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Optimizing Occupational Safety through 3-D Simulation and Immersive Virtual Reality

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Abstract. This paper evaluates the effectiveness of computer simulation and the immersive virtual reality (IVR) technology for occupational risk assessment improvement. It achieves this by conducting a risk assessment on a 3-D simulation of a Lithium-Ion battery (LIB) manufacturing factory. This is necessary since calls for the enhancement of occupational risk assessments continue to dominate safety improvement measures in manufacturing context. Meanwhile, industries such as aviation, mining and healthcare employ advanced versions of IVR for risks awareness with successes. However, applications for safety in manufacturing context is only at the infancy although it utilizes IVR profitably for product and production optimization issues. The study involved 19 participants who performed the assessment with the aid of a safety checklist followed by open-ended semi-structured questions and interviews. Results indicates an outstanding utilization capability of IVR for risk assessment. Furthermore, the assessment pinpoints specific safety issues in the factory that requires attention and improvement.

Keywords: Risk assessment · Hazard identification · 3-D simulation · Immersive Visual Reality · Manufacturing industry.

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1 Introduction

This study integrates the potentials of the Immersive Virtual Reality (IVR) technology for enhancing occupational safety through a 3-D simulation of a lithium-Ion battery (LIB) factory. Specifically, the study aims to evaluate the extent that this technology can be employed to conduct an effective industrial risk assessment procedure that is key to occupational health and safety of manufacturing factories [1]. The Occupational Health and Safety Assessment Series standard (OHSAS 18001:2007) defines risk as the combination of the probability of occurrences and results of a predetermined hazardous event [2]. Risk assessment is therefore defined in the document as the process of calculating risk magnitude and deciding if the risk is tolerable. Besides, evidence indicates that safety measures are best implemented during the planning stages of a facility. Moreover, traditional means of analyzing risks at the planning stages is handicapped due to its inability to envisage details of production processes adequately [3,4]. Implications are that, the safety of detailed manufacturing processes cannot be critically assessed until after construction and production. For this reason, the IVR technology which has the capability to simulate manufacturing equipment, the environment, robotic manipulations, products and production processes in real-time is currently gaining industrial acceptance [4,5].

Although this technology was initially developed for computer games, today it has evolved as a viable industrial tool in example; engineering, construction, telecommunications, military and healthcare to optimize operations, product design and processes. Moreover, it is employed for safety improvements in some instances [5]. Generally, industrial applications of the technology for safety proves that IVR is the best currently known method for safety training, hazard identification and accident reconstruction [6].

However, there is scanty evidence to support its successes in manufacturing for safety improvement despite these impressive strides in provided by the virtual technology. For example, in a 154-article review relevant to Virtual Environment (VE) applications in manufacturing from 1992 to 2014, only 4 addressed applications of the technology for human factors [7]. One touched on workers safety training [8], another on safe working environment for the disabled [9] and two on simulations of human models for risk assessments [10]. Furthermore, future research directions of some of these applications seek to apply the technology pragmatically for safety analysis in emerging manufacturing fields. For these reasons, this paper formulates the following research questions:
RQ1: Is it possible to conduct a risk assessment in a 3-D model of a manufacturing factory?
RQ2: How close is a 3-D simulation to a factory in terms of layout, equipment and manufacturing procedures?

RQ3: What extent can IVR identify hazards and risks of a 3-D simulation in manufacturing context?
RQ4: Does a 3-D simulation of a manufacturing edifice and analysis through IVR provide better means of evaluation compared to traditional means of risk assessments at the planning stages?

Hence this paper is structured as follows to address these questions; in the next section, the methodology describes the structure, data and empirical framework of the research follows. Subsequently, literature based on applications of this technology for occupational safety optimization in manufacturing is reviewed to provide a theoretical background. Thereafter, presentation of results follows which elaborates and discusses the research findings. Finally, the study concludes in retrospect with the limitations and suggestions for further research.

2 Methodology

Figure 1 describes the design of the research which starts with the afore mentioned problem statement about the need to strengthen occupational risk assessments in manufacturing through simulation and IVR.

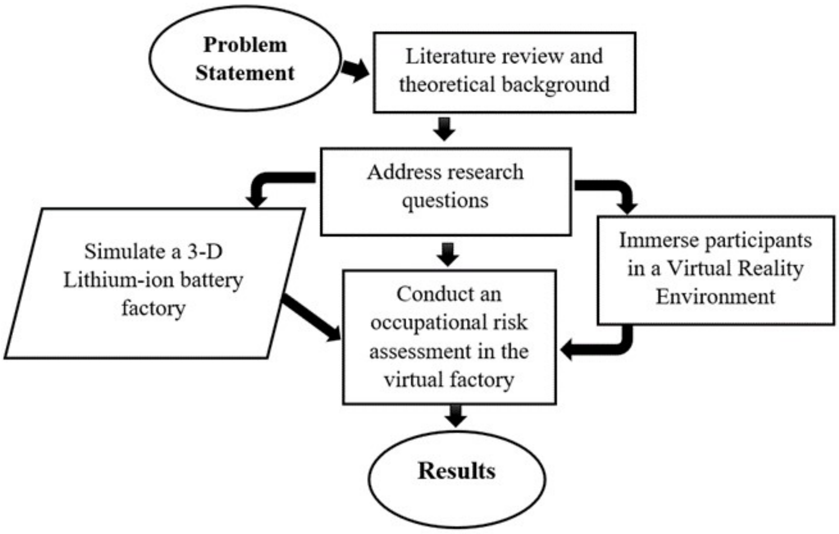

Fig.1. The design of the research

The research follows both qualitative and quantitative research methods that includes experiments and surveys with yes or no answers. Three open-ended questions proceed this to complement the data. None of the participants had any adverse issues with an IVE nor mental disability. The mean age of participants was 34 (SD = 8.1) and had

8.5 (SD = 6.2) years of work experience. 47.4% of the respondents were from industry and manufacturing while others were from research and education institutions. The purpose and procedure of the research, particularly the experiment was first explained to participants individually. Afterwards, the researchers provided detailed tutorials for the navigation and control of the LIB virtual factory through utilization of the stereoscopic HMD device. Emphasis on the safe use of the system such as the proper adjustment of the head set for clarity and visibility follows. Subsequently, the researchers' highlighted the safety zone for the immersion. Thereafter, the signing of the informed consent form by both the researcher and each participant follows. After a thorough walk and inspection of the facility, example (Figure 3), participants then completed the risk assessment form. This constituted 35 questions according to the workplace safety checklists (WSC) which conforms to the occupational safety and health (OSH) answer fact sheet. The safety checklist covers a broad range of health and safety issues that includes the factory environment, availability of First Aid kits, presence of safety signs and fixed guards for articulated robots and running machinery. Other issues are storage for chemicals and explosive materials, fire protection, warning systems and the possibility of electrocution. The first part of data gathered constitutes a quantitative analysis for the risk assessment based on disagree or agree questions and thematic categorization for the open-ended questions.

The Visual Components (VC) simulation software was used to build the 3-D virtual factory. This enables scrutiny of all processes for the manufacture of the 2170 LIB cell. The simulation processes consist of the raw material offloading stages through anode and cathode mixing, coating, calendaring and slitting. Others are cell winding, electrolyte filling, and cell welding. The formation cycling and packing into modules follows. Finally, the palletizing and shipment stages completes the simulation.

3 Theoretical Background

Several industrial applications of IVR simulations for safety exists. These are; training of employees in a simulation through IVR for safe operation [11,12], Likewise, in risk assessments associated to human responses in emergency situations [13]. Furthermore, safety levels have been improved through the application of a Plant Simulator (PS) that constitutes process simulation and accident simulation for normal as well as abnormal accident scenarios [7,14]. Moreover, the simulation-based training (SBT) software enhances human-robot collaboration (HRC) safety training. Meanwhile, virtual prototypes are also suitable for human factors and ergonomics at factory design stages [15]. Thus, through the application of 3-D simulation and scrutiny with IVR, a rise of safety levels in some high-risk sectors such as in the construction industry has become possible [16]. Similarly, the mining industry records successes for safety improvement [17,]. Theoretically, applications of the technology for risk assessment involves (a) analyzing and evaluating the risks associated to a specific hazard: Termed risk analysis and/or risk evaluation. (b) Determining the most appropriate methods to eliminate the identified hazards and (c), controlling the risks when the hazard posed is impossible to eliminate. Termed: risk control. Accordingly, this research utilizes this sequence while participants experience immersion in the 3-D virtual factory.

3.1 Occupational Risk Assessment

The primary and key technique to achieve optimum workplace safety is an active and vibrant occupational risk assessment (ORA) procedure [18]. In manufacturing cycles, hazard-based qualitative risk assessment with risk management implies locating and identifying jobs, operations and procedures that have the tendency to increase the likelihood of exposure to injury, damage or even fatalities [19]. OHS management system therefore clarifies risk according to time horizons and severity such as imminent and serious risks to prioritize and structure control and intervention mechanisms. A workplace survey is vital in achieving a serene occupational safety environment. This implies identifying and assessing all health and accident risks at the workplace with suggestions for improvement. The design of this paper hopes to achieve that. Section 5 on Act 701/2006 of the Finnish Occupational Safety and Health Enforcement and Cooperation Act for Workplaces emphasizes and enforces requirement for frequent and efficient inspections to uphold safety standards [20].

3.2 Technology and Simulated Environment

According to Wang et al., [21], there are four independent definitions of the reality-virtuality (RV) simulation technology. These are augmented reality (AR), augmented virtuality (AV) pure real presence, and pure virtual presence (VR). Currently, the pure virtual presence termed Virtual Reality has gained industrial attention and acceptance [22]. Primarily, this is because in the immersion, VR possesses better visibility, accessibility and much more capable for analyzing complete virtual environments. In addition, it generates complete virtual images with the head mounted display (HMD), sensory handheld controllers and base stations. A Virtual reality environment is a 3-D real time graphical environment that makes it possible to visualize and interact with simulated models in a virtual environment [15]. One is immersed (termed immersive VR) in the environment when using the technology to interact with seemingly real or physical situations. The purpose of the application of IVR technology is to transfer the user of the headset from the current natural location to the simulation in the virtual realm. This makes it possible for critical scrutiny of the factory for hazards at the planning stages.

In order to run the 3-D simulation and immersion needed in the virtual realm, a Windows 10 computer with the following specifications and accessories was utilized: An Intel core i7 processor having a speed of 3.6 GHz Dual-Core and a random-access memory (RAM) of 32GB. Importantly, it is installed with an NVIDIA GPU (GTX 1070 GeForce gaming graphics card. For the immersion, an HTC VIVE equipment incorporating a head-mounted display (HMD) coupled to hand-held controllers connects to advanced gesture controls for navigation. Two base stations track movements to produce the virtual environment of the 3-D simulated models. Figure 3 shows a participant immersed in the virtual environment of the LIB manufacturing factory.

3.3 Lithium Ion Battery (LIB) Manufacturing Factory

The choice of a Lithium Ion Battery (LIB) manufacturing factory for this simulation is due to growing concerns of global warming and the current interests and growth for green energy. The facility incorporates advanced automation, robotics and state-of-the-art technology (Figure 2) to produce the LIB that powers electric vehicles (EV).

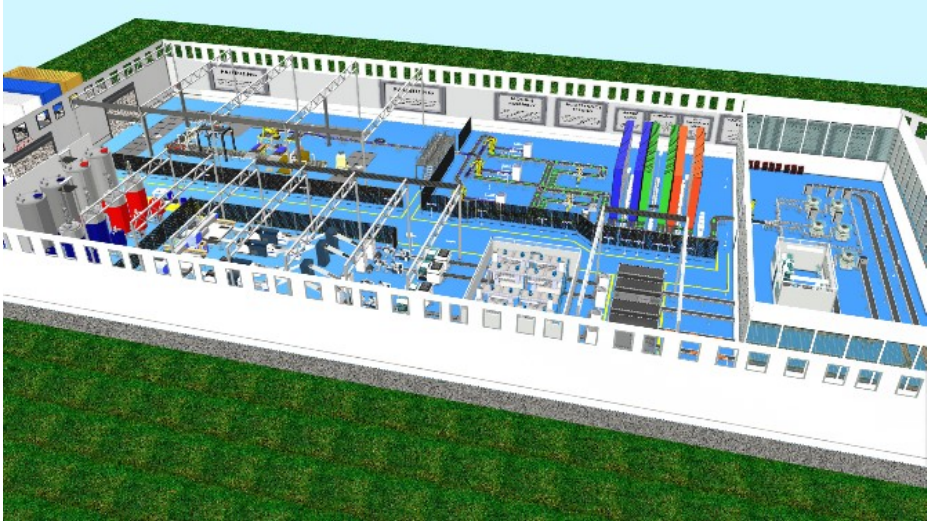

Fig. 2. The 3-D model of the utilized LIB factory

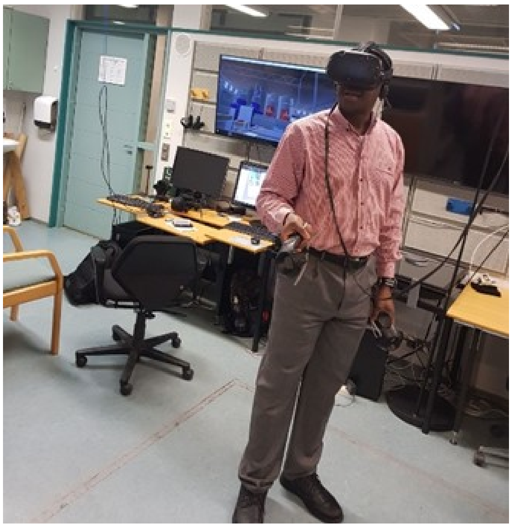

Fig. 3. Risk assessment of the 3-D LIB factory through IVR.

4 Results and Discussions

Table 1 presents results of the risk assessment that answers RQ1 which seeks to investigate the possibility of conducting a risk assessment in a 3-D simulation through IVR. While answering the question in relation to statement A in Table 2 about the possibility of conducting risk assessments in the simulation, 52.63% of participants agreed and 47.37% strongly agreed. Accordingly, the mean value of 4.47 (SD = 0.50) for the statement A (Table 3) indicates proximity of respondent's perception. Furthermore, the answers obtained for statement C also in Table 2 of the capability of IVR in analyzing the safety of production attests to RQ1 in the affirmative.

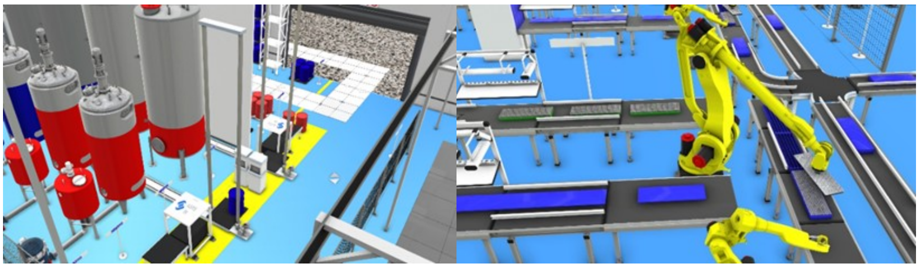

Fig. 4. Inside view of the factory showing mixer tanks and articulated robots at work

Table 1. Combined risk assessment results

Risk assessment results (in percentages)		YES	NO	No answers
1	Are floor surfaces free of water, oil or other fluids?	95	5	0
2	Are passageways clearly marked?	68	32	0
3	Are walkways/doorways clear of boxes, cords and litter?	68	32	0
4	Are stairways clear of boxes, equipment and other obstructions?	95	5	0
5	Are stairs and handrails in good condition?	100	0	0
6	Will personnel be working above where others may pass?	63	37	0
7	Will personnel be working below others?	53	47	0
8	Are covers/guardrails in place around pits, tanks and ditches?	95	5	0
9	Is the level of light adequate for safe and comfortable of work?	100	0	0
10	Are work items that are regularly used within easy reach?	89	11	0
11	Is there sufficient access to machines/equipment?	100	0	0
12	Are appropriate manual handling aids readily available?	74	21	5
13	Are all machine parts adequately guarded?	74	16	11
14	Are warnings appropriate for any hazardous areas?	68	32	0

15	Are all hazardous products stored appropriately?	74	21	5
16	Is stored material stable and secure?	84	11	5
17	Are items placed neatly and securely on shelves?	79	21	0
18	Can items on high shelves be easily reached?	79	16	5
19	Are the elevated platforms properly and handrails secured?	89	11	0
20	Are switchboards in a safe operating condition and secured?	89	11	0
21	Are machine guards in place on all operating equipment?	84	16	0
22	Are emergency stop buttons clearly visible and operational?	53	47	0
23	Are chemical and hazardous substances stored safely?	89	5	5
24	Are hazardous products stored away from heat sources?	74	21	5
25	Is there a possibility of electrocution?	26	74	0
26	Is there adequate ventilation or an exhaust system?	84	16	0
27	Is ventilation equipment working effectively?	79	21	0
28	Are First Aid Kits easily accessible and prominent areas?	84	16	0
29	Is the location of the First Aid Kit clearly identified?	74	26	0
30	Are exits and exit routes equipped with emergency lighting?	79	21	0
31	Are exits and exit routes accessible?	84	16	0
32	Are there signs and arrows indicating the direction to exits?	68	32	0
33	Are locations of fire alarms/firefighting clearly identified?	89	11	0
34	Are extinguishers properly mounted and easily accessible?	84	16	0
35	Are there enough extinguishers present?	58	37	5

Concerning the simulation's proximity to a real factory (statement D in Table 2), 63.16% agreed while 26.32% strongly agreed and 10.54% neither agreed nor disagreed. Similarly, 63.16% agreed while 31.58% strongly agreed and 5.26% disagreed to the proximity of the simulation to actual manufacturing processes (statement E in Table 2). The mean value for the statement D is 4.16 (SD = 0.59) and for the statement E it is 4.12 (SD = 0.69). These responses complement RQ2 that indeed, the simulation is quite close to a real factory.

Table 2. Results of IVR's suitability for risk assessment of the 3-D simulation

Perceptions of 3-D simulation and IVR for risk assessment (in percentages)	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

A. Possibility to conduct a risk assessment	0	0	0	52.63	47.37
B. Ergonomics of the HMD	0	0	21.05	21.05	36.84
C. Capability to analyse production safety	0	0	0	63.16	31.58
D. Proximity to a real factory	0	0	10.54	63.16	26.32
E. Proximity to actual processes	0	5.26	0	63.16	31.58
F. Preference to IVR than traditional methods	0	5.26	10.54	42.10	42.10

Although much of the response showed a high level of correlation, there were however some questions that had YES and NO spit answers. For example, in question 22, that asks about the visibility and operational performance of emergency stop buttons. The split was because some participants concentrated on a YES answer for the visibility while others chose a NO answer based of its operation. Actually, there were emergency stop buttons, but they were not operational in the simulation. Hence, the split answers.

While analyzing the extent to which the IVR can identify hazards and risk factors present in the plan as RQ3 asks, statement C in Table 2 provides 63.16% in agreement and 31.58% strongly in agreement to the capability of IVR to analyze safety of production in the real factory. Secondly, the mean value of 4.21 (SD = 0.69) obtained from question F of Table 2 shows that IVR is more suitable for risk assessment than traditional means of assessment. Consequently, results from Table 2 and Table 3 shows that IVR is truly a more appropriate and effective means of assessing risks at the planning stages compared to traditional methods such as text and 2-D plan and answers the RQ4.

Table 3. Results of IVR's suitability for risk assessment of the 3-D simulation

Questions related to the simulation and IVR walk (Strongly disagree= 1, disagree=2, neither /nor agree=3, agree = 4, strongly agree= 5)	Mean	Standard deviation
A. It is possible to conduct a risk assessment in a 3-D simulated factory	4.47	0.50
B. Ergonomics of the HMD for the assessment	4.16	0.74
C. Capability to analyse production safety	4.21	0.69
D. Proximity of the simulation to a real factory	4.16	0.59
E. Proximity of the simulation to actual manufacturing processes	4.21	0.69
F. Preference to IVR for risk assessment than traditional methods	4.21	0.83

During the risk assessment, participants identified diverse hazards present in the factory that requires attention. Two mentioned the potential for falling as the main hazard while four indicated gas leakage and another four participants also observed that the presents of fast-moving robots and machinery were the main hazards present in the simulation. Besides, there were nine hazardous issues that were reported only once. (identified as other in Figure 5a).

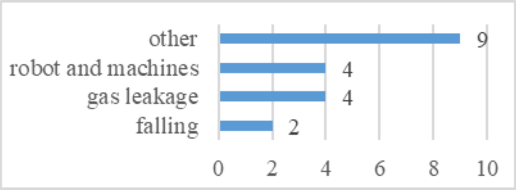

Fig. 5a. Hazards identified in the LIB factory

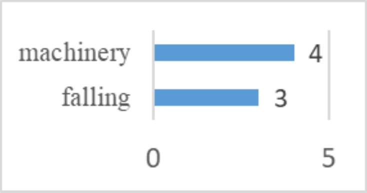

Fig. 5b. Probable accidents

However, the most probable accidents identified in the simulation were related to machinery and falling (Figure 5b) which are actually prevalent amongst the high causes of accidents in the industry [23].

5 Conclusions

This paper has employed an IVR technology for occupational risk assessment to a 3-D model of a LIB manufacturing factory. The risk assessment constituted the 35 WSC questions administered by 19 participants individually while immersed in the virtual realm. Overall, results of the research indicate that IVR is highly capable to improve work place safety through a more active occupational risk assessment that constitutes hazard identification and a safety walk of the facility even in the plan. Furthermore, the assessment provided ample suggestions for instituting and implementing the necessary control measures. Generally, participants overwhelmingly indicated preference to IVR risk assessment of the factory at the planning stages to traditional methods of risk assessment. The exercise has demonstrated abundantly that indeed, a full-scale occupational risk assessment procedure can occur in a 3-D simulation of a manufacturing factory with the aid of an IVR technology. Despite these results, the research encountered a few limitations necessary for recognition. Firstly, the exercise concentrated exclusively on VR and the simulation was equally limited to LIB production. Therefore, in the future, the researchers intend conducting the simulation and IVR in other manufacturing factories to compare and validate the results presented in this paper. Likewise, we hope to involve the safety, health and environment (SHE) managers within the sector for the risk assessment. Secondly, the overall simulation process froze repeatedly due to simultaneous multiple simulations of the production process. As such, the exercise sometimes took more time than initially anticipated although most participants enjoyed the walk and scrutiny in the virtual realm. While

IVR's utilization for safety in manufacturing context is only at the initial stages, this paper demonstrates both empirically and pragmatically its utilization potentials in manufacturing to fill this research gap.

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