Combining Virtual Reality with Mixed Reality for Efficient Training in Battery Manufacturing

Lucie Denisart[a] [b] [c], Diana Zapata-Dominguez[a] [b], Xavier David[a], Aubin Leclere[d], Romain Lelong[d], Chaoyue Liu [a] [b], Jiahui Xu [a] [b], Emilie Loup-Escande[c], and Alejandro A. Franco*[a] [b] [e] [f]

[a] L. Denisart, Dr. D. Zapata-Dominguez, X. David, Prof. Dr. A. A. Franco*,
Laboratoire de Réactivité et Chimie des Solides (LRCS), UMR CNRS 7314,
Université de Picardie Jules Verne, Hub de l'Energie,
15, rue Baudelocque, 80039 Amiens Cedex, France
*E-mail: alejandro.franco@u-picardie.fr

[b] L. Denisart, Dr. D. Zapata-Dominguez, C. Liu, J. Xu, Prof. Dr. A. A. Franco*,
Réseau sur le Stockage Electrochimique de l'Energie (RS2E),
FR CNRS 3459,
Hub de l'Energie,
15, rue Baudelocque, 80039 Amiens Cedex, France

[c] L. Denisart, Pr. Dr. E. Loup-Escande,
Centre de Recherche en Psychologie : Cognition, Psychisme et Organisations (CRP-CPO), UR UPJV 7273,
Université de Picardie Jules Verne
1, Chemin du Thil - 80025 Amiens Cedex 1

[d] R. Lelong, A. Leclere
Reviatech SAS
Parc Technologique des Rives de l'Oise
Rue les Rives de l'Oise - 60280 Venette, France

[e] Prof. Dr. A. A. Franco
ALISTORE-European Research Institute, FR CNRS 3104
Hub de l'Energie,
15, rue Baudelocque, 80039 Amiens Cedex, France

[f] Prof. Dr. A. A. Franco
Institut Universitaire de France
103 Boulevard Saint Michel, 75005 Paris, France

Abstract. The manufacturing process of batteries can be complex and time-consuming. We introduce a new version of the digital twin of our lithium ion battery pilot line, Simubat 4.0 Gen-2, based on a new combination of Virtual Reality and Mixed Reality. This digital twin is designed to deliver training on the lithium-ion battery manufacturing process and electrode properties. This tool aims to make users active learners, helping them visualize and understand complex concepts and meets a strong need for skilled labor linked to the blooming of battery gigafactory, in particular in our region. We report here a detailed study of the educational contribution of Simubat 4.0 Gen-2. This study was performed during two filmed training sessions: the first one with chemistry MSc. students, and the second one with AESC Gigafactory trainees. We used questionnaires to measure the usability and usefulness and at the same time, we studied the usage by analyzing errors and by qualitatively assessing communications among the participants. Our study revealed that users had more knowledge after using our digital twin; our digital twin was evaluated as being efficient by the users and it has been proven to be suitable for training in battery manufacturing.

1. Introduction

1.1. Context

Global warming awareness has driven government legislation and consumer consciousness to develop suitable renewable energy development strategies and associated energy storage systems for decreasing greenhouse emissions [1]. Among the different energy storage devices, rechargeable lithium-ion batteries (LIBs) are the best choice for their use in portable electronic devices and electric vehicles (EVs). The growth of EVs needs to go along with the development of battery production, with cells having high energy and power densities, high safety and recyclability, and low production CO_2 fingerprint [2][3]. The rapid upscaled production of LIBs to satisfy the increasing EV demand can be tackled by constructing large-scale factories, known as *gigafactories*, that reduce the cost of fabrication and increase manufacturing efficiency. Pre-production optimization is usually undertaken in smaller-scale plants, known as prototyping or pilot lines. The manufacturing process of LIBs involves multiple steps and numerous parameters [4]. Electrode and battery cell fabrication consist of a sequence of actions linked between them, such as pre-mixing, mixing, coating, drying, calendering, cutting, final assembly of the battery cell, filling and formation [5]. Training new technicians, operators and engineers to comprehend the interplay between manufacturing steps and parameters for efficient optimization of the battery production is time and cost-consuming. Digital technologies, such as Virtual Reality (VR) and Mixed Reality (MR) can support the guidance to increase users' attraction to accomplish and understand this challenging task more efficiently.

1.2. Virtual Reality, Augmented Reality, Mixed Reality: definitions and characteristics

Milgram and Kishinio defined the Reality-Virtuality Continuum as a continuous scale that covers the possible variations between real environments perceived without technology and virtual environments, which immerse the user and eliminate the perception of reality (Figure 1). MR is the fusion of the real and virtual worlds, with two intermediate states, Augmented Reality (AR) and Augmented Virtuality [6].

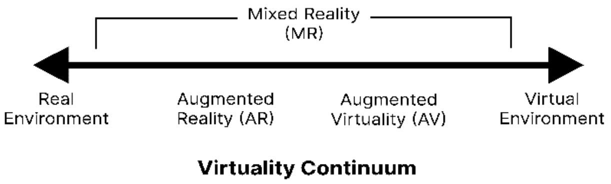


Figure 1. Milgram and Kishino's reality-virtuality continuum [6]

VR can be defined as "*an artificial 3D environment created by a computer and presented interactively to a person*" [7]. AR adds virtual elements to the real environment using smartphones or tablets [6]. MR is based on AR technologies and enables actionable information to be anchored in the real environment [8]. Microsoft, which designed the HoloLens 2 glasses, defines MR as *"a blend of the physical and digital worlds, enabling natural and intuitive 3D interactions between humans, computers, and the environment.*" [9]. Unlike VR, in which the user interacts in a fully immersive environment with physical controllers, in MR the user wears a helmet visor that lets him/her perceive the real environment around. Digital holograms are embedded in the real environment, creating a mixed environment (real and digital). MR requires no remote control, leaving users hands-free. They can manipulate physical objects and holographic objects according to their needs.

For several years now, these technologies have become popular, particularly in the field of education and professional training. VR is used as a tool for professional and university training in a variety of fields, including military, health, and technical training, *e.g.* learn how to weld, and theoretical training, *e.g.* to visualize physical concepts [10]–[13]. VR provides trainees with an immersive environment in which to learn theoretical knowledge and practical tasks [14]. Immersive technologies such as VR offer a number of benefits, such as entertainment and attractive aspects that play a role in motivating users to learn and increase their engagement during the learning process [15][16].

Several studies show that immersive and interactive 3D environments increase the interest of users because the material is perceived as more attractive and increases users' positive emotions [16][17]. Through immersion in an environment where their attention is focused, users perform better in information retrieval tasks with VR compared to traditional learning methods [16][18].

Virtual environments provide simplified access to complex fields with high realism, without risk, and at a lower cost. In this training context, VR allows learners to visualize situations and concepts that are very difficult or impossible to represent in reality [15]. This improves users' performance and reduces cognitive load as it gives them the opportunity and the time to control their learning [19][20].

One of the most common applications of AR is training and activity assistance, as it complements the real environment with digital elements relevant to the activity [21][22]. This type of use shows reduced error rates as well as superior performance with AR training than without AR training [22][23]. It is important to note that the training population and type of task influence the effectiveness of training using VR/AR [24].

The use of AR during professional training offers the user the opportunity to be trained individually and has a positive impact on learning [22][25]. Likewise, the level of user engagement is higher during training with AR technology [23].

However, the visual quality of virtual environments, malfunctions that can lead to image shifts, and the risk of simulator sickness are sources of limitation that can reduce the effectiveness of the training using these technologies [24].

In the context of vocational and academic training, MR makes it possible to implement digital interactive elements that cannot be represented in reality, while giving the user the possibility of perceiving the external environment. This is not possible with VR. This tracking technology in MR enables the helmet to create a sense of presence and immersion during use, allowing users to interact with virtual objects as if they were real [26]. Training and assistance are applications compatible with MR, as they can considerably facilitate, support and optimize production, assembly and maintenance tasks in real time in industrial environments and in particular Industry 4.0 [27]–[29]. MR increased training efficiency by improving knowledge acquisition and retention [29]. This technology is notably used for training in invasive surgical procedures [8][30].

Training tools using immersive technologies should form part of a complete program comprising traditional courses and practical work to supplement theoretical knowledge and technical skills [31]. However, immersive technologies such as VR and AR are not the only solution for providing educational training. It is essential that training tools are usable and efficient from a pedagogical point of view. Despite trainees' interest for VR and AR, some studies show relative or limited contribution of these technologies for learning compared to traditional training [24]. We need to bear in mind that VR, AR and MR are technologies that can increase the interest and understanding of trainees, but the content of the training also needs to be worked on [16][23][30].

Several tools that enable users to collaborate simultaneously in a digital environment have been developed. At the end of the 1990s, the Teal project at the Massachusetts Institute of Technology developed a digital tool usable via computers to simulate and visualize Physics concepts for first-year students, for example by illustrating complex electromagnetic phenomena. It was used in a classroom, with tables arranged as islands for the occasion to encourage collaboration [12]. In 2012, McArdle and Bertolotto presented a VR e-learning system that creates a collaborative virtual environment usable remotely to stimulate learners during their learning [32]. The ease of use of the tool, together with its collaboration and socialization features, increases user's engagement and motivation, thereby reducing the drop-out rate [32].

Navantia used a collaborative MR-based system to train and assist through ship assembly tasks [28]. System users have rated the tool as very useful, particularly for tasks requiring visual reinforcement using accompanying documentation. The MR frees up the user's hands to view digital elements collaboratively, which is beneficial for remote assistance, assembly tasks, or implementing additional information [28][29].

The Microsoft Mesh application also enables remote collaborative work *via* avatars animated with MR. Users wear a HoloLens 2, and in a digitally augmented environment, they are represented as avatars to collaborate, converse and train with their colleagues [33]. This tool is usable and easy to use, with low demand in terms of cognitive load [34]. Surprisingly, MR was never applied before in the battery field before. To summarize, previous reports have shown that training with MR and VR will help in the creativity and easiness to learn new tasks. In this Concept, we present an innovative digital educational tool combining VR with MR that facilitates users' experiences in a battery prototyping room.

1.3. Examples of digital educational tools developed in our research group

VR can be a key medium for efficiently learning theoretical concepts in the field of batteries. To this end, tools using VR and VR interacting with real objects, have already been developed at our Prof. Alejandro A. Franco's research group at Laboratoire de Réactivité et Chimie des Solides (LRCS) of the Université de Picardie Jules Verne (Amiens, France) [35][36].

For instance, we have developed a VR serious game in which the user drives an electric car with a chosen type of battery and has to collect three gifts placed on a virtual map. While driving the car, the user sees a 3D microstructure of the battery cell cathode that evolves as the car is used. As the car accelerates, the virtual battery cell discharges faster and the available charge decreases [35]. We have already reported the technical details and case studies about these serious games and others in previous publications (Figure 2) [35]–[37].

Figure 2. Some screenshots of Simubat 4.0 Web version: a. mixing step, b. coating and drying step, c. calendering step and d. electrolyte filling step (the other manufacturing steps existing in our tool are not represented in this image).

We have also generated and analyzed a VR digital twin of our battery manufacturing pilot line, Simubat 4.0 Gen-1, also usable from the web [36][38].

With Simubat 4.0 Gen-1 it was possible to explore our battery pilot line using VR allowing users to immerse themselves in a battery production line and virtually manufacture a cell by going through all manufacturing steps in succession. At each step, the user has to choose the right input parameters so that the electrochemical properties of the battery cell matched the objectives set at the first step [36]. Simubat 4.0 Gen-2 uses the virtual environment from Gen 1 and adds an innovative MR functionality (Figure 3). Simubat 4.0 Gen-2 (Figure 4) responds to a strong need arising

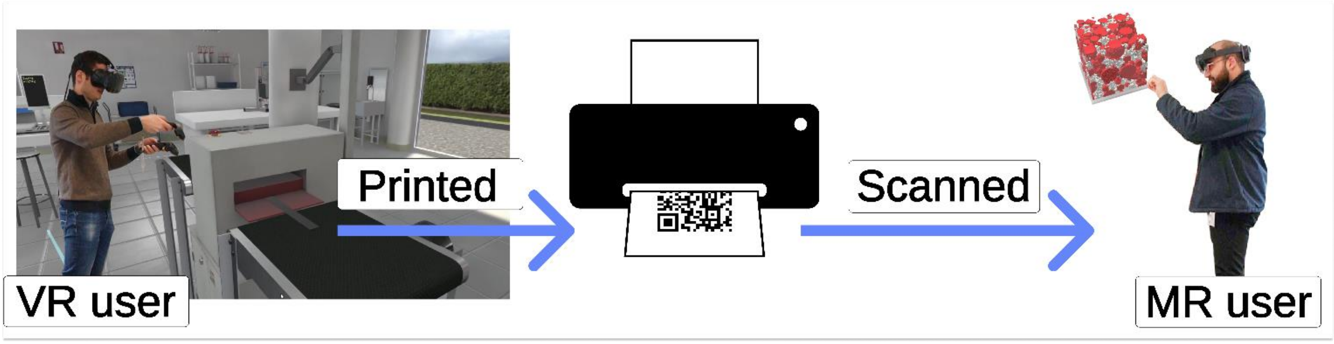


Figure 3. Schematic representation of usage concept of Simubat 4.0 Gen. 2.

from the construction of several battery Gigafactories, particularly in the Hauts de France region, home of our Université de Picardie Jules Verne. [39][40].

LIBs manufacturing is a complex process involving advanced materials, complex machinery, and skilled, trained engineers and technicians. Training in manufacturing processes is difficult because access to battery production lines is challenging. Due to confidentiality restrictions and the presence of hazardous chemicals, access to this type of equipment is rare, and the skills required to operate them are highly complex. Immersive technologies such as VR, AR and MR eliminate risks associated with real-life training by placing individuals in a position of safety and avoiding to damage the machine [24]. In this way, users can acquire a high level of knowledge, here understanding the manufacturing processes, the interaction between the different input parameters, and the formulation of the electrodes without risking injury or damage to the equipment.

In trying to reproduce the prototyping room as faithfully as possible in a digital twin, usability defects or malfunctions could occur, thus reducing the educational usefulness of the tool [15]. The usability of a tool is an essential field in ergonomics, which refers to the degree to which a system, product, or service can be used, by specified users, to achieve defined goals with effectiveness, efficiency, and satisfaction [41].

To summarize, Professor Franco's team has already developed several tools using VR, and Simubat 4.0 Gen-2 is the first one to combine VR and MR. To our knowledge, there is no training tool on battery manufacturing processes that couple VR with MR. The aim of this article is twofold: firstly, to study the usability and usefulness of Simubat 4.0 Gen-2 from a pedagogical point of view, and secondly to characterize the contribution of coupling VR and MR in a battery manufacturing training process.

This Concept is organized as follows. First, we present the technical details of Simubat 4.0 Gen-2, and then the methodology deployed (Section 2). Then we present the results obtained using Simubat 4.0 Gen-2 during two training sessions (Section 3). These results are put into perspective and discussed in relation to the literature (Section 4). In conclusion, we review the contributions of this study and suggest ways of using Simubat 4.0 Gen-2.

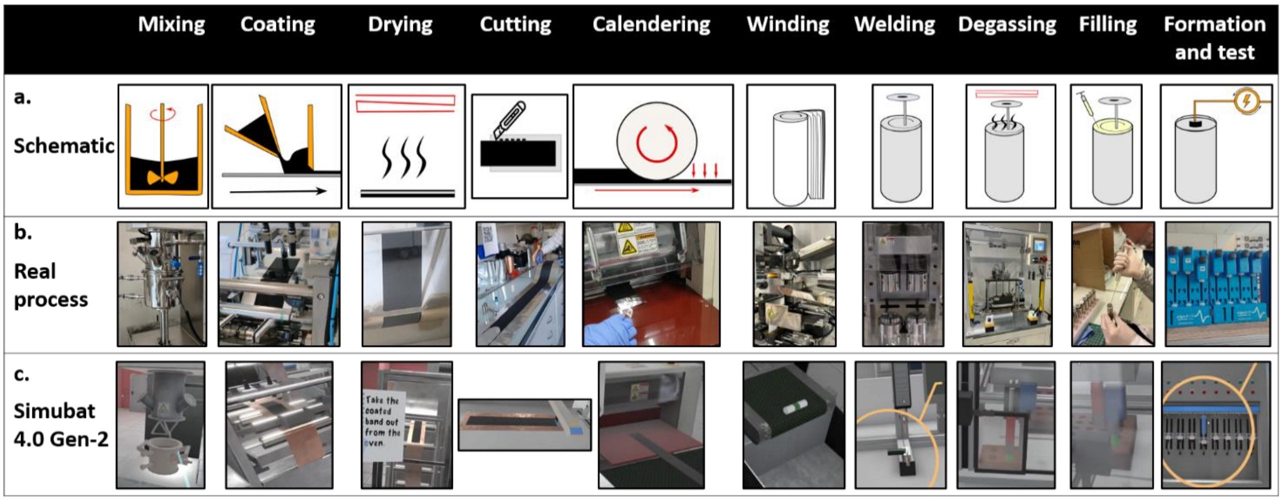


Figure 4. Table showing the manufacturing process for a LIB cell from three points of view: a. schematic representation, b. photos of the process in real life, c. screenshots of the process in VR with Simubat 4.0 Gen-2.

2. Method

2.1 Simubat 4.0 Gen-2

Simubat 4.0 Gen-2 is a training tool that combines VR to move through a virtual production line and MR to visualize the 3D electrode microstructures arising from the manufacturing process carried out in the virtual environment. Simubat 4.0 Gen-2 uses HTC Vive VR headset connected by cable to a computer simulating the virtual environment, a HoloLens 2 headset for the MR, and a printer. One person uses the VR environment and another person uses the MR at the same time (cf. Figure 3).

This tool has been designed to help novice users understand the highly complex manufacturing process and the composition of the cells by placing users as actors rather than observers.

Both applications of Simubat 4.0 Gen-2, are developed using the Unity3D VR/AR/game engine and deployed on the devices. The first one runs a configurable simulation written in C# language, plus some XR plugins and interaction libraries ; while the MR app manages the storage of the 3D-resolved electrode microstructures and use the on-board camera to detect QR-codes and match which electrode microstructure to display; it then allows manipulation using the HoloLens MRTK framework and C# custom code.

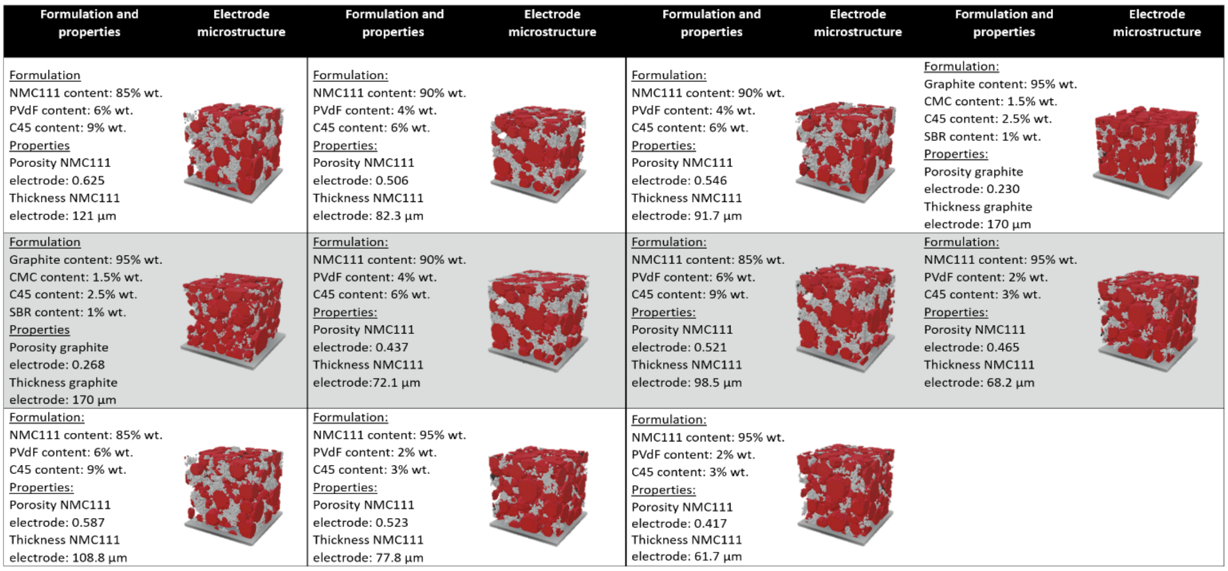
As with Simubat 4.0 Gen 1, the VR user is immersed in a battery production pilot line. He/she has to learn about the formulation and electrochemical properties of the battery cell to be manufactured. The user starts by manufacturing each electrode and then assembles them to form a cell. At the end of the calendering step, when an electrode is manufactured, a QR code is automatically printed. Thanks to the MR, the second user can scan this QR code with the HoloLens 2 headset to manipulate the 3D holographic microstructure of the virtually manufactured electrode (Figure 5). This tool could be particularly useful for users to explore and practice on a production line, something that is often difficult to achieve in traditional practical work.

The tool developed does not teach how to handle chemicals safely or how to adjust highly complex machines such as the coater. However, it does allow the user to visualize the steps of the process and to understand the action of the input parameters on the manufacturing process progresses and that will ultimately modify the electrochemical properties of the battery. This application has been designed for teaching purposes and is intended to support the training of chemistry students and future battery manufacturing professionals.

Placed in a virtual and immersive environment, users participate in learning and play an active role. In Simubat 4.0 Gen-2, they explore the environment and the functionalities of the application. MR also allows them to manipulate the 3D representations of the manufactured electrode microstructures as they wish.

2.2. Participants

Our study sample consists of 17 students from the MESC+ (Materials for Energy Storage and Conversion)[42] MSc. program and students from the CD-MAT (Sustainable Chemistry-Materials) MSc. program, as well as 8 mechatronics engineers, who are doing their end-of-studies work placement at the battery Gigafactory AESC (Automotive Energy Supply Corporation) in France. First, the 17 chemistry MSc. students attended a lecture on Industry 4.0 with a Professor. The AESC trainees took part in



Formulation and properties	Electrode microstructure	Formulation and properties	Electrode microstructure	Formulation and properties	Electrode microstructure	Formulation and properties	Electrode microstructure
Formulation NMC111 content: 85% wt. PVdF content: 6% wt. C45 content: 9% wt. Properties Porosity NMC111 electrode: 0.625 Thickness NMC111 electrode: 121 µm		Formulation: NMC111 content: 90% wt. PVdF content: 4% wt. C45 content: 6% wt. Properties: Porosity NMC111 electrode: 0.506 Thickness NMC111 electrode: 82.3 µm		Formulation: NMC111 content: 90% wt. PVdF content: 4% wt. C45 content: 6% wt. Properties: Porosity NMC111 electrode: 0.546 Thickness NMC111 electrode: 91.7 µm		Formulation: Graphite content: 95% wt. CMC content: 1.5% wt. C45 content: 2.5% wt. SBR content: 1% wt. Properties: Porosity graphite electrode: 0.230 Thickness graphite electrode: 170 µm	
Formulation Graphite content: 95% wt. CMC content: 1.5% wt. C45 content: 2.5% wt. SBR content: 1% wt. Properties Porosity graphite electrode: 0.268 Thickness graphite electrode: 170 µm		Formulation: NMC111 content: 90% wt. PVdF content: 4% wt. C45 content: 6% wt. Properties: Porosity NMC111 electrode: 0.437 Thickness NMC111 electrode:72.1 µm		Formulation: NMC111 content: 85% wt. PVdF content: 6% wt. C45 content: 9% wt. Properties: Porosity NMC111 electrode: 0.521 Thickness NMC111 electrode: 98.5 µm		Formulation: NMC111 content: 95% wt. PVdF content: 2% wt. C45 content: 3% wt. Properties: Porosity NMC111 electrode: 0.465 Thickness NMC111 electrode: 68.2 µm	
Formulation: NMC111 content: 85% wt. PVdF content: 6% wt. C45 content: 9% wt. Properties: Porosity NMC111 electrode: 0.587 Thickness NMC111 electrode: 108.8 µm		Formulation: NMC111 content: 95% wt. PVdF content: 2% wt. C45 content: 3% wt. Properties: Porosity NMC111 electrode: 0.523 Thickness NMC111 electrode: 77.8 µm		Formulation: NMC111 content: 95% wt. PVdF content: 2% wt. C45 content: 3% wt. Properties: Porosity NMC111 electrode: 0.417 Thickness NMC111 electrode: 61.7 µm			

Figure 5. Formulation and properties of the 3D-resolved electrode microstructures available in Simubat 4.0 Gen-2. Other electrode microstructures can be continuously added.

a half-day workshop with an instructor. They used Simubat 4.0 Gen-2 as part of a 2-week training course to learn about battery manufacturing for the future gigafactory workforce. Before attending the training session, the trainees had already observed the cell manufacturing process in the battery prototyping room of our laboratory.

2.3. The task

We organized two training sessions to analyze the performance of user testers: one with the MESC+ and CD-MAT MSc. students, and another one with the AESC Gigafactory trainees.

We wanted to observe the learning of the complex manufacturing process in our tool supported on the coupling between virtual and mixed environments. We wanted also to investigate the appropriation strategies as well as the difficulties and malfunctions that users might encounter while using our tool. Within the framework of observation in an ecological situation, it is difficult to quantify the mental load induced and the difficulties encountered during use [43].

The VR user's first task was to read the characteristics of the battery cell to be manufactured on a whiteboard in the VR environment. The VR user had then to move through the virtual pilot production line to manufacture the two electrodes proposed by the VR digital twin on the VR whiteboard. At each step, the user had to choose the appropriate input parameters to achieve the objectives. If the user did not choose the right parameter, he/she could not proceed to the next step. Once the two electrodes had been manufactured, he/she had to assemble them to obtain a battery cell for filling and testing. For each electrode manufactured, a QR code was automatically printed for the MR user, who had to validate the composition of the electrodes from interactive 3D holograms of the electrode microstructures overlied in the real environment.

2.4. Data collection procedure and methods

Before using Simubat 4.0 Gen-2, the trainees from AESC completed a knowledge questionnaire to assess their level before using the tool. The questions concerned:

- The sequence of steps in the electrode manufacturing process (“name the steps in the order in which an electrode is manufactured”);
- The impact of a parameter on the quality of the electrode (“the solvent drying rate that may influence the quality of the electrode in the process”);
- An explanation of a step in the process and its usefulness (“explain the mixing step”).

The participants then used Simubat 4.0 Gen-2 in a training session that was filmed.

At the end of the session, they completed a second knowledge questionnaire to assess the contribution of Simubat 4.0 Gen-2 and the Computer System Usability Questionnaire (CSUQ) about their experience with VR and MR. The CSUQ was developed and validated within IBM in 1995 by Lewis [29]. This standardized questionnaire is a derivative of the Post Study System Usability Questionnaire (PSSUQ) [30]. This questionnaire is used to measure the usability of a system, the system's performance in performing a task, and the user’s satisfaction. The CSUQ questionnaire comprises three dimensions in addition to the overall score. The first dimension evaluates the usefulness of the system (“*Overall, I am satisfied with how easy it is to use this system.*”), the second dimension is the quality of information (“*The system gives error messages that clearly tell me how to fix problems.*”) and the third dimension concerns the quality of the interface (“*The interface of this system is pleasant.”*). The score for each dimension was obtained by averaging the items concerned.

Finally, they answered questions about their impressions of Simubat 4.0 Gen-2 (*e.g.*, “What did you like about using Simubat 4.0 Gen-2?”).

The course with the MSc. students, taking around 3 hours, took place in an amphitheater, in which a HTC Vive VR headset, a HoloLens 2 MR headset, and a printer were used. The students were divided into four teams combining the two MSc. programs. Before starting, the teams were asked to assign the following roles to their members: VR user, MR user, and advisors. Each team was asked to work together to manufacture a battery cell in the VR digital twin that corresponded to the electrochemical properties proposed by our tool in the first step. The VR user was assisted by the student 'advisors' to choose the appropriate input parameters at each step of the virtual manufacturing process. Once one electrode was manufactured in the virtual environment, a QR code was printed. The MR user then scanned the QR code, and learned about the formulation and properties of the corresponding electrode microstructure. Then the MR user had to pass the information to the other members of the team, who checked whether the parameters defined at the outset corresponded with the formulation and electrochemical properties proposed at the first step by the VR digital twin. Using Simubat 4.0 Gen-2 with the MESC+ and CD-MAT MSc. students took 55 minutes (Figure 6).

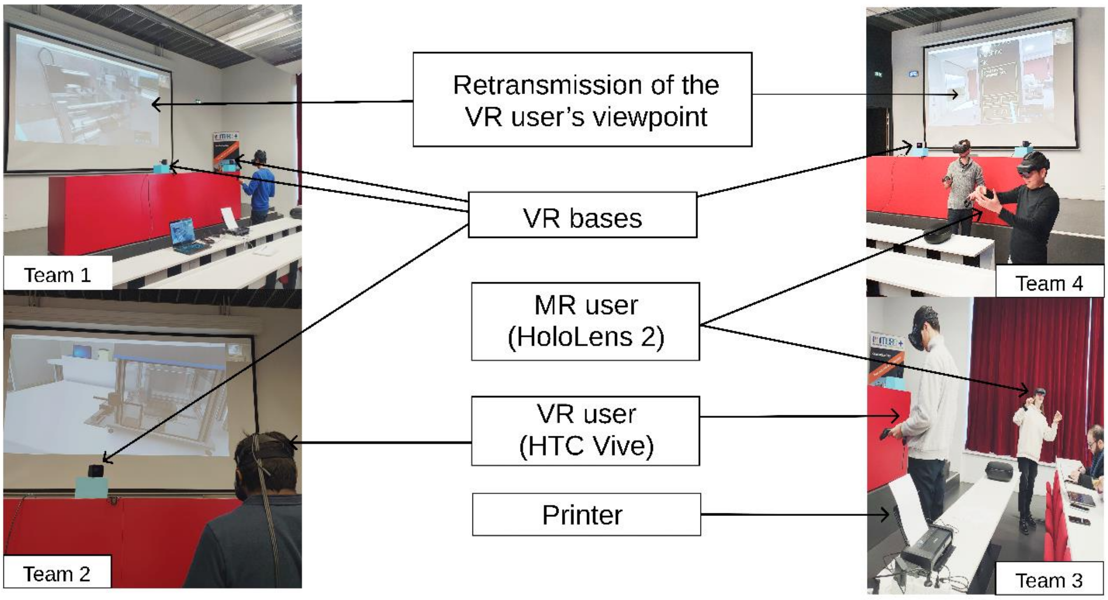


Figure 6. Photos of the MSc. MESC+ and CD-MAT students using Simubat 4.0 Gen-2.

As mentioned above, we also used Simubat 4.0 Gen-2 with AESC Gigafactory trainees. During this approximately 3-hours workshop, the 8 participants began by learning how to use VR using a serious game on the concept of tortuosity previously reported by us [35]. They then get some practice with the web version of Simubat 4.0 Gen-1 the serious game already reported by us [36]. Then, two trainees agreed to use VR to manufacture a virtual battery cell in the digital twin. All participants agreed to use MR to observe and interact with the 3D holographic representations of the virtually produced electrode microstructures. The class was organized so that the view from the VR headset was broadcasted on television so that all the trainees could follow the utilization. At the same time, the instructor could comment on using the headset and complete the training with additional information. The first participant built a cell virtually on his/her own to do the process without any explanation from the instructor. After the first participant, a second use try VR and he/she was supported by comments and questions from the instructor in order to stimulate the audience.

The use of Simubat 4.0 Gen-2 lasted 53 minutes with the AESC Gigafactory trainees (Figure 7).

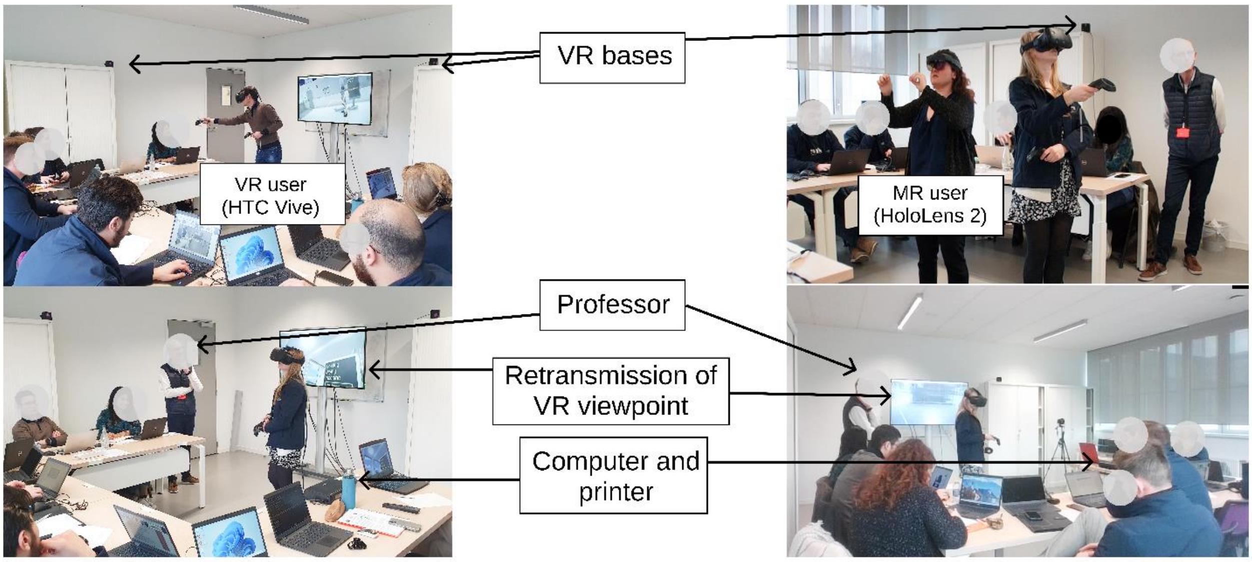


Figure 7. Course photos with AESC's Trainees using Simubat 4.0 Gen-2.

2.5. Data analysis method

All the responses to the questionnaires were transcribed into an Excel document. The responses to the knowledge questionnaires were transcribed and then labeled as "*correct response*", "*incorrect response*" or "*incomplete response*". We calculated the average and standard deviation of CSUQ responses for the overall score and each dimension.

The use of Simubat 4.0 Gen-2 with VR and MR were filmed using a camcorder and analyzed using Boris software [44]. We also transcribed the communications made at the two training sessions.

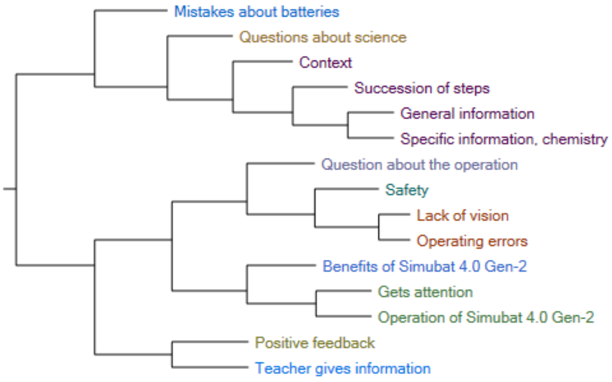
Nvivo 12 software was used to code the verbatims according to a classification we defined during encoding. This software is used to structure and analyze the corpus of communications during the training sessions. We performed several analyses, such as thematic analyses and the grouping of codes by similarity. The verbatims were classified into nodes (themes) during the encoding step. We extracted the information using lexical analysis and similarity tests to obtain a distribution diagram and causal relationships between the different nodes.

3. Results

3.1. Results of verbalizations

30 verbatims were encoded from the transcript of the course with the MESC+ and CD-MAT MSc. students, and 59 verbatims from the transcript of the AESC workshop. A discourse analysis was performed to identify three thematic categories (Figure 8).

Figure 8. Dendrogram of elements grouped by word similarity with Nvivo 12.



The first category refers to the knowledge transmitted orally by the Professors while using Simubat 4.0 Gen-2. For example, the Professor said: "*It is also a way of welcoming you to Industry 4.0, where the digital and the real worlds work together*", and the instructor said: "*Where is it done?”* (Participant): “*Dry, I do not know… the clean room, the dry room....*".

This category (knowledge transmitted orally) includes three nodes: a succession of steps, general information, and specific information.

The first node relates to information about the steps in the battery cell manufacturing process: the instructor with the AESC trainees emphasized the last step in the process: "*What is this step called?*” (Participant 07): “*Test*”. (instructor): “*Where we look at the available energy*”. (Participant 06): “*Load testing*” (instructor): “*It's the famous cycling we have at the end, it's the very last step.*"

The Professor insisted on the electrolyte filling step: "*Filling with electrolyte. This is the machine that also welds the cells. You can see this large unit that fills the electrolyte with a robotic arm.*"

The second node is related to general information about batteries: the instructor asked the AESC trainee, "*The cell includes two electrodes and a third component, which is it? two electrodes and a third element?*".

The third category involved specific information on electrochemistry: the Professor asked the students, "*Why do we heat? To remove the water, otherwise it forms hydrogen with the electrolyte under electrochemical operation*". The instructor said: "*Did someone explain anything to you about CMC yesterday (during the observation in the pilot line)? It's a polymer that can be dispersed, and it's the temperature that's going to be interesting.*”

This category is linked to other nodes, the context of use, students' questions, and students' errors, for example "*yes, it's the battery, well, the battery*".

The second thematic category defines communication during the use of our tool. Lack of vision and operation errors are the closest nodes.

The first node defined the "*lack of vision*" category. The instructor said, "*Be careful, there's a table in front of you*” This problem happened with MSc. students. A VR user showed that he was lost and could no longer locate himself in space: "*Is there something there or not?*” Users were sometimes lost in the real environment because the VR is fully immersive and makes it impossible to see the real environment around. The VR user had to return to the center of the physical game area to get the game working properly again but did not know which direction to move in because he cannot see the world around him. At the same time, the same the student was also lost in the game and he did not know which step of the manufacturing process to perform. The Professor wanted to help him: "W*hat's written in the notebook?*". Indeed, Simubat

4.0 Gen-2 features a notebook in the user's hand, which can be used to give instructions on the ongoing manufacturing step.

The second node refers to operating errors and questions during use. The first VR user at the AESC training session shows his confusion verbally: "*I just want to... Then how do I change?*", and later he said "*But I want to put this down, I don't know where I am*". This category also includes the consequences of not seeing the VR environment. Here, the participant was out of the zone of use: "*I haven't turned it on, if it's OK, I've a black screen. I have a black screen.*"

The third thematic category is related to Simubat 4.0 Gen-2 and brings together the nodes that gets attention, the operation of Simubat 4.0 Gen-2, and the benefits of Simubat 4.0 Gen-2. The instructor introduced the use of Simubat 4.0 Gen-2 to the AESC trainees based on the main benefits "*The interest here is being able to handle the tools and also to understand better the steps of the manufacturing process with the specific vocabulary.*".

The instructor with AESC trainees also drew the users' attention to this at the start of the session: "*But I'll say it again, take the instructions carefully because they will have an influence on what happens next. So you move around the room to come back and look at the instructions board on which you have visual indications that are going to be important*."

About the operation of Simubat 4.0 Gen-2, the Professor gave instructions to MSc. students before they started using it: "*You'll have to communicate them to your team and to the MR user*". He also described Simubat 4.0 Gen-2's controls: "*You have to position yourself with the pad, which is the disc you have on the remote control. You have to interact with the triggers, you have a mixing time of 1 hour but in the game it is represented in a few seconds*". The instructor with the AESC trainees also described how the controllers work: "*What you have to remember is that to pick up objects and put them down, a little hand will appear from time to time, allowing you to do some actions.*".

The categories defined above are not distributed in the same way between the two training sessions (Figure 9).

For the MSc. students’ course, 20% of the encoding concerned the operation of Simubat 4.0 Gen-2, 10% specific information and 8.51% the sequence of steps (Figure 9.a.). In the session with the AESC trainees, the course focused mainly on transmitting specific information (31.63% of the encoding), the sequence of steps, and the operation of Simubat 4.0 Gen-2 (8% each) (Figure 9.b.).

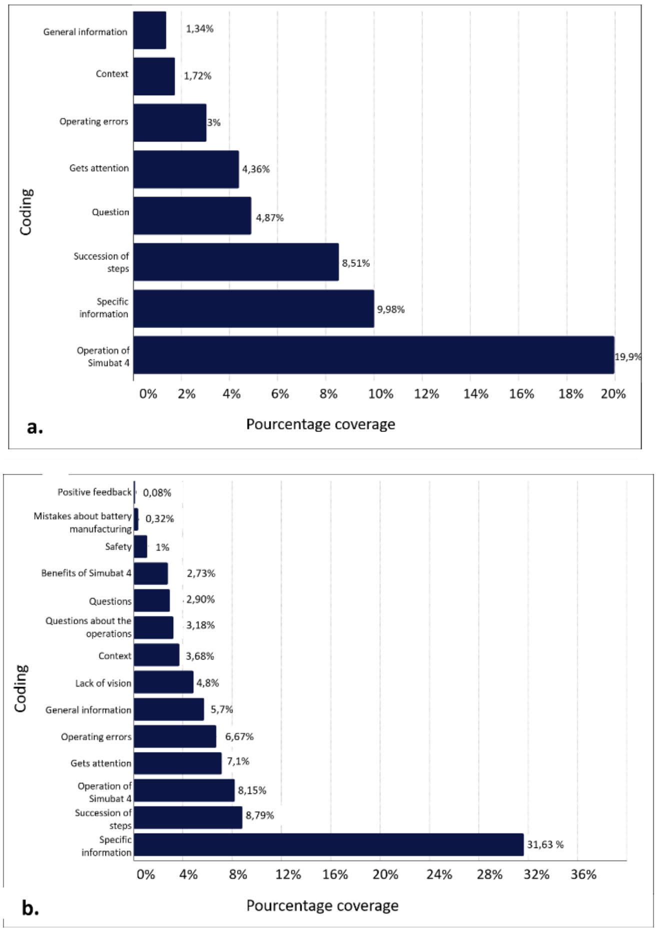
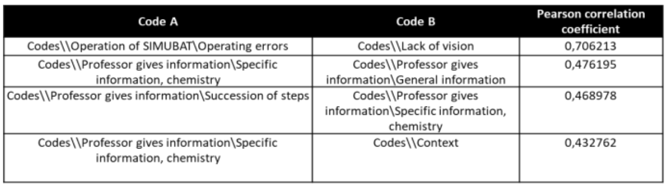


Figure 9: Analyses of the percentage of encoding in each category with Nvivo 12: a) MSc. MESC+ and CD-MAT courses b) training session for AESC trainee.

Using Nvivo 12, we were able to perform a cluster analysis to calculate an encoding similarity index between each training session using similarity measures known as Pearson correlation (Table 1). From this similarity analysis, we can say that the verbatims related to order errors (known as "operational errors") are strongly correlated with the verbatims related to the lack of visibility of the external environment (r = 0.71).

We also note that the categories related to the transmission of knowledge are linked with correlations of 0.48 between specific and general information, 0.47 between the succession of steps and specific information, and 0.43 between specific information and the context of use.



Code A	Code B	Pearson correlation coefficient
Codes\\Operation of SIMUBAT\Operating errors	Codes\\Lack of vision	0,706213
Codes\\Professor gives information\Specific information, chemistry	Codes\\Professor gives information\General information	0,476195
Codes\\Professor gives information\Succession of steps	Codes\\Professor gives information\Specific information, chemistry	0,468978
Codes\\Professor gives information\Specific information, chemistry	Codes\\Context	0,432762

Table 1: Cluster analysis between encoding categories.

3.2. Results of observations

The analysis of errors during the use of Simubat 4.0 Gen-2 with the Boris software enabled us to investigate the difficulties encountered by VR users during the use of the tool (Figure 10). Error analysis was used to generate two chronograms, one for the course with the MSc. students (Figure 10.a.), the second for the course with the AESC trainees (Figure 10.b.). We only analyzed the user errors of the VR users, as the MR users did not make any user errors. Two trainees used VR. The first one used it alone; the second trainee with the instructor, who gave comments and asks questions to stimulate other observing trainees. The trainee, accompanied by the instructor's comments, made no mistakes and produced a virtual battery in 19 minutes 30 seconds. The average use time of VR users is about 11 minutes.

This analysis shows that there are three types of error:

- Content errors (the user chooses the wrong input parameter, black lines on the chronogram (Figure 10)) the four MSc. students and AESC trainees using VR made this type of error, see the number of errors in Table 2;
- Operational errors (the user wants to select a parameter and activates the move command, blue squares on the chronogram (Figure 10)), see the number of errors in Table 2;
- Simubat 4.0 Gen-2 malfunctions (the user leaves the area of use of VR defined by the VR bases sensors, green square on the chronogram) see the number of errors in Table 2.

This error analysis shows that five out of the six users of VR (four in the MSc. students' course and two among the AESC trainees) made at least one content error. Among users of Simubat 4.0 Gen-2 without instructor's or Professor's comments, all made several types of errors. It can be seen that malfunctions related to the output of the user surface were more prevalent. We can observe that the malfunctions are prevalent when the user is outside the area of use defined by VR sensor bases.

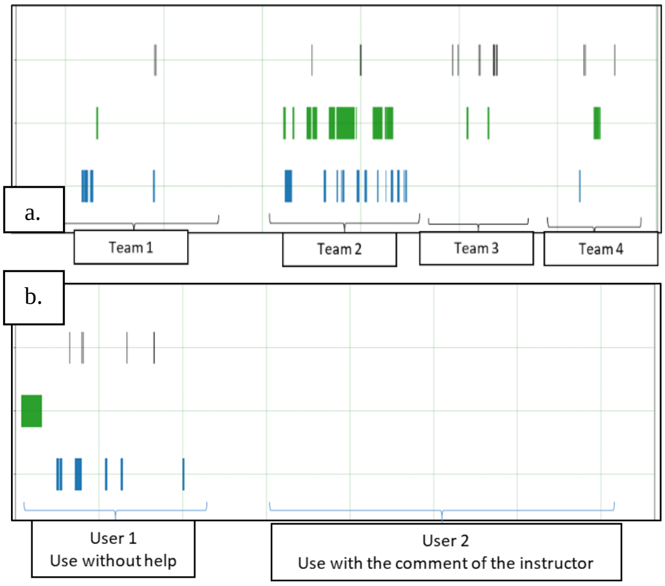


Figure 10: Chronogram of error analysis using Boris software: a. MSc. MESC+ and CD-MAT courses b. training session for AESC trainees.

The MSc. MESC+ and CD-MAT students attended a lecture in an amphitheater, using VR and MR in a restricted space that can be represented in the form of a narrow rectangle (Figure 11.a.). The user from Team 2 encountered 20 malfunctions (third type of errors) 312 seconds (5 minutes 12 seconds) out of a total of 895 seconds (14 minutes 55 s) of use. In the case of this user, we note that malfunctions linked to spatial organization also led to content and operations errors (first and second types of errors).

The AESC trainees attended a training session in a spacious meeting room. The area of use was defined on three sides by the tables and on the fourth side by a television which retransmitted the user's VR viewpoint. The user space can be represented in the form of a large square (Figure 11.b.).

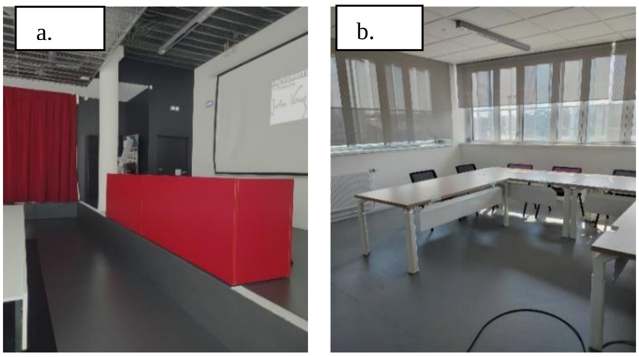
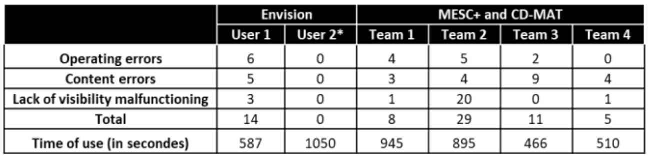


Figure 11: Photos of Simubat 4.0 Gen-2: the. amphitheater for the MESC+ and CD-MAT masters courses b. the training meeting room for the training session with AESC trainees.

The user from Team 3 was the fastest to make a battery cell in the virtual environment, taking 7 min 46 s (Table 2). However, he also made the most content errors. In order to move faster, the user selected the input parameters without thinking beforehand. Four out of six users made operational errors. These errors appeared for three of them within the first minutes of use and disappearing when they felt more familiar with the tool.

Analysis of the observations allows to understand how Simubat 4.0 Gen-2 is used by the two types of users. In summary, optimal use of Simubat 4.0 Gen-2 is subject to 3 parameters: knowledge to choose the right answers (to avoid content errors), understanding of how the controllers work and how to use them (to avoid operational errors) and a large area of use (to avoid malfunctions).



	Envision		MESC+ and CD-MAT			
	User 1	User 2*	Team 1	Team 2	Team 3	Team 4
Operating errors	6	0	4	5	2	0
Content errors	5	0	3	4	9	4
Lack of visibility malfunctioning	3	0	1	20	0	1
Total	14	0	8	29	11	5
Time of use (in secondes)	587	1050	945	895	466	510

Table 2: Number of errors made by VR users and time spent using VR during MESC+ and CD-MAT training sessions and AESC trainees.

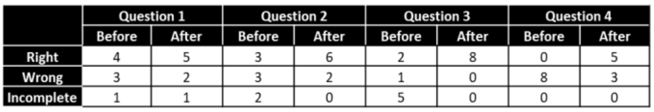
3.3. Results of questionnaires

AESC trainees evaluated the usability of Simubat 4.0 Gen-2 using the CSUQ. On average, users rated the overall usability at 6.40 out of 7 and a standard deviation of σ = 0.4 which suggests good overall user satisfaction. This means that the overall usability of the tool is very good.

System usability had the lowest value (μ = 6.53) indicating that the tool was appreciated by users who considered the system easy to use. “Information quality” and “interface quality” dimensions of the questionnaire scored higher than the overall score, respectively μ = 6.21 and μ = 6.28.

Users expressed their satisfaction during use. The first user of VR in the AESC training said "*it is great*". At the end of the session, several participants wrote positive comments: "*Simplicity and explanations, simple visuals*"; "*Realism and the possibility of discussing with a concrete example without taking risks*".

In addition, knowledge questionnaires were performed before and after using Simubat 4.0 Gen-2. The Table 3 below lists all the correct, wrong, and incomplete answers. We note that the number of correct answers is always higher after the use of Simubat 4.0 Gen-2. The question 4, on the effect of the input parameter on the quality of the battery, showed no correct answer before use, and more than half of the AESC trainees had the correct answer at the end of the training session.



	Question 1		Question 2		Question 3		Question 4	
	Before	After	Before	After	Before	After	Before	After
Right	4	5	3	6	2	8	0	5
Wrong	3	2	3	2	1	0	8	3
Incomplete	1	1	2	0	5	0	0	0

Table 3: Table summarizing the number of correct answers, wrong answers and incomplete answers to the knowledge test before and after using Simubat 4.0 Gen-2.

In summary, users rated the use of Simubat 4.0 Gen-2 as satisfying. They appreciated how easy it was to use and how easy it was to understand information. Similarly, the answers to the knowledge questionnaires also demonstrate the educational contribution of the tool.

4. Discussion

In this section, we discuss the contributions of Simubat 4.0 Gen-2 in terms of pedagogical objectives, ease of use, and knowledge acquisition.

4.1. Simubat 4.0 Gen-2, a training tool with several objectives

The results of our study show that the use of Simubat 4.0 Gen-2 can be applied to several types of training with different user’ profiles. We have observed that the distribution of information themes differs depending on who attends the training course. The MSc. students from MESC+ and CD MAT, had already completed four years of academic training in the field of materials chemistry and attended courses on battery manufacturing. Therefore, they already had knowledge in this field.

The session with the AESC trainees was focused on two-week professional training course hosted by our laboratory, designed to give them the knowledge they need to work as process engineers on AESC's production lines. The aim was to give novices the knowledge they needed to be ready to go into operation quickly and deliver optimal results.

4.2 Using Simubat 4.0 Gen-2

4.2.1. Measuring usability and utility

The AESC trainees gave a very positive assessment of the usability of Simubat 4.0 Gen-2, scoring well in all dimensions of the CSUQ (usefulness of the system, quality of information, quality of the interface). These results are in line with the comments made by the trainees during their use of the game and the written comments in the post-use questionnaires. In particular, they highlighted the simplicity of use and the game's ability to synthesize and visually explain complex concepts. Thanks to the information provided and the interactive functions both types of users and participants were comfortable using Simubat 4.0 Gen-2.

We also note that the tool makes an interesting educational contribution. AESC trainees had already visited our (LRCS) pilot line before participating in this training session and filling in the pre-use knowledge questionnaire. After using Simubat 4.0 Gen-2, they fill a post-use knowledge questionnaire. The scores of this post-use knowledge questionnaire were higher than pre-use knowledge. In summary, Simubat 4.0 Gen-2 provides additional knowledge to that acquired through observation in a real pilot line.

4.2.2. Become familiar with Simubat 4.0 Gen-2 in training

We performed a study on the analysis of errors during use, which enabled us to differentiate three types of errors of different origins. The first type concerns content-related errors when users choose incorrect input parameters. This type of behavior is linked to a lack of knowledge or misunderstanding of the user's initial instructions. Users could use the virtual notebook in one hand to find out a description of the current step. They could also return to the instruction board at the entrance to the room. When users choose wrong parameter due to a lack of knowledge, the virtual environment provided no explanatory feedback to support the user's reflection. The instructor's intervention was essential to obtain additional information and succeed in the game. The analysis of the errors allowed us to see that the instructor's intervention during use meant that the user did not make any error relating to the content. The instructor asked several questions to challenge others AESC trainees to get involved and reflect on the situation. In the same time, these questions guided the user through the virtual manufacturing process. Therefore, we note that Simubat 4.0 Gen-2 does not yet enable novice users with lack of knowledge to avoid errors in selecting input parameters during the manufacturing process. In the case of a wrong answer, the user is warned with a message but there is no explanation in our serious game to help them find the right answer. It is then difficult for a novice to find the right answer himself without any explanation or hint.

The second type of errors is linked to difficulties in understanding the commands labeled as *operating errors*. Users often mixed up the “move” command, which was operated with the thumb, with the “select“ command, which was a triggered operated with the index finger. The activity chronograms (Figure 10) shows that this type of confusion is very common at the start of use. They also appeared when the user is hindered by malfunctions (the third type of error). Results show that operating errors are linked to the ease of learning how to use Simubat 4.0 Gen-2. Despite the difficulties and confusion associated with the commands, we found that the participants were able to use the application quickly and correctly, indicating that it was easy to use. As in the study written by Criollo *et al.*, we can therefore identify this type of behavior as being linked to getting to know the tool. Regarding the qualitative content analysis and the CSUQ score, there were no technical drawbacks significant enough to reduce participants' enthusiasm [25].

The third type of error is malfunctions which appeared when the user went outside the area of use of the tool or when they were hindered by an obstacle. VR characteristics prevent the user from perceiving their external environment. When the user went outside the area of use defined by the VR sensors bases, Simubat 4.0 Gen-2 presented slowdown, and the use became increasingly irregular. This had to do with VR technology itself. When it happened, the user could not perceive that he/she had left the area of use. In this case we noted that, users were lost and tended to be more confused about the commands (operating errors) and content (content errors). Analysis of the verbalizations shows a strong correlation between the lack of vision nodes and operational errors nodes. In our study, we noted that narrow spaces could be hindrance for VR users.

In fact, the spatial organization of learning environments affects teaching and learning activities [45]. The literature shows that organizing lessons in clusters facilitates learning by encouraging active collaboration between students [46]. This type of spatial organization fosters informal exchanges. The results of our study show that organizing the area of use into squares (*e.g.* training room with AESC trainees) avoid users to go outside preventing Simubat 4.0 Gen-2 from malfunctioning. Nevertheless, narrow spaces (*e.g.* course amphitheaters with MSc. students) restrict movement and make VR users uncomfortable (cf Figure 11). In the same time, MR users are not bothered by this area of use parameter because this technology does not use external motion detection bases and it allows to perceive the real environment around.

Ganier, Hoareau, and Devillers (2013) showed that in the context of learning, virtual environments could help individuals to learn new procedures [43]. They also showed various indicators of use to evaluate the learning of a procedure *i.e.* the total time taken to complete the task, the number and duration of times instructions were consulted, the time taken to execute actions and the number of errors decreased as trials were repeated.

4.3. Knowledge acquisition through the use of Simubat 4.0 Gen-2

We also showed that the AESC trainees had more knowledge in battery manufacturing processes after using the Simubat 4.0 Gen-2. It should be noted that the VR and MR training took place in the afternoon of the fourth day of training. The trainees had already followed several theoretical training sessions on energy storage systems and battery manufacturing process, as well as observations in the LRCS pilot line which served as a model for the digital twin.

These results on the gain of knowledge using Simubat 4.0 Gen-2 (in VR and MR) can be explained in three ways.

The first explanation is that virtual environments enable a better conceptual understanding and reduce the failure rate by improving the visualization of complex theoretical concepts [12]. In our study, VR users were able to follow a complete battery manufacturing process for a few minutes whereas in the real world it takes several hours. MR users were also able to understand easily the composition of an electrode.

The second explanation is that by using Simubat 4.0 Gen-2, the users are actors of their training. VR and MR allow users to experience action and processes as part of the "learning by doing" theory which is a method of teaching [47]. One of the difficulties in learning battery manufacturing process is the inability to work and experiment in laboratories with dangerous and expensive materials, chemical solutions, and machinery. VR and MR offer learners advantages such as the flexibility to take their time and hands-on learning [48]. This method of learning is a long-term investment and using digital twins is a safe and cost-effective option [34]. The training program for AESC trainees combined theoretical classes, observations and practical classes, as well as the use of VR and MR environments. These immersive environments acted as intermediaries between theory and real-life observation and experimentation, enabling trainees to reach a higher level of understanding than when they enter the real laboratory environment [49]. Constructivist theories of learning emphasize the importance of students playing an active role in their learning, constructing their knowledge rather than listen it passively. This is one of the most important consequences of cognitive science research in education [50]. Simubat 4.0 Gen-2 using VR and MR places trainees as active learners to build their knowledge and be engaged in the learning process [16]. In the MSc. students' course, a collaboration between the student "advisors" and the student using VR quickly got underway, *e.g.* “advisors” indicated the next step to be performed or the correct input parameters to be chosen. Thanks to the instructor’s questions AESC trainees also played an active role, which helped them to be involve and promote conceptual and operational understanding. The advantage of VR in these situations is that it can freeze the situation to focus on a problem, get attention, ask questions or provide an explanation, which would be impossible in real environments [15]. The aim of using Simubat 4.0 Gen-2 is to enable users to develop their own understanding of LIBs manufacturing process and apply it to new situations. Technological environments such as Simubat 4.0 Gen-2 aim to involve users as a preparatory step towards professional life and collaboration with peers [12].

The third explanation is the principle of "encoding specificity" theorized by Godden and Baddeley, which indicates a dependency between the encoding context (*i.e.* the learning environment) and the information retrieval context which corresponds to the place where the individual needs the information in their activity [51]. Therefore, it could be considered that the use of digital twins such as Simubat 4.0 Gen-2 could help professionals retrieve information once they are in a real pilot line.

We believe it is important to emphasize that we investigated the contribution of Simubat 4.0 Gen-2 on a very small group of users. We concentrated on MSc. students in chemistry and trainees from AESC Gigafactory who had no knowledge in the field. We proved that after using the tool, the AESC trainees had additional knowledge, even after observing the real activity in the pilot line. In the other hand, we did not measure the knowledge acquired before and after use by the MSc. students. So, we do not know whether the tool provides knowledge to users with prior knowledge about materials chemistry and the LIBs manufacturing process.

In the case of the AESC trainees who came to the laboratory for a two-week training course, we did not set up a control group (who would not have used Simubat 4.0 Gen-2) to be able to compare the level of knowledge of the users at the end of the two-week training program. Similarly, we did not have the opportunity to measure the theoretical and operational knowledge of users over time at the end of their 2-week training course or within the Gigafactory itself or at long term. These are elements that need to be investigated to determine the real added value of Simubat 4.0 Gen-2 as a teaching tool. The indicators defined by Ganier, Hoareau, and Devillers could be useful for investing long-term learning with Simubat 4.0 Gen-2 [43]. It is therefore essential to use this tool with a wider range of users, particularly those with different needs, and this is part of our planned activities for the future.

5. Conclusion and perspectives

Based on the results reported here, Simubat 4.0 Gen-2 is a usable and useful tool for battery manufacturing educational purposes. From the point of view of usability (or ease of use), we have shown that Simubat 4.0 Gen-2 is a training tool that allows users to easily, quickly, and visually understand the complex processes involved in battery manufacturing and the composition and properties of the anode and cathode from a different level of visualization.

The usability of our tool was particularly highly rated by users. Furthermore, the results indicate that Simubat 4.0 Gen-2 coupling VR and MR is suitable for training, offering challenge, fun, and collaboration during its use.

Nevertheless, this study has enabled the identification of sources of difficulties encountered by the users during the training sessions. These difficulties provide us ideas for improving the design of future virtual environment devices intended for human learning. In fact, we have shown that the lack of explanatory feedback in Simubat 4.0 Gen-2 make its use dependent on the instructor’s comments specially on content errors. At the same time, the size of the physical area of use available to VR impacts the ease of using this device.

In the long term, we believe that certain characteristics of VR, such as the absence of perception of the real environment, make the user unable to see the external environment which can be a limitation. We believe that the use of MR as a training tool will become more widespread because of its ability allowing users to perceive the environment around them. We believe this technology promises to revolutionize training in battery manufacturing. This technology could be used in experimentation rooms and battery production lines. We also plan to make this technology an efficient tool to break the barrier between the digital and the real world by maximizing the impact of digital technologies to support battery operators in their day-by-day work.

Supporting Information

We include several supporting information files.

The first one is a video showing the use of Simubat 4.0 Gen-2. We show the use of the Mixed Reality, photos and videos of the use of the tool by the MSc. MESC+/CD-MAT students and the AESC trainees.

The second one is a video of the use of Simubat 4.0 Gen-2 Web version.

The third one is a video of the use of the virtual reality component of Simubat 4.0 Gen-2.

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Keywords: battery manufacturing • training • virtual reality • mixed reality • digital twin

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