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Applicability of 3D-factory simulation software for computer-aided participatory design for industrial workplaces and processes

Luigi Pelliccia*, Michael Bojko, Riccardo Prielipp, Ralph Riedel

Department of Factory Planning and Factory Management, Chemnitz University of Technology, Chemnitz, Germany

* Corresponding author. Tel.: +49 (0) 371 531-33949; fax: +49 (0)371 531-833949. *E-mail address:* luigi.pelliccia@mb.tu-chemnitz.de

Abstract

Industry 4.0 is transforming the way the design process is conceived. Digital technologies allow simulating complex systems, in instances such as human-robot-collaboration (HRC), implementing changes in a time- and cost-effective manner. However, these technologies do not yet fit participatory design requirements. Consequently, they do not yet allow to effectively conduct computer-aided participatory design workshops. This article addresses the applicability of state-of-the-art 3D factory simulation software to computer-aided participatory design sessions for developing industrial workplaces and processes. The study's outcomes define the fundamental requirements, and outline the necessity for further developments, for a software tool aimed at effectively conducting computer-aided participatory design.

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Keywords: Computer-aided Participatory Design; Factory simulation; Human-robot collaboration

1. Introduction

Engineers usually work independently or in specialized teams when designing factories, workplaces and processes, or when optimizing existing ones. This also accounts for designing scenarios involving Human-Robot Cooperation (HRC). Hence, expertise from other domains, experts, and workers is often not taken into account in the early stages of the development process [1]. This often results in solutions that do not fully meet the requirements in the first attempt and modifications must be implemented e.g. during start-up or operation. This makes the design process time-consuming and costly and can lead to frustration of the affected workers.

Furthermore, industrial engineers, who are in charge of conception, design and implementation, rarely have extensive personal experience in the practical utilization of the workplaces and processes they design due to their role and job description. For this reason, including expertise from multiple domains and sources, results in improved solutions that better fit the requirements of the actual users, as well as other relevant stakeholders, such as safety officers and maintenance staff [2]. In particular, workers' skills and expertise can be of great importance during the design of an HRC workplace or a work process, as they are the end-users, and can provide valuable insight that can lead to an increased acceptance of the final solutions. This also results in a more effective and efficient design process with reduced needs for redesign and optimization. For this reason, to reduce sources of errors and to provide more preferable solutions to the workers, involving additional stakeholders in design processes is getting more important.

A well-known design approach aiming at involving all relevant stakeholders as active contributors into the design process is known as Participatory Design (PD) or also Co-Design [3]. Using PD, the expertise of different persons and/or groups, such as factory workers, management and external engineers, whom all have a different set of skills, competencies and backgrounds, can alike contribute to the design results as well as assess the final solutions, ensuring the result meets the specified and actual needs and is effectively usable [4,5]. Furthermore, a great deal of research shows that designers create more innovative concepts when working within a co-

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design environment than they do on their own [6,7]. Nowadays PD is used in a variety of fields, such as software design, architecture, and product design, but still rarely in HRC workplace and process design, mainly due to a lack of software tools capable of effectively supporting the PD concept and process. This article presents a study aimed at assessing the applicability of state-of-the-art 3D factory design and simulation software for PD.

2. State of the art

Design of HRC workplaces and work processes using 3D modelling and simulation software, i.e. computer-aided design (CAD) and simulation, is nowadays state of the art in most companies, especially in medium to large-sized companies of the automotive sector. CAD and simulation tools allow implementing design changes easily, in a time- and cost-effective manner, and at an early stage of development. Modelling and simulation are part of the methods that have been transforming industrial design and production processes for a long time, allowing to run experiments with virtual models even before the first physical prototype is available. With the arising of Industry 4.0, digitalization, modelling and simulation are spreading to most industries and are introduced to Small and Medium-sized Enterprises (SMEs) as well [8–10].

New digital technologies, such as Virtual Reality (VR) and Augmented Reality (AR), are transforming the way the design process is conceived. They allow reviewing and discussing designs and changes virtually in a 3D setup, at an early stage in a time- and cost-effective manner. Recently developed VR and AR tools are more user-friendly than in the past, allowing users to interact with the models also without extensive technical knowledge. Thus, also end-users can evaluate the production system performance and can provide their feedback. Consequently, simulation and VR seem to be valid tools to support PD as they facilitate collaboration as well as knowledge exchange among designers and users [11]. Nowadays a broad variety of software is available on the market, which allows achieving highly detailed simulation. We decided to focus on Visual Components (VC) Premium [12] and Siemens Tecnomatix Plant Simulation (PS) [13], as they represent state of the art 3D factory simulation software and are internationally well known.

PS is a discrete-event factory simulation software that allows 2D/3D-modelling and simulation of highly complex production systems. It can be used to evaluate and optimize material flow, resource utilization and logistics chains. The object-oriented, hierarchical models form the basis for the analysis of throughput, resource utilization and bottlenecks. As discrete event simulation software the resulting simulations are faster than continuous simulation software, even if they provide more approximate solutions [14].

VC, on the contrary, is a 3D factory simulation software based on a continuous simulation engine developed by Visual Components Oy (a subsidiary of the KUKA Group). VC provides a wide range of functionalities to simulate industrial processes and workflows, including offline robot programming, and to assess their performances (e.g. statistics). VC also provides an advanced Graphical User Interface (GUI) and a comprehensive library of predefined components and machines, with a very detailed 3D representation. VC provides also the possibility of running python scripts via API. However, as continuous simulation software, simulations take normally longer compared to discrete-event software such as PS [14]. Alternatively, a dummy process can be utilized, excluding animations and focusing only on the processing time, allowing a faster simulation. Both software tools provide interfaces for VR functionalities. PS relies on the 3rd party extension moreViz, developed by the Siemens PLM Solution Partner more3D, to enable the connection of VR systems, which allows a deeper immersion into the 3D scene [15]. VC provides the software extension VC Experience that allows the simulation to be used with VR systems, such as HTC VIVE, enabling a high degree of immersion in the 3D scene [16]. The scene also can be visualized simultaneously on an external monitor, allowing even a numerous audience to visualize the 3D model and exchanging feedback in real-time.

3. Methods

To provide a realistic scenario to assess the applicability of VC and PS as effective tools for computer-aided PD, two workshops aimed at optimizing the layout of a real production process were conducted, using one software for each workshop, at the Experimental and Digital Factory (EDF), an industrial-near and factory-like laboratory with a functional production system, at the Department of Factory Planning and Factory Management of the Chemnitz University of Technology (TUC). The 3D simulation models were prepared by an expert before each workshop.

The workshops focused on monitoring and assessing parameters related to four categories, such as *features*, *final matching grade*, *task concentration*, and *usability*, for each tool. *Features* gathers aspects related to object library, model building, programming flexibility, evaluating the overall functionality of the software. *Final matching grade* refers to the matching of the final model with the proposed idea(s). If the match is good, then the software has well satisfied the users' expectations with regards to the process to be optimized. *Task concentration* refers to the level of concentration that participants exhibit during the workshop. A high level of concentration helps in finding effective solutions and fostering communication among participants. This means the platform and the design task are engaging and the participants are motivated. *Usability* is directly related to the ease of use and the ease of learning of the tool. Modifications requested by the participants during the workshops were then implemented ad hoc into the simulation models and subsequently have been assessed by the participants by running the simulation and evaluating the results (statistics). At the end of each workshop session, a questionnaire has been provided to the participants to collect their feedback and assess their experience with the software and the computer-aided PD workshop.

To evaluate the aforementioned parameters for each software, participants were asked to fill in a questionnaire to better understand their perceptions and to gather new proposals. Some of the questions for each parameter were, for instance:

Features

- How do you evaluate the software in terms of object-control (move, rotate, resize, drag & drop, interact, delete, etc.)?
- How do you evaluate the software in terms of overall capability and functionality?

Final matching

- How much does the simulated model match the proposed idea(s)?
- How much does the simulated model match the real process?

Task concentration

- How much does simulation software help for improving communication in the working group?

Usability

- How do you evaluate the ease of use of the tool?
- How do you evaluate the ease of learning?
- How do you evaluate the model building in terms of logical aspects (coding, time settings, routing and queuing rules, …)?

A 5-point Likert-type scale was associated to each question, ranging from 1 meaning “not at all” to 5 meaning “very much”. The arithmetic mean was calculated for each parameter to score each software. To take the differing importance of the categories into account, the weight of each category was determined by pairwise comparison.

4. Setup

As workshop scenario, the optimization of an additive part production process was introduced. The initial process and layout configuration included two type-A 3D printers and two type-B 3D printers (Ultimaker 2 Go units), two milling stations (Stepcraft D.420 and D.840 units), an inspection machine (Stepcraft D.420), and a manual assembly table that received parts through an automated line. Pick-and-place and set-up tasks were performed by three human operators. The task and process parameters were initially set as follows:

- 3D Printer A:
  Processing time = 5 min
  Set-up time = 10 s
  Batch size = 20 parts

- 3D Printer B:
  Processing time = 4 min
  Set-up time = 15 s
  Batch size: 10 parts

- Milling Machine
Processing time = 1 min

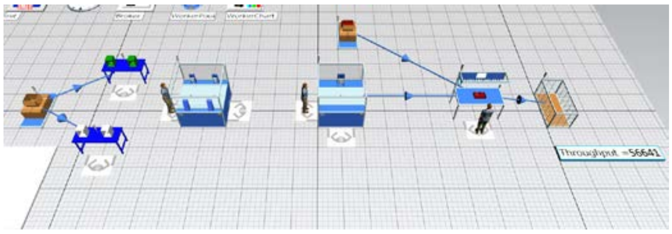

Fig. 1. Production layout modelled in Plant Simulation 15.1.

- Inspection Machine
  Processing time = 90 s

- Assembly Station
  Processing time = 20 s
  Batch size = 6 products

Workshop participants amounted to 10 and were selected among professors, researchers, student assistants and students from the TUC having different background and skills. Two workshops were conducted with five participants each, using one software for each workshop. Most participants had above-average computer experience, although only 20% of them admitted having 3D modelling experience. They were seated around a conference table. Pen and paper were not allowed. A moderator and a simulation expert were participating to ensure the discussion flowed smoothly and to support at utilizing the tools, if necessary. The time scheduled for each workshop was about 1.5 hours. Minutes of the workshops were also written by an observer, who was previously instructed in the aspects that required particular attention. The software tools PS 15.1 and VC Premium 4.1 were provided on a laptop (6th Gen Intel i5, 8GB RAM) linked with an external monitor, allowing the whole audience to visualize the 3D model and simultaneously discuss with each other about the design.

The layout of the processes and the workplaces to be optimized have been presented to the audience using both software tools. Figure 1 shows the initial layout modelled in PS while Figure 2 shows the initial layout modelled in VC. It is worth noticing that the presented layouts were slightly different. The reason lies in the fact that in this way it is avoided that the first group could influence the opinion of the second group in case that they would discuss their experience. However, this does not affect the outcome of the experiment.

Modifications requested by the participants during the workshops were then implemented ad hoc into the simulation models and subsequently assessed by the participants by running the simulation and evaluating the results (statistics). At the end of each session, the questionnaire has been provided to the participants to collect their feedback and assess their experience, assigning a score to each software.

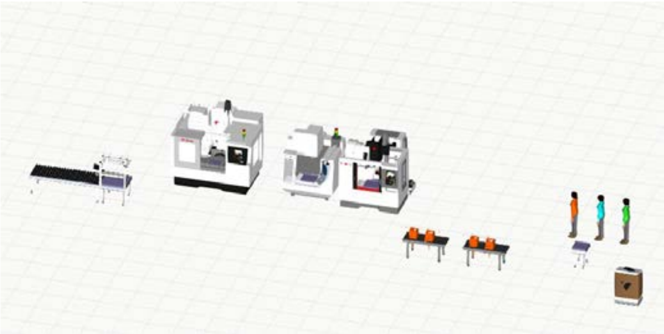

Fig. 2. Production layout modelled in Visual Components 4.1 Premium.

5. Results

Table 1 summarizes the assessment of the two simulation software used during the computer-aided PD workshops by calculating the average rating. From the table results that PS has been preferred mainly because it allows a higher level of concentration during the PD workshop. Conducting computer-aided PD workshops with two state-of-the-art 3D factory simulation software tools with partly untrained participants provided valuable feedback for the optimization of the layout. However, it did not result in the expected high degree of involvement of the participants and interactivity during the computer-aided PD process. The feedback of the participants pointed especially towards the needs of further development, adaption and simplification of the 3D simulation tools.

Table 1. Assessment of each software based on questionnaires

	PS	VC
Features	3.8	3.5
Final matching grade	3.9	3.9
Task concentration	3.5	2.7
Usability	2.6	2.6
Mean	**3.4**	**3.2**

Concerning the workshop conducted using PS, the participants appeared to be interested in the activity, and the task concentration was high. However, implementing modifications to the simulation model required specific skills, e.g. coding skills utilizing SimTalk, which are not immediate to acquire. For this reason, participants were not able to use the software on their own, needed the software expert to take over and to implement the modifications following their verbal instructions. For this reason, there was often a considerable interruption in the discussion and ideation flow due to the time needed by the expert to implement the proposed modifications. The graphic interface of the software appeared to be dispersive, even though they also appreciated the way statistics were showed.

Concerning the workshop conducted using VC, the simulations were rather slow compared to PS, and this led to a lack of concentration of the participants. They also expected a better real-time integration of statistics in the 3D environment. The animation set was considered the main advantage of this tool. The users liked some functionalities, like the quick insertion or duplication of components, although they didn't like the way tasks and processes are created.

Nevertheless, the study showed several important requirements for simulation tools to be utilized in the context of a computer-aided PD workshop:

- Stakeholders, especially workers, involved in a computer-aided PD workshop need to be trained to use the software upfront, so to have the required understanding of the tool's functionalities, capabilities, and limitations. This can be time-consuming and expensive in an industrial context. More intuitive tools would reduce time and costs with regards to this aspect.
- A stronger focus on tangible, immersive and easy to use interfaces for implementing effective cooperation among the participants, e.g. relying on XR technologies. The currently available software only can be utilized effectively if the participants are sufficiently skilled in controlling and interacting with 3D software, such as CAD tools.
- Due to the character of expert tools with a multitude of functions, elements, parameters and modelling methods, the implementation of changes to the initial layout, processes and equipment turned out to be too time-consuming during a PD workshop. Existing modelling and simulation tools need to be more intuitive to be utilized in computer-aided PD workshops. This will reduce the expenses for preparing a workshop and allows to increase the participation of the stakeholders.
- Modelling and simulation tools to be utilized for PD workshops need to provide interfaces for an intuitive and immediate variation of parameters and logics to not stop the ideation process when medium to major adaptations are requested. Otherwise, PD workshops should be suspended to enable the experts to implement changes before resuming the workshop.
- To achieve structured knowledge exchange and design process, it is necessary to rely on tools that allow participants to focus on the same model/process at the same time, allowing them to implement modifications and conduct assessments in real-time. The usability is fundamental for achieving a successful design. In this way, each stakeholder would be able to evaluate independently the effectiveness of the modifications.
- Involving a moderator and software expert for organizing, preparing and leading the computer-aided PD workshop session is essential. The study has shown that available 3D modelling and simulation software does not yet properly fit PD requirements. For successful application further development of the software as well as additional pre-training of participants is needed.

Participants also proposed a "Top-Down" approach for PD workshops, which will take place in two sessions. The first session aims at assessing only the layout design; while the second session assesses the work activity. Between the two sessions, the software expert has the time to implement the control logic and graphic additions, which are time-demanding activities. This approach would also allow the use of two different software for the two sessions. For example, discrete-event simulation software like PS can be used for the first phase, because it is faster and allows 2D modelling. Then, in-depth studies on smaller scenarios, such as work cells and HRC workplaces, can be done using another software with a better graphic compartment such as VC.

6. Conclusions and further developments

Despite the problems raised during the computer-aided PD workshops, VC and PS were recognized from participants as powerful tools for the 3D factory simulation, as they allow to define numerous parameters to achieve a realistic simulation of the workplaces, work processes as well as the layout. Nevertheless, their advanced features and options turn into a drawback when it comes to the applicability for PD, as it requires an expert user to define all relevant parameters, logics and models for the simulation. The definition of an interactive and animated 3D model is complex, requiring a skilled user to prepare the models beforehand. Thus, without training most stakeholders will not be willing and/or able to use the tools on their own, e.g. as a means for a continuous improvement process. For this reason, the expert is also essential for conducting the PD workshops. Participants who are not familiar with the software depend heavily on the expert to implement their proposals. Since only one person at a time can implement the modifications, workshops become time-consuming and creativity fades, as participants have to wait for the expert to put the ideas into action and the ideation flow stops. When implementing major changes in the simulation models the participants were distracted and started parallel discussions on additional alternatives or specific details. Over the course of the workshops, this led to reduced participation in the design session. Divergent from the PD approach, in general, the participants could not directly implement and test modifications to the layout by themselves. Further development of the software should move forward additional simplifications, allowing all the stakeholders an intuitive interaction with the software. However, it is worth noting that this study was conducted using the then available VC 4.1. Recently Visual Components 4.2 has been released, with several improvements mainly concerning the user interface and process design, resulting in a potentially improved usability for computer-aided PD. In conclusion, the study's outcome clearly defines requirements for software aimed at effectively conducting computer-aided PD. As future work, the study can be extended to a larger number of participants randomly chosen, broadening the questionnaire and testing it for statistical quality criteria, and taking more variable into account (e.g. level of experience of participants).

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