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Application of Virtual Reality Technologies for Achieving Energy Efficient Manufacturing: Literature Analysis and Findings

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Abstract. Improvement in current manufacturing settings for enabling energy efficiency is a challenge for many manufacturers. Although virtual reality has been so far applied in manufacturing for training, visualization and product development, the use of this technology in manufacturing for increasing energy efficiency has been less addressed. This paper investigates the potential of virtual reality for a better analysis of energy demands in manufacturing. By envisioning and illustrating energy flows and consumption, virtual reality can support energy efficiency. The paper provides a systematic review of the literature. The findings are analysed from the perspective of research gaps in making virtual-based technologies to enable energy-efficient manufacturing. Particularly, the elements and factors (opportunities) and methods that can be transmitted from current research to energy-efficient manufacturing, are identified and discussed.

Keywords: Manufacturing · Energy efficiency · Virtual Reality

1 Introduction

Today's manufacturing is one of the world's biggest consumer of energy. By 2030 a target of 32.5% energy savings has been endorsed through negotiations between the European Commission and Parliament [6]. Consequently, European manufacturers face today the challenge of reducing energy consumption while maintaining quality and productivity. Besides, advances of Industry 4.0 provide new opportunities to better measure energy, understand its patterns or mechanisms and improve manufacturing operations concerning energy. Determining and understanding energy consumption at each stage of manufacturing is crucial for enabling energy efficiency. Though improvements in energy efficiency (EE) have been made across all branches of manufacturing, significant potential still exists [5].

One technology of Industry 4.0 that can further contribute to the efficient consumption of energy is virtual reality (VR). In general, VR makes it possible for users to step into a three-dimensional (3D) illustration of a real-world environment, through a computer interface [13]. VR-solutions pose good potential for saving energy in manufacturing industries. Since they can add a layer of energy information to the machinery and equipment. Areas of research, such as smart buildings and facility management, have managed earlier than manufacturers to adapt VR to the energy analysis. For example, authors including [9] provided a VR-tool for the modeling and analysis of energy as well as its 3D-visualization within buildings.

The findings on VR-solutions from the area of smart buildings can be transferred into the manufacturing industries, i.e., analyzing the higher energy consumers on the shop floor of a manufacturing plant. Inspired by this possibility, this research seeks to identify the components (elements) of manufacturing, such as machinery and processes, other than buildings, which affect the energy consumption in manufacturing. In addition, factors and opportunities to include in the energy modeling with VR are noted. Knowing the available methods is also important for developing VR-solutions about energy. To the best authors' knowledge, engineering tools for the design and development of VR-applications in energy-efficient manufacturing (EEM) are not published or reported yet. Further, results of surveys as [4, 2] suggest that only a few studies have tackled VR-technologies for achieving efficiency in terms of energy consumption. Consequently, practical studies related to EE on VR from the current research need to be identified; so that meaningful insight can be leveraged.

This paper provides an overall analysis of the potential of VR into EEM, whereby it answers the following research questions (RQ) through a review of state-of-the-art:

- RQ1. Which factors and elements should be considered for the transmission of currently available research to apply VR for increasing EE in manufacturing?
- RQ2. What are the methods available in the literature to apply VR in EEM?

The paper is structured as follows: Section 2 presents the literature search methodology. Section 3 reveals and discusses the results of the literature review. Section 4 reports the findings in terms of research gaps as well as the knowledge acquired after the analysis of studies. Here limitations of VR are also presented. In section 5, conclusions are drawn.

2 Methodology based on Systematic Review of Literature

For the literature review, a methodology called PRISMA [16] is adopted. Two leading online databases, Scopus and Google Scholar, are selected. While Scopus provided papers with a good scientific contribution, Google Scholar is used as a complementary search tool to find articles from a more practical point of view. As Fig. 1 shows, three sets of keywords are searched. The period considered is 2004-

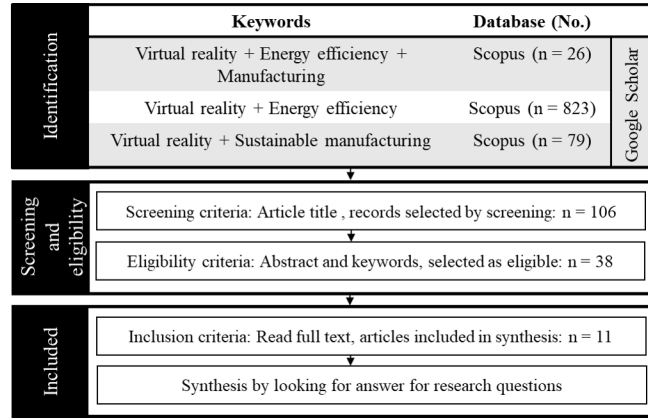


Fig. 1. Methodology for literature review

2020. The first search criteria lead to around 928 articles. The identified papers were screened through reading the title and 106 papers are selected. The excluded papers primarily addressed VR in, i.e., reconfigurable manufacturing systems and sustainable engineering education. These trends within manufacturing are not the focus of this paper. Afterward, abstracts and keywords of 106 papers were justified. The result was a selection of 38 eligible papers for this study. These papers were read in full-text and later, 11 papers were selected for answering the above research questions.

3 Results and Discussion

The results of the literature review are recapitulated in Table 1 and Table 2. The answers to RQ1 are provided in the Table 1. In order to understand the elements and factors, column "(Level) Elements" investigates to what extent state-of-art of VR is linked to which elements of the manufacturing level(s). The considered manufacturing levels in this paper are operational and tactical. Therefore, the first column of Table 1 assesses the area of application within manufacturing. Next, the column "Opportunities to EEM" shows the results of identified factors related to energy efficiency. This column also assesses the focus of the studies on different aspects of EEM.

In contrast, Table 2 assesses, which environment(s) the research has been validated on (case studies). The review of case studies reveals manufacturers the feasibility and potential of VR-applications in particular environments and it indicates similarities (or not) for possible transfers into new practical studies. For the RQ2, the last column of Table 2 presents methods and tools for implementing VR. Furthermore, the next two sub-sections analyse the contents of Table 1 and Table 2 concerning VR for EEM. In section 3.1, the analysis of Table 1 respecting to RQ1 is presented. Section 3.2 provides a discussion about Table 2 for RQ2.

3.1 Elements and Factors in Current Research to Apply VR for Increasing EE in Manufacturing

Table 1 shows that the gathered studies of VR mainly focus on the operational level. Among the results of Table 1, 8 of 10 selected papers address VR in EEM for the operational layer of manufacturing. The elements of the operational level are process, machine, line and facility. The classification of these elements can be considered valid, as many approaches within EEM, such as the study of [7], divide the analysis of energy into the same set of elements. Also, the analysis of Table 1 shows that the current research has addressed these elements individually. That is, there is still no research, which examines the flows of energy between the elements of manufacturing, especially during operation. Therefore, developing a model of processes-machines-lines and their interdependencies in a manufacturing facility can better evaluate energy demands.

Table 1. Results of the literature review for RQ1

Ref.	(Level) Elements	Opportunities to EEM
[1]	Process, Machine, Line at design phase	Integration of EE-KPIs into expert systems (transparency, decision-making)
[3]	Management	Sustainable KPIs in game-fuction (adv./disadv., understanding, impacts)
[15]	Machine	Energy-flow techniques for visualization (causes, awareness)
[11]	Line	In-process virtual management of energy, workflow, and quality error
[8]	Facility	Spatio-temporal energy model(X-time series, y-consumption devices, z-energy consumption)
[12]	Process, machine	Machine and product design to EE (awareness, transparency)
[10]	Process, facility	Augmentation of energy flows demands (process states, maintenance, instructiveness)
[17]	Management	KPIs as integrative energy management
[18]	Line	Visual interface for asset information
[14]	Facility	Immersive thermal simulation in virtual environment

Other findings from the Table 1 shows that the majority of the research concentrates on the transparency of energy performances. As energy is not visible to the human eye, which complicates the impairment of energy efficiency. Therefore, the availability and visualization of energy data and information of energy assets, for example, in the form of sustainable key performance indicators (KPIs) or flows increase awareness about demands and support its efficiency [1, 15, 18, 17, 10, 12]. Nevertheless, energy demands in real applications are influenced by complex settings, such as the effects of different process parameters, workflows and quality requirements. But energy flows and energy consumers considering multiple configurations of parameters are almost absent in the literature (Table 1).

In [14, 15, 8, 12, 10], computer-aided design (CAD) models are used for the interactive examination and manipulation of VR-applications. However, most geometries on VR are not reflecting the real dimensions of, i.e., a certain machine. So, it makes the energy model inaccurate. Moreover, visualizations of many

energy flows in one component or many components in one visualization such as [14, 15, 8] in Table 1 can become unclear to the observer.

Besides, energy demands in [15] were assumed to be constant, whereas the energy losses of, i.e., a cooling system, were neglected. Furthermore, the EE-KPIs defined in [1, 3] do not account for the fluctuation of the process times and/or cycle times. Both process time and cycle time influence the energy consumption of a particular line at the production phase. Thus, energy performances can become misleading when time-series factors are not taken into account.

Lastly, from Table 1, an estimation about the potential of the energy savings through VR-solutions is neither visualized nor (at least) quantified. Despite the fact that evaluative information about the savings (actual and ideal energy demand) may raise awareness among manufacturing practitioners. In this context, a VR-based solution can assist in determining the energy costs of a process or machine with a particular set of parameters and predefined quality.

3.2 Methods of VR for Enhancing EEM

Firstly, simulation and CAD modeling are the most common methods listed in Table 2. The VR-tools in Table 2 were mainly selected concerning to the case studies. As an example, VueOne is an engineering software environment, which supports the assembly. It is selected by [1], respecting the case study of the battery assembly.

About the methods that are specifically designed for the analysis of EE in manufacturing, there are only a few works available (Table 2). For machines, the technique of particle system on VR allowed the visualization of dynamic changes in energy flows over time [8]. In the particle system, the direction of energy flows is also highlighted. In [11], a 3D-regression method evaluated the correlations of workflow, consumption of energy and quality error. However, evaluation of other potential factors affecting energy demands as settings of process variables were not included.

Secondly, a tendency in Table 2 exists to base VR on point-cloud models and particle systems when it comes to virtual buildings [18, 8]. These methods can be combined with the use of drones and photogrammetry for quicker creation of 3D-models on VR. This approach from smart buildings is also applicable and rentable in manufacturing when it comes to elements such as lines and building of a factory.

Thirdly, the literature analysis showed that the majority of the VR-methods in Table 2 are developed from a theoretical point of view. Then, their performances are validated in specific case studies and experiments [1, 3, 18]. Hence, there is a need for contributions from a more practical point of view, which addresses the real-world application of VR in EEM.

Lastly, in the context of manufacturing, VR-technologies constitute augmented reality (AR), mixed reality (MR or XR) and virtual manufacturing (VM) [13, 12]. According to [12], AR is VR placed over the real world, but with the provision of additional information. Thus, the authors of [12] infer that AR can be seen as a subset of VR. MR encompasses both virtual and AR technologies.

Moreover, VM is a term represented as a virtual world for manufacturing. This paper addressed all these mentioned VR-technologies.

Table 2. Results of the literature review for RQ2

Ref.	Case Study	Method(s) : Tool(s) of VR
[1]	Battery module assembly	Discrete event simulation tools: VueOne, Witness DES
[3]	Serious-games learning env.	Virtual twins
[15]	Turning, milling	3D-Sankey, Billboard and 3D-Particle methods: CAD
[11]	Shop-floor	3D-Virtual simulation
[8]	None	VR with immersive visual data mining: 3D-CAVE, CAD
[12]	None	Discrete event simulation and 3D-particle methods:CAD
[10]	Galvanic and oven process modules	Holographic augmentation, interactive visualization: CAD
[18]	Railway maintenance	4D reality, point-cloud methods
[2]	Human operators, packaging, interior tractor	3D-Visualisation suite: RTT DELtaGen, Siemens Jack, Autodesk VRED, ESI ICIDO

4 Findings

From the previous section, it can be drawn that VR in EEM has been mostly used to reduce the time required to collate and understand energy information. An energy model for the context of manufacturing should consist of many elements such as machinery, production line, facility, processes and interdependence of energy demand from them. More detail about the essential factors in the application of VR for EEM, namely, transparency of energy flows, assessing energy demands and energy losses, process parameters affecting energy demands are discussed in section 3.1. The highlighted opportunities to EEM on VR have a high degree of flexibility. They are quickly adaptable, as they are not bounded by physical hardware. This allows to experience different settings and/or scenarios of higher energy consumers that are, in reality, too costly or not available in hardware.

Further, our observations show that a tendency exists in the literature to research VR-technologies related to time and costs, quality and reduction of design errors. However, the different settings of parameters influence the results in the form of energy but also in the form of emissions and wastes of processes, e.g., in a milling process. Wastes and emissions are difficult to integrate on VR and hence their embodied energy can not be quantified. To our understanding, it is also a matter of what designers (users) can do from a VR-technology standpoint but also how human actions in the virtual environment influence decision making.

Additionally, best practices and benchmarks of energy efficiency in manufacturing on VR-solutions are still not published. Probably, as a consequence of the ambiguity of the cause-effect relationships in the manufacturing processes.

Limitations of VR in EEM. Although the VR's advantage in reproducing a controllable environment is desirable for application in EEM, there are some limitations too. (1) Costs of establishing a VR-based system is rather high.

Before designing a VR-based system for EEM, the long-term benefits of this technology, in terms of savings, should be calculated against its costs. (2) Multi-sensor illustration of energy flows. It is challenging to split several energy flows and illustrate them in a virtual environment. There can be overlaps between the illustrations of energy. This point can confuse the observers or bring errors in energy analysis. (3) The danger of continual use for the health of employees. On the one hand, the currently available head mount glasses for VR and MR are heavy. The weight is because of battery or processing appliances. Therefore, they might cause problems such as neck pain for the employee if they are used for a long time. On the other hand, they are placed over the eyes. Too much use can cause eye-sight problems.

5 Conclusions

Our research provides a literature review on 11 papers about VR-technologies for enhancing energy efficiency in the manufacturing domain. Opportunities and tools of VR for the context of EEM were presented and discussed extensively in sections 3 and 4. The results of the analysis admit that using VR on EEM can improve knowledge about energy consumption in manufacturing environments. Future studies may transfer, combine and adjust the analysed methods (Section 3.2) of VR for further exploring its opportunities in EEM (Section 3.1 and 4). As the deployment of VR-technologies and its usability demands considerable energy at a cost to manufacturing too.

Beyond the scope of this paper, several types of research tackle the connection of digital twins to VR for establishing digital factories of the future. However, they do not discuss VR in energy analysis about efficiency, considering a whole factory. Therefore, there is a need for future research of EEM on VR, not only as a stand-alone solution but also as a multi-level holistic approach.

It should be noted that in this paper, because of limitation in space, only the results of the analysis for 11 selected papers that has the most relevancy to the research questions, have been published. Analysis of all 38 eligible papers from the perspective of EEM will later be provided in the special issue.

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