improve the efficiency of maintenance tasks on the shop floor [14].

- At Case Western Reserve University MR is used in training and education in the field of medicine. With an HMD, knowledge can be holographically imparted on internal body functions, thus lowering the barrier of abstraction from two-dimensional drawings [15].

3. The interpretation phase in Life Cycle Assessment

Independent from the focus of an LCE study (social, economic, environmental and/or technical), interpretation is an essential part as it structures the process that needs to be followed in order to gain insights for decision making. In accordance to the modern scope in LCE, we set the focus on the analysis of environmental issues. Nevertheless, the range of applications of MR technologies towards sustainability can in the same way support activities assessing economic and social aspects of technical systems. The ISO standards define the interpretation phase of LCA as the phase in which the results from the inventory and from the impact assessment are considered together [16]–[18]. Moreover, in the interpretation phase conclusions must be reached that help explaining limitations and providing recommendations [19]. The Life Cycle Assessment (LCA) methodology can be thought of as the bridge linking human-made technical systems (technosphere) and their inherent material and energy transactions to the different phenomena occurring in the biosphere's natural systems (biosphere). The interpretation phase in LCA plays two main roles in this [9]. On the one side, this phase aims at assessing the effect of the modelling choices and assumptions made in the goal and scope definition step. These are for example issues regarding the selection of a functional unit, the methodological choices made to set the system boundary of the product systems and the assumptions made in order to handle multi-functionality. On the other side, the interpretation phase is expected to give a proper structure to the large amount of information derived from the inventory and the impact assessment phases. This means that a proper interpretation analysis should contribute to understand how and in which manner all the material and energy flows generated to manufacture a product and its components lead to specific damages in the biosphere. In other words, the analysis in this phase shall describe thoroughly the product-emission-impact pathway.

One step in the interpretation phase of an LCA study that helps building these impact pathways is referred to as identification of significant issues. Its goal is to find all the systems parameters that have a significant influence on the impact assessment results. A selection of these parameters and the according tasks is shown in figure 2 (A-M). As noted, significant issues of interest show in both the technosphere and the biosphere. In the technosphere the parameters to be analyzed (A-G) aim at depicting how the specific aspects of a product system contribute to its environmental impact. For instance, in the technosphere it is important to understand which materials and components of a product system imply the highest environmental concern and how a particular local or regional context affects this result. A practical example this could be in which way a specific local electricity mix used to power a manufacturing process affects the environmental impact potential of that process and of the product system.

In the biosphere, in turn, significant issues to look after (H-M) are essentially those delivering information which impact categories dominate the total impact of a product system, what are the elementary flows driving those impacts and what are further regional and temporal influences (e.g. through application of spatially differentiated characterization factors). All the data gathered from the analysis of significant issues not only presents a particular structure, but will also have specific re-structuring requirements in order to be visualized in a particular manner. The interpretation phase in LCE consists not only of data visualization though. For an applicable interpretation, interaction with the data needs to be possible enabling the investigation of scenarios. Further information interpretation guidelines can be imparted in this phase. Collaboration with other LCA experts and non-experts can also be very significant for the implementation of measures and suitable decisions.

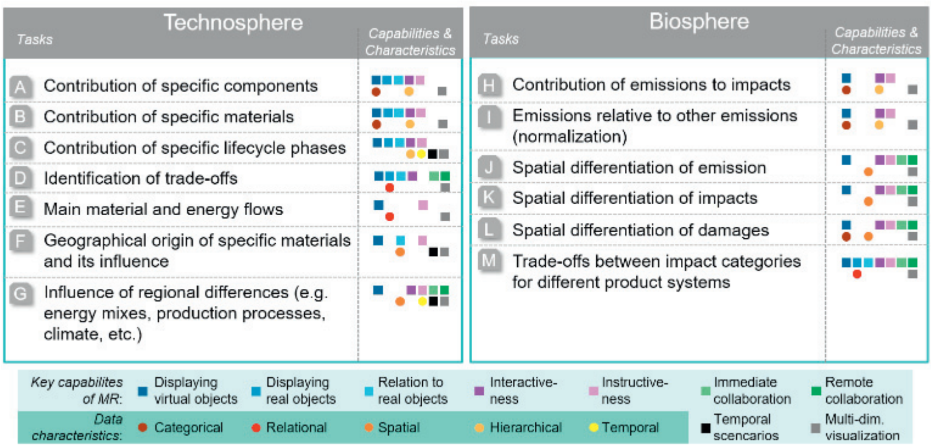

Fig. 2. Selected tasks in LCA interpretation phase and the corresponding key capabilities of mixed reality and underlying data characteristics

4. Exploring the potentials of mixed reality for life cycle engineering

In order to identify the potential of MR for LCE and suitable applications, key capabilities of MR and the characteristics of the underlying data are mapped to selected tasks in LCA interpretation phase as shown in figure 2, as this phase seems to have the highest potential for MR application.

4.1. Mapping capabilities and characteristics to LCA tasks

The allocation of MR capabilities and data characteristics to each task is indicated in figure 2 by color-coded squares (capabilities) and circles (characteristics) next to each task. As described in section 3, one goal of the interpretation phase of LCA is the visualization and investigation of system parameters in the technosphere and biosphere. Thus, all tasks involve to some extent the visualization of multi-dimensional datasets. Due to the nature of LCA, connecting a foreground system to a spatial and functional larger background system, virtual objects and their display are part of all tasks as well. A need for instructiveness can also be found for almost all selected tasks as imparting knowledge and information is one of the main goals of the LCA interpretation phase.

For the tasks related to the technosphere (A-G) in nearly all cases a relation to real objects (e.g. the product system) and its components can be found. This is in close connection to displaying real objects and interactiveness, which are capabilities of MR that can be potentially beneficial in more than half of the technosphere related tasks. Looking at the biosphere (H-M) again, a focus lies on interactiveness, but is here closely connected to interaction with virtual rather than real objects. The impacts on the biosphere and the underlying mechanisms are of an elusive nature for human perception. Thus, a relation to real objects in spatial proximity is in most cases not sensible. Collaboration for assessing the impacts, giving decision support and communicating results is accordingly more difficult so that MR capabilities can potentially support the user in these applications. For the data characteristics, a many-faceted picture evolves. MR applications with the ability to visualize multi-dimensional datasets in an interactive way can support to cope with the different data characteristics in all tasks.

4.2. Exploring the potential of MR for LCE

In order to understand the potential applications of MR, the selected tasks in LCA are located in the reality-virtuality continuum (see figure 3) according to the mapping of the key capabilities of MR to the same continuum (figure 1). This results in an allocation of the activities to their potential degree of virtuality and reality depending on the identified requirements. Each task is represented by a bar stretching along the horizontal axis covering the section of the reality-virtuality continuum in which the task can be beneficially implemented. Further, the potential of MR for the activities is displayed along the vertical axis. The higher up an activity is shown the more potential is seen in utilizing MR applications to improve and support the execution of it. The rating was allocated in accordance with the key capabilities of MR implementation concepts and taking into account the complexity of the task, current and near-future available MR technology as well as experience from existing application examples of MR. Examples are given in the following list how to read figure 3:

- For the assessment of the contribution of specific components of the product system (task A) a high potential for MR application is predicted. The optimal allocation in the continuum suggests an implementation with significant shares of both real and virtual objects. Possible MR technology for implementation ranges from spatial AR and holographic spatial AR to Semi-Immersive VR. Also minor potential is seen for Tangible Interfaces and Immersive VR.
- A low potential of MR application for the task of analyzing the contribution of emissions to impacts (task H) is predicted. With this task having no requirement of relation to real objects, it is allocated on the virtual side of the continuum and implementation in Immersive and Semi-Immersive VR is suggested. Holographic Spatial AR is a possible MR technology for this task as well.

In general, the tasks allocated to the biosphere can be found rather on the virtuality side of the continuum, whereas tasks in the technosphere also reach onto the reality side. The technosphere is stronger linked to the product system with real objects and components. This opens the possibility to integrate the real objects in the interpretation phase. There is a high

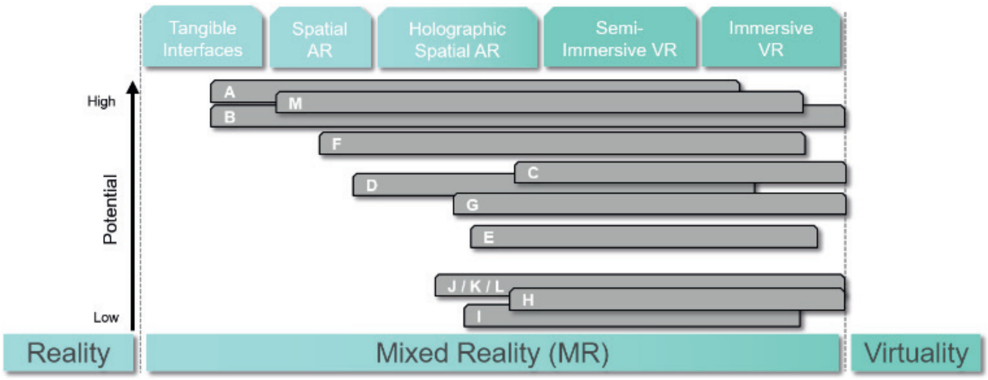

Fig. 3. Map of the potential of mixed reality applications for selected tasks in LCA interpretation phase (A-M, see fig. 2) along the reality-virtuality continuum

potential for MR to support the interpretation of contributions of specific materials and components in a product system. A link to the physical product system (if existing) can also be made with mixed reality by incorporating it as real objects displayed together with the data analysis.

A high potential for tasks involving immediate or remote collaboration with LCE experts and non-experts is further identified. Examples are the identification of trade-offs between different product systems (M), involving also the virtuality of scenario data together with the reality of product systems. The same applies to trade-offs in the technosphere (D), although here collaboration is more limited to experts of the same or neighboring fields. Rather low MR potential is predicted for the spatial differentiation of emissions/impacts and damages (J, K, L), the contribution of emissions to impacts (H) and their normalization (I). These tasks are seemingly better qualified for implementation in virtual environments, but if combined with a collaborative approach also these tasks might benefit from an MR implementation. Overall, MR is predicted to bear a high potential for the application of LCE in industry to overcome the two main challenges of data visualization and information communication. But not all activities of LCA have the same potential and attention needs to be paid to the MR technology and implementation concept used for each specific task.

5. Summary and outlook

Mixed reality applications already surround us in everyday life. With new technology currently filling the middle part of the reality-virtuality continuum, the professional use of MR reaches a state of productiveness. The potential of MR applications for LCE is recognizable and for some applications a very high potential benefit of employing MR technology in LCA can be predicted. The reality-virtuality continuum can serve as a framework for allocating the tasks of LCA to suitable implementation concepts and technology. It can be summarized that LCA tasks related to the technosphere should rely on an MR implementation approach that integrates real objects and their properties. For tasks related to the biosphere a tendency to the virtual side of the continuum is noticeable due to the vast spatial scope involved.

Not only MR technology is currently experiencing rapid development, fostering the implementation potential for all industrial applications. The workflow for creating MR application is becoming easier to follow. Today, development environments originating from the gaming industry are widely used to create MR experiences. At the same time data driven methodologies are being increasingly introduced to LCE. As efficient algorithms will be even more at the center of attention the dependency of result quality on the data input will be of major importance. MR can play a significant role in reaching and communicating LCA results and might bridge the gap between LCA experts and non-experts. For the concepts of data driven LCA and live LCA, applications in MR can be the tools to interact intuitively with the resulting complex data. In a future scenario, almost only background data for materials and process models could be required to conduct LCA for specific products in near real-time, controlled and visualized in Mixed Reality. The presented approach should serve as a starting point for future development of application procedures.

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