Designing complex manufacturing systems by virtual reality: A novel approach and its application to the virtual commissioning of a production line

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Designing Complex Manufacturing Systems by Virtual Reality: a Novel Approach and its Application to the Virtual Commissioning of a Production Line

Abstract

The design of complex manufacturing systems (CMSs) is challenging, because of the requirements of efficiency, safety, and ergonomics, and the need of optimizing resources, i.e., space, machines, operators, and data. Virtual reality (VR) – one of the promising technologies at the base of *Industry 4.0* – is able to address the design issues of CMSs, and even decrease costs and time when employed from the initial conception to the final validation of production lines, since it facilitates their virtual commissioning, i.e., it enables the full verification of systems and related components by virtual inspection and tests. Despite the above advantages, VR is still rarely used in the design of CMSs, and there is no standard VR approach in industry yet. In addition, the related scientific literature is scarce and often limited to small or simplified cases. To fill this gap, this work presents a novel VR-based approach for designing CMSs, composed of four phases: Three-dimensional CAD Export, Model Import, Scene Creation, and VR Review. The proposed approach is applied to a real industrial use case related to the virtual commissioning of an electric axles production line and it is evaluated through a questionnaire from industry professionals. The case study shows that using the VR technology enhanced the technical communication between experts in the teamwork, and it was particularly effective in finding ergonomics flaws like issues in visibility, reach, and posture using a virtual golden zone. In addition, all users found the VR interaction enjoyable and easy to learn, and beginner users perceived a comparable workload as advanced users.

Keywords: Industry 4.0, Complex manufacturing systems, System design, Virtual reality, Virtual commissioning, Human computer interaction.

1. Introduction

The new paradigm of *Industry 4.0* is significantly pushing the implementation of the so-called smart factory, where physical and digital systems are strongly integrated in view of the final goals of achieving efficient product development with flexible mass customization [1, 2] and satisfying increasingly competitive markets that require fast time-to-market and high quality products [3, 4]. To achieve these challenging objectives, industrial complex manufacturing systems (CMSs) – the collection of machines aimed at converting raw materials, components, or parts into value-added finished products – must implement a high level of connection between the physical and the virtual worlds and obtain a high grade of operational productivity and efficiency in terms of costs, time, and space [5, 6]. CMSs are called complex because of their structural, configuration, and operational intricacy and their high variety of components, transportation mechanisms, interconnections, and inter-dependencies [7].

Due to their complexity, the design of CMSs is a challenging activity, requiring multidisciplinary proficiency in the definition of several dependent machines' requirements and constraints, the management of large scale layout, the integration of hardware and software, and the implementation of human-robot and robot-robot collaboration. An additional issue is to the long lifespan of projects (normally, 2-3 years of development), during which requirements can change in terms of design.

The success of the CMS design significantly depends on the ability of teams from different engineering sectors to collaborate and work effectively in solving complex problems [8]. As a common industrial practice in the CMS industry, the design and review phases are typically performed on desktop PCs equipped with a CAD (Computer Aided Design) software and a two-dimensional (2D) screen. However, complex three-dimensional (3D) problems – such as optimizing space, keeping a suitable distance between different sub-systems, enabling the correct interaction between moving parts, and ensuring the human-machine ergonomics and safety (e.g., body posture, reach, visibility) – may be difficultly assessed by using a 2D interface. As a consequence, it is very common that problems arise only during the final implementation of the CMS, causing high cost and time of re-design. To overcome these issues, the commissioning of CMSs is recently leveraging on the benefits of the novel concept of virtual commissioning [9]. This paradigm enables the full validation and verification of a CMS by virtually visualizing and testing the system and related components, thus reducing time to market, lowering costs, and increasing productivity [10, 11].

Against this background, the main motivation of this work lies in the collaboration of the authors with a worldwide leader of CMSs, employing *virtual reality* (VR) as a key technology to address CMSs design issues, with the final aim of achieving ambitious industrial goals and high customer satisfaction [12]. Indeed, VR provides a 3D interactive simulation of the CMS (see the example in Figure 1) and supports the multidisciplinary design process, while facilitating the detection of issues in the early phase of the design process [13] and reducing the testing and integration time during the developmental phase [14]. Despite these advantages, VR is not often used in the industrial practice for the design of CMSs and the related scientific literature is still scarce, being mainly focused on the design review activity only, while addressing simplified manufacturing systems or consumer products [15]. Developing and deploying a real VR application in the industrial field is still challenging, because there are no well-established and standard procedures to follow. Therefore, this work contributes to filling the above identified gap by presenting a novel and general procedure for the design of CMSs supported by VR. The proposed approach is implemented on a real case study related to the development of an electric axles production line, thus showing a direct hand experience and validation. In particular, evaluating the effectiveness of the proposed approach, by means of the case study, in this paper we aim at answering the following research questions (RQs):

- *RQ1: Does the presented VR approach support the CMS design process?*

(a) (b)

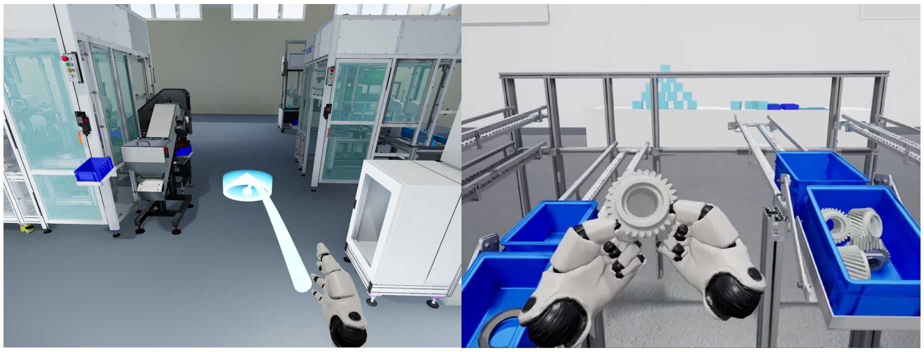

Figure 1: Examples of interaction tasks used in the VR environment for CMSs: teleport for exploring large spaces (a), touching and grabbing for assessing ergonomic aspects (b).

- *RQ2: Which steps of the CMS design process can benefit from the use of VR?*
- *RQ3: What is professionals' acceptance of the VR approach for CMS design?*

The rest of the paper is structured as follows. Section 2 illustrates the state of the art on the use of VR in the industrial setting, positioning the paper in the related literature on VR methods used in the design of the manufacturing systems. The novel VR-based approach for the virtual commissioning of CMSs is presented in Section 3. The application of the proposed approach to the real case study is illustrated in Section 4, showing the effectiveness of VR in supporting the critical phases of CMS development. Section 5 discusses the evaluation of the proposed VR approach from the users' perspective through a questionnaire. Finally, some concluding remarks are reported in Section 6.

2. Related Works and Paper Contribution

Numerous VR technologies have been proposed over the last years to enable humans to experience a virtual environment. VR is based on computer graphics, which can build virtual scenes and items to be manipulated by the user through input devices, such that the user can feel highly immersed in the virtual scene[16, 17]. VR technologies are widely employed in several industrial fields, such as the automotive, aerospace, bioengineering, and construction sector, [18, 19]. In particular, the most common and promising applications of VR in the industrial setting employ VR to simulate actual environments and are usually used for training [20], maintenance [21], and design [22]. In particular, efforts to implement design changes in the conceptual development phase require significantly lower resources than late project updates and revisions, and this condition results in the conceptual review having a high impact on a design solution.

Recently, VR has also been used in virtual commissioning in order to facilitate the integration and assembly planning, testing, and debugging steps [23]. In line with the final goals of virtual commissioning, the VR technology allows the immersion of the users into a virtual model of the production system and experience as if they already existed, allowing designers and operators to not only observe the CMS but also proactively interact with it in a virtual environment without any risk of physical destruction. For instance, Dahl *et al.* [14] describe a method where VR provides the interaction with a virtual simulation environment as an extension to the virtual commissioning project.

Nevertheless, the design phase is one of the crucial phases of the CMS development process [24]. For this reason, a large portion of the literature is focused on the use of VR to improve the design. For example, Bordegoni and Caruso [25] highlight the importance of checking the design issues before assembly and during reviews with the customer. The authors present a methodology that enables the collaborative design review of automotive interior components by allowing experts to interact with the virtual product prototype through a mixed reality design platform [25]. During the design phase, design reviews represent a cognitive process that allows users to see project issues in a 3D model and collaborators to share expert information for efficient decisions [26]. In this regard, Wolfartsberg and Wolfartsberg *et al.* [27, 28] describe the development and evaluation of a VR-based tool to support the engineering design review, presenting an approach to counteract the social exclusion in VR applications and to support the communication among users in a time-efficient fashion. The design assessment is the basis of design review activities, since experts from different disciplines have to discuss and concur on a design solution while exchanging project information according to well-defined standard procedures [29]. Similarly, Gebhard *et al.* [30] present a VR application implemented in the field of factory planning, which provides planners with the ability to perform realistic walk-throughs in digital factory models, while achieving a good integration in the factory planning workflows.

As shown above, VR has been applied successfully in the related literature during the design review with the customer, but it is not yet employed as a common standard tool in the company internal procedures. The hesitation regarding the VR technology integration in the manufacturing world is probably due to the negative experiences with old VR tools generations, to the lack of VR technology know-how and competencies in the companies, and to the lack of adequate engineering-oriented VR standards [31]. In this context, user's questionnaires may be helpful. For example, Berg *et al.* [32] present the empirical results of interviews with VR users and practitioner. Through a series of on-site visits to different factories, participants are asked to outline the steps involved during the common VR use case scenario. The correlation between the design review and the company process has yet to be clearly defined.

We finally would like to remark that the VR environment, differently from a 2D tool, helps stakeholders make realistic evaluations. Indeed, different researches also contribute to the field of VR-supported design reviews for ergonomic considerations. For instance, immersive VR has been proposed as a solution to improve workers' safety by virtually replicating the operations of the shop floor [33]. In this context, Manghisi *et al.* [34] describe a design of the automatic ergonomic monitoring for the evaluation of postural risks and a training system for increasing operators' awareness. Moreover, Peng [35] proposes the use of VR for ergonomic evaluation and verifies the reachability of door handles within a vehicle. Instead, Caputo *et al.* [36] present a framework that uses digital twins of stations to minimize the time needed to develop a new assembly line and to enhance the integration of ergonomics in the workplace design. Automotive industries employ virtual prototypes to establish design criteria and verify the visibility and reach-ability of the instrument [37].

In conclusion, the previous literature review highlights that using VR as a support tool for the design of CMSs [38] is effective but also raises various technical challenges. VR is not a well-consolidated practice yet: no standard implementation procedure exists, whilst practical applications present only isolated or scattered experiments, that are usually limited to simplified systems or a single machine or final product [39, 40, 41]. This work contributes to the virtual commissioning design of CMSs, by providing a novel procedure that explains step-by-step how to integrate the use of VR in the CMS design process and by discussing the benefits offered by VR sessions to stakeholders compared to more traditional methods. The case study – related to a real CMS design scenario – investigates the VR potential in virtual commissioning to define design and parts, competencies, requirements, equipment, and services.

3. The Proposed VR Approach for the CMS Design

The project design of CMSs is a central part of the larger business activity of the manufacturing system turnkey providers [42], and it is typically organized into three phases: commercial proposal, CMS development process, and after-sale service (see Figure 2a).

The project acquisition is finalized through the acceptance of the *commercial proposal* taylored to the customer, thus allowing the company to set up the *CMS development process*. Conversely, the *after-sale service* consists in following the customer in the system installation, first run, ramp-up, and maintenance. During the key *CMS development* phase of the CMS life cycle, a multidisciplinary team conducts the project activities in accordance with a Gantt chart, that is typically divided into 7 phases (see Figure 2b): Analysis, Engineering, Supply Chain, Assembly, Test and Debug, Shipment and Installation, and Service. Each of these 7 phases starts with the corresponding milestone: Kickoff Meeting, Project Start, Procurement Start, Assembly Start, Machine Switch-on, Internal Validation, and Client Final Validation [43].

This work is specifically focused on the key *Engineering* phase (see Figure 2c), that is in turn divided into 3 sub-processes: Concept, Design, and Finalization. The main outcomes of the Engineering phase are the milestones denoted as Concept Review (CR) and Design Review (DR), which are in turn the start and end points of the Design phase. Typically, the involved actors in the engineering phase are: the Project Manager, that defines the timing and costs of the project, the Project Engineer, that is responsible for the technical decisions, the Technical Leader, that is in charge of the designers' coordination, and the Mechanical, Electrical, and Fluid Designers.

In a general engineering phase, the engineering team studies all the customer's requirements for the CMS (layout of the factory, output rate, takt time, number and kind of stations and workers, etc.). This phase typically makes use of different software platforms, ranging from general purpose tools like presentation programs to specific tools like 2D/3D CAD and simulation softwares. The outcome of the *Concept* phase is a preliminary concept draft of the project requirements that typically has a conceptual 2D CAD representation as a milestone in the CR.

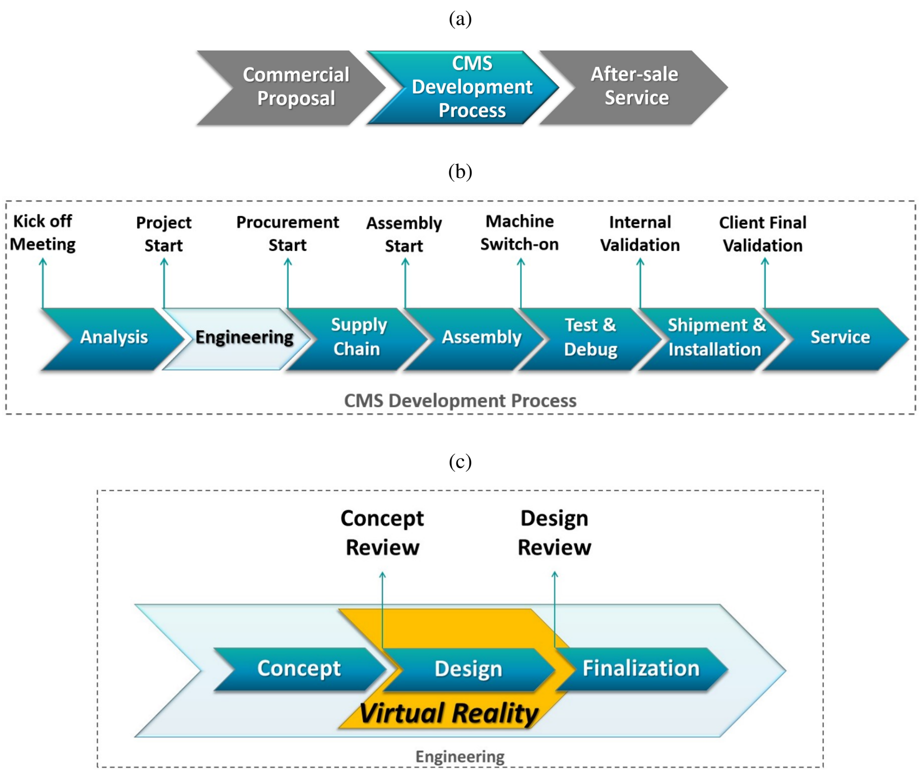

Figure 2: VR integration in CMS development process: CMS life cycle (a), CMS development process (b), and Engineering phase with the integration of VR (c).

The CMS *Design* is the core phase of the Engineering phase and typically starts by creating a 3D CAD model of the production line, detailed to all the single machine components. These can be fully outsourced systems or, as occurs in most cases, a custom integration of sub-assemblies, supported by complex logic, wiring, and services (compressed air, power lines, water, oil, waste, etc.). Due to the high level of customization, complexity, and multidisciplinarity, this phase requires multiple internal and external design review phases with different design expertises: electrical, mechanical, ergonomic, etc. In addition, it is common to conduct regular audits with the customer to receive comments and feedbacks aimed at improving the system [44]. Specifically, according to the IEC-61160 standard [45], the DR meetings are key activities that, if properly implemented, enhance the potential for delivering a product with the required dependability, quality, performance, safety, and for reducing costs and delivery times.

Communication has a substantial role during the design process because it allows to exchange messages and convey ideas to people with different skills and interests. VR tools can provide a very good representation of space and are used in parallel with the traditional mechanical design tools (CAD, simulation tools) as a complementary communication and review method and support tool for the main 3D CAD software

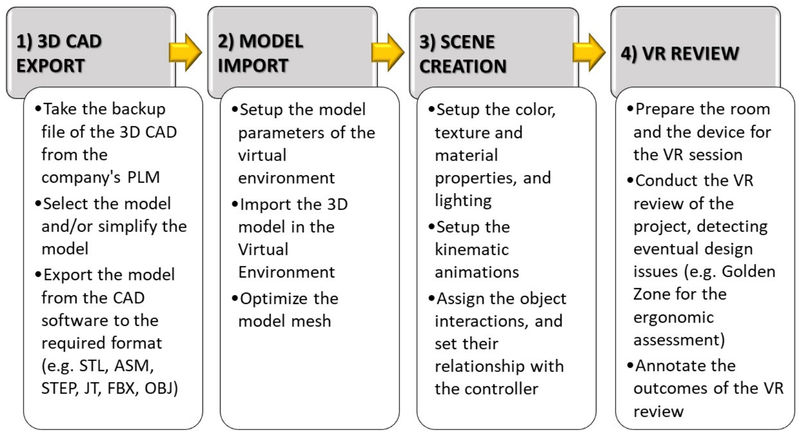

Figure 3: The proposed VR-based approach supporting the design of CMSs.

platforms (e.g., NX Siemens, PTC Creo or Dassault System Catia).

After the Design phase, the *Project Finalization* phase includes the bill of material export in the enterprise management software closing the engineering top-level phase, and working as input for the next phase of the CMS development process supply chain.

3.1. Procedure for VR Integration into the Engineering Design phase

The integration of VR into the core CMS engineering phase, i.e., the design phase, is described in the sequel. For the sake of optimally preparing and executing the VR session, we present a novel approach for the VR-supported CMS design composed by four steps, as shown in Figure 3. The final users – comprising not only the internal but also the external staff – play specific technical roles in the VR sessions as indicated in Table 1.

Starting from the Concept, the Project Engineer plans the steps for the efficient and accurate manufacturing of the model. The presented approach is based on the four steps detailed in the sequel: 3D CAD export, Model Import, Scene Creation and VR Review.

3D CAD Export

This phase consists in exporting the CAD file of the project – usually stored in the company product life-cycle management (PLM) database – with the final goal of preparing the conversion from the CAD format (i.e., a full geometrical and mathematically-exact representation) into a graphical version (employing meshes) that is compatible with the interactive visualization on the VR platform. This conversion is computationally intensive. A common mistake is to export the model without preparation, causing time-consuming operations, since the geometrical complexity of CMSs generally significantly exceeds the maximum number of geometries required by interactive graphics in VR. For this reason, a first effective simplification is performed in this phase by selecting and isolating the key subsystems from the ones which are not important to the

Table 1: Team of users involved in the VR reviews and their roles.

Category	Role
Competence Leader	Organization of large projects, management of staff, and definition of goals as a department leader. Her/his participation during the VR reviews is required due to her/his wide experience.
Project Manager	Organization and management of time, costs, and resources that are necessary to complete a project. Partecipation in the VR reviews is needed to update the project's Gantt chart.
Project Engineer	Make all technical decisions, ensuring work is being completed safely and efficiently. During the VR reviews she/he checks the project's updates, confirming and making planned and new decisions, respectively.
Sales Engineer	Prepare and finalize the commercial proposal for the project acquisition and make all the commercial decisions during the project life. Her/his participation during the VR reviews is linked to the economic aspects affecting suppliers and partners.
Technical Leader	Coordinate all the designers from the technical aspect of the project. Participation during the VR reviews is conducted as an expert designer.
Designers	Mechanical, electrical, and fluid-dynamics designers that realize the project and communicate with suppliers. During the VR reviews they check the CAD model issues and analyze how to apply the required upgrades and modifications.
VR Specialist	Building the VR application following the proposed procedure, preparation of the VR environment with objects interaction and animation, and controls that the VR experience meets the intended goals.
Assembly Leader	Responsible for the team during the assembly stage. Partecipation in the VR reviews is needed to anticipate the detection of eventual assembly issues to the engineering stage.

simulation and can be thus removed or approximated. An example of this mode of operation occurs in the design review of a specific station, where the rest of the line is just contextual and can be replaced even by a virtual background environment map texture. Further simplifications are achieved by disabling or deactivating CAD elements through engineering or drawing semantics such as layers, and parts grouping available only at this stage. This operation is very effective in removing elements that are not visible (e.g., internal mechanics) and not of interest in the design (e.g., light projections), thus avoiding to generate very complex meshes (like fasteners, or cabling). In this phase, engineers play a crucial role, being responsible of the CAD decisions to be taken on the ground of the simulation. Another critical aspect concerns the setup of the CAD origin and other reference points in a convenient location, e.g., zeroing the system in the desired station, preparing camera orientation axes, placing dummy objects to reuse key positions and axes (e.g. for setting constraints and animation paths) and to save time avoiding retrieving these data on a meshed model.

In the 3D CAD export, CAD data have to be converted into graphical meshes, which may or may not include materials, camera and light positions, and animations. The FBX format (Filmbox) is recommended because it is well supported and can contain material textures embedded in the file, thus resulting more practical than the OBJ format (Object). As a second choice, the STL format (Standard Tessellation Language) [46] is very common but does not contain materials. Recently, other formats, such as ASM (Autodesk Shape Manager) [47] and JT (Jupiter Tessellation) [48], are available; however, they are not properly supported into the graphical libraries used for VR. As an alternative, mathematical formats –such as the CAD native format STEP (STandard for the Exchange of Product model data) [48] and IGES (Initial Graphics Exchange Specification) [48] – can be used in conjunction with external third-party meshes-optimizers to successfully perform the conversion. However, we remark that it is very common that, due to commercial reasons, CAD export rarely transfers all the potentially available CAD data in the target file format; hence, conversion is commonly associated with lost data, such as materials graphical proprieties and textures, kinematic animations, grouping and layering, cameras and lights. Unfortunately, these data must be recreated in the target platform by cost and time-consuming manual procedures, with high risk of creating inconsistencies. On the ground of these considerations and according to the specific process of CAD and VR libraries, all the possible export paths must be evaluated and tested in order to find the optimal choice.

Model Import

The 3D CAD model must be then imported into one of the available VR platforms: Unity3D [49] and Unreal Engine [50] are the most common. On the one hand, Unity3D supports only mesh formats like FBX, OBJ, or STL; consequently, all CAD data must be converted before being imported in Unity3D [33]. On the other hand, Unreal Engine uses a plugin called Datasmith that directly supports common CAD data formats [51]. We remark that also this import conversion suffers from loss of data such as materials, animations, light, and camera; hence, it is crucial to optimally set the different options offered by the import phase before using the model. For instance, when the scene author applies scales and rotations to each object, ineffective time-consuming operations can raise in the case the model scaling and the main axes rotation parameters are not properly set.

Another key aspect concerns the complexity of the mesh. A complex CMS CAD model conversion generates a huge number of graphical elements (e.g. triangles, materials, animations, etc.) that could lead to an unacceptable level of frame rate [52]. Studies on VR applications show that a frame rate lower than 100 frames per second can produce discomfort to users, and the long term can even lead to cybersickness effects, such as disorientation and nausea [53]. Based on the target VR graphics hardware, it is possible to estimate the maximum number of supported graphical elements (e.g. number of triangles) for achieving the minimum frame rate. The mesh simplification task can be executed inside the VR environment when possible or using third party external tools (e.g. Simplygon [54], Meshlab [55], etc.). These mesh optimization tools implement re-mesh algorithms aimed at reducing the triangle count and the organization of the materials, while creating a level of detail nodes checking the perfomance of the obtained models. Even though the performance of these tools is becoming better and better, an engineering supervision is still required, since some key geometries may be eliminated or simplified with benefits in terms of usability and collision evaluation. For instance, using edge selection – which enables the lowest visual change to the model –

is an effective trick for producing good low-polygon models [56].

Finally, it should be noticed that the VR hardware requires a dual rendering (one per eye), and the required results by the graphic card and frame rate can vary according to the specific scenario and type of interaction. Therefore, employing a trial and error approach with higher levels of simplification is suggested.

Scene Creation

This phase aims at creating the realistic simulation of the CMS, allowing to use the virtual experience as a decision tool for spotting issues, finding solutions, and even simplying showcasing and marketing. For this reason, multiple scenes may be created to fulfill each activity and support the approach and language of the dedicated team. The converted mesh generally lacks materials or is not sufficiently realistic because it does not use shaders or multiple texture maps. Therefore, in this phase, a crucial activity is performed by the VR specialist that improves the model by adding material properties, texture, lighting, sounds, and animations. The resulting level of realism can vary according to the specific needs, ranging from a quick approach using default materials (e.g., space evaluations) to very realistic environments that can help stakeholders visualize the final product in the marketing setting.

Object manipulation is a key aspect in the simulation as it serves for human-machine interaction evaluations. Models files that need to be freely manipulated, such as tools, must be identified in conjunction with the engineering team, which must always have technical supervision to the scene. Differently from what happens using 2D CAD software, VR requires different metaphors that mimic natural (grabbing) or supernatural where traditionaly mouse and keyboard are employed on a 2D surface (grabbing with a ray at distance) [57]. Physical constraints between objects previously set in CAD are commonly lost in this phase, hence the VR conversion, so the specialist must group them under a unique node in order to be manipulated as a single element.

A similar problem arises for kinematic animations, as the CAD joints and formulas are lost in the VR conversion. Therefore, the VR specialist must find a viable solution in collaboration with the engineering team. Some options characterized by a growing fidelity and effort are listed in the following ones: (i) reproduce the animation manually using the authoring tools provided in the VR library; (ii) create kinematic joints manually using the VR library physics; (iii) export trajectories key-frames from CAD files and import them in the VR environment (assuming that CAD files are compliant to VR environment and the integration of custom coding is available). Also, 3D sounds can be inserted in the VR scene to mimic real manufacturing noises and alters. The VR specialist can record from real or artificial machinery the manufacturing noises and locate them in the virtual scene together by the conditions to be triggered.

Another important aspect of the scene creation is interaction design. Based on the requirement analysis, and the particular objective of the VR simulation, the scene can have different interaction schemes. There are two common approaches: the first is the third person's point of view, and allows the VR user to act as a supervisor and observe the CMS; the second approach is the operator's point of view and allows the VR user to perform the task as occurs in the real production line. VR platforms offer default interaction prefabs, using VR controllers, to perform looking, walking, and teleporting, touching, and grabbing tasks (see Table 2). There is also the possibility to

Table 2: Interaction tasks performed during the VR reviews.

Interaction task	Description
Looking & Walking	Features provided by most common VR platforms to see and walk around the scene. In the case of CMSs these features help to mimic the operators' paths to reach key positions (e.g., maintenance).
Teleport	Supernatural features that allow the users to be transported across space instantly. In the case of CMSs these features are very helpful due to their large dimensions (see Figure 1a).
Touching & Grabbing	Features that mimic the natural interaction of grabbing and moving objects with and without gravity or kinematic simulation. In the case of CMSs these features are used to replicate the workers operation (e.g., picking tools and components) and move pallets on the conveyor (see Figure 1b).
Other Specific tasks	Features that implement (through appropriate scripts) specific interactions in CMSs, such as pushing a button to start machinery, opening a door for maintenance, setting a timer using a virtual LCD display, modifying the objects during the production process, showing ergonomic zones.

customize the specific interaction to modify the default options such as changing the walking speed, optimizing the buttons on the controller depending on the interaction activation. Moreover, specific interactions can require scripts to program different and personalized behaviors (e.g., when operating machinery).

VR Review

After completing the VR scene, the fourth and last step of the VR design approach, i.e., the VR review can be conducted. First, the VR specialist prepares a room dedicated to the VR sessions, with a large space for the virtual experience without collision objects (such as tables and chairs) for the user's safety. Subsequently, the VR specialist has to set the VR device. For example, Oculus Quest [58] is a standalone device that can run projects in wireless mode under an Android-based operating system. It uses an internal sensor and an array of cameras in the front of the headset that can support positional tracking with six degrees of freedom. Thus, the VR specialist defines a boundary area for the session, useful for the users' safety, where the users are able to know if they are exiting from the area thanks to the camera. As an alternative, HTC Vive [59] is a virtual-reality system that incorporates room-scale tracking, using two infrared tracking stations located in opposite corners of the room to monitor the movement of the users, thus allowing them to freely walk around a play area, with their real-life motion reflected in the VR environment.

Hence the team performs the VR review and analyzes the project. The team addresses different design issues also by loading scenes and configurations dedicated to highlighting specific aspects such as visibility, ergonomics, design, and logistics. A key

Figure 4: Manikins and golden zones used in CAD software and imported in VR environment for the CMS ergonomics evaluation: representation of three safety working areas in the task of manual order picking.

strategy useful to carry out the ergonomic assessment is the so called "Golden Zone" [60], a method that represents the optimal pick volume (see Figure 4) that begins at knee height and closes just below shoulder elevation. This window minimizes lifting, reaching, and bending motions, and strain, thus the potential for long-term injury. Accordingly, we define the Virtual Golden Zone. More precisely, the Golden Zone model file is implemented in the VR environment as a tool for highlighting ergonomic issues that we called the Virtual Golden Zone. The VR specialist can implement the interaction during the scene creation to make the user able to activate and turn off the virtual golden zone in the VR scene using the controller. Additionally, during the scene creation could be imported a manikin CAD file with the golden zone to make the user able to analyze the issues as a "spectator" and turn around the machine. At the end of the VR session, the team collects the outcomes as a basis for analysis and evaluation. Generally, one person on the team keeps track of issues when the VR user detects it in the simulation. The VR experience can be organized to be single user or multi-user, while a larger screen is used to share the individual point of view to the other participants in the session.

4. Application of the VR Design Approach to a Real Case Study

In collaboration with an automotive company leader of the Italian and European market, we present as a case study the design of the production line of a 1.2 tons electric axle (e-axle) of heavy-duty vehicles.

4.1. Presentation of the Electric Axles Production Line Design

The e-axle line extends on 1864 square meters and is composed of a core section, with five modules for the e-axle assembling, and three support areas: the kitting area, where operators prepare the sub-assembly of motors and transmissions, the loading and unloading area for the e-axle box positioning on the cart, and the testing area at the end of the line (EoL) (see Figure 5). In addition, the core section is divided into two parts: the subline and the mainline. On the one hand, the subline includes a module with the rotor and transmission preparation stations (i.e., some press-fitting stations). On

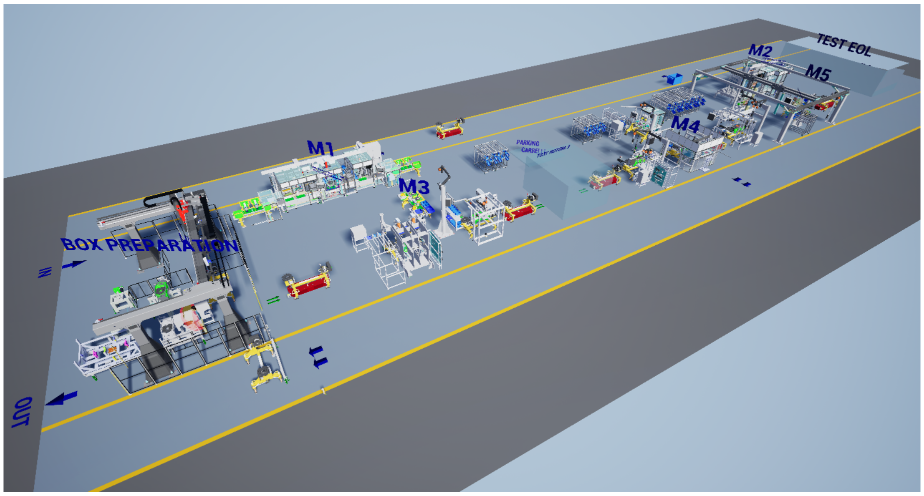

Figure 5: Layout representation of the e-axle production line analyzed during the VR review session, including the loading and unloading for the box preparation areas, the core section with five modules divided into mainline (M2, M3, M4, M5) and subline (M1), and the testing area.

the other hand, the mainline is composed of further four modules, including the area where the e-axle is assembled on a cart and moved by AGVs between the machines.

The VR design was aimed at analyzing only the core section of the CMS, i.e., the portion of the line with five modules for the e-axle assembling, and the loading and unloading area, including a total of 5 workers. The e-axle engineering phase lasted 25 weeks, and the first VR review was scheduled after 6 weeks from the start in the Gantt chart by the Project Manager. The team was composed of internal company members and representatives of the customer and suppliers. Usually, one review per week was organized only with the internal company members, whilst from 1 to 4 sessions per month were conducted inviting the customer staff, according to the updates. Sometimes also the representatives of suppliers took part in the VR reviews. Therefore, each session was generally composed has 2 to 25 people. The VR device was worn by one selected participant, while the rest of the team observed the user's point of view on a large screen or remotely, thus creating an interactive co-working environment.

4.2. Implementation of the VR Design approach

The VR design approach described in Section 3 was implemented in the selected company using Windchill as PLM system, NX as CAD software, Unreal Engine as VR platform, and Oculus Quest headset as hardware with a field of view of 110 degrees, is a six degrees-of-freedom and inside-out tracking. Moreover, the VR sessions were conducted in a VR room offering a PC equipped with a high-performance graphics processing unit (namely, the Nvidia GeForce RTX 2080 8GB Super). In the sequel the implementation of each step of the VR procedure is described in detail.

3D CAD Export

A total of 21 assembly CAD files was exported from the NX 3D CAD model (i.e., stations conveyors, tools, equipment, gravity rack, carts, and AGVs) available in the Windchill PLM repository, whilst all the machinery and components (such as screws, nuts, bolts, and other similar small components) that were not important for the simulations were removed. The CAD files were exported using the native NX, STEP, and JT formats. The native NX format was able to realize quick VR reviews during project updates (e.g., checking whether the CAD received from suppliers and partners met ergonomic requirements) since its execution requires low computational effort. The STEP format was used for CAD models with animation because it preserved the configuration of components in presence of CAD constraints (e.g., for the press-fitting machine with a prismatic constraint, the STEP files allow to store the last position of the piston, which has been used in the previous VR session). Lastly, the JT format required more conversion time but provided better meshes.

In addition to the CAD files related to the production line layout, two CAD manikins (namely, a woman with a height of 1.65 meters, and a man with a height of 1.75 meters) and their relative virtual golden zone were obtained. In the CAD platform these manikins were usually positioned by the designers in front of the stations to perform a first ergonomic assessment. This method was replicated in the VR environment where the manikins were exploited by the VR users to mimic the workers' movements and safety procedures and thus to improve the evaluation of ergonomics and safety aspects.

Model import

During the Model Import phase, the Datasmith Plugin was employed to compute the optimal triangular meshes of the input geometry for about five thousand components of each model. This operation required the manual tweaking of all the main geometries by setting the Chord Tolerance, Max Edge Length, and Normal Tolerance parameters. By tweaking these values, it is possible to control the complexity and fidelity of the Static Mesh geometry that Datasmith creates for curved surfaces. The values generally used for these import options were: 5.0 mm for Chord Tolerance, 0.0 mm for Max Edge Length, and 20.0° for Normal Tolerance. For instance, using these values, importing the model of the press-fitting tool for the rotor pallet (see Figure 6) produces a mesh that included 11508 triangles.

Scene Creation

For the e-axle project, 7 scenes were created. First, the VR specialist focused on conveying a realistic experience by setting texture, material, color, and lighting according to the design specifications. The Baked lighting option required to setup the Lightmap UV channels as "static" flags after the 3D model import. Baking lighting means precalculating the static global illumination which does not change in runtime. Alternatively, for scenes including several components, the fully dynamic lighting was used to avoid the computational effort required by the complete baking. The lightmap resolution (usually ranging between 32 and 256 lightmaps) was a trade-off between the requirement on the light simulation quality and the performance optimization: higher resolution produces better shadows, but increases graphic resources. Quality materials were assigned manually to the scene using a library. The used materials were mainly

(a) (b)

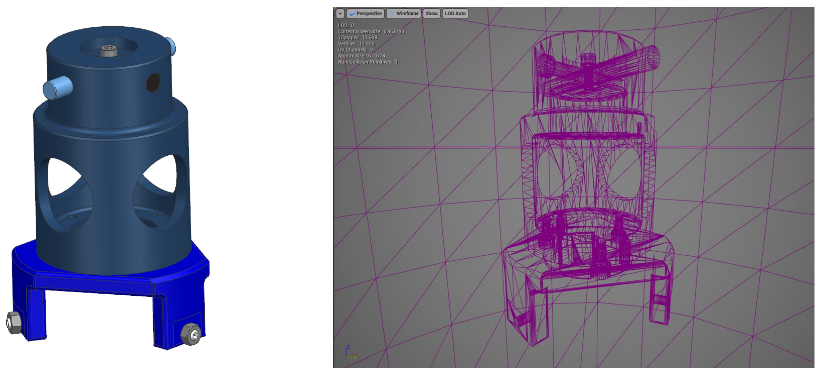

Figure 6: Example of model import results: the press-fitting tool for the rotor pallet in the native NX CAD environment (a) and in the Unreal Engine platform (mesh with 11508 triangles) (b).

reflective metallic (steel, aluminum, copper, and zinc) and plexiglas for the machinery, plastics, industrial floor, glass for windows and doors. Figure 7 represents a simple example of how the subline was realistically loaded in the VR scene, with windows, shadows, and artificial lighting.

Second, the VR specialist assigned the basic interactions *Looking & Walking*, *Teleport*, and *Touching & Grabbing*. Given the complexity of the e-axle production line, particular attention was given to the *Grabbing* command, which allows the user to perceive the relationship with the environment as if it was real. The grabbing interaction was based on a simple or complex collision area created on the object. As soon as the Oculus controller enters a construction group's collider, the VR tool triggers specific interactions and thus the actuators integrated into the Oculus controller triggers a short vibration. To do this, the components including different parts were grouped so that they can be manipulated as a single object to simplify the physic simulation and also to create the requested kinematic animations. For example, the imported press-fitting tool showed each part as an individual part –i.e., screws, bolts, and tool body– (Figure 8a-b); however, all static meshes of individual parts were grouped into only one entity. The collision shape needed by the grouped meshes allows the user to grab the whole object (Figure 8a-b). The interactions were enabled in the Unreal Engine platform thanks to a visual scripting, called Blueprint. In particular, to manage the grab interaction, a simple Blueprint was created aimed at implementing the input action for the grip on the controller. Figure 8c illustrates the details of the press-fitting station highlighting the touching and grabbing of the rotor press-fitting tools from the user's point of view.

Lastly, some specific interaction tasks were included in the VR scene with different levels of detail. In the e-axle project, three different specific interactions were implemented in the created VR scene: the virtual golden zone, the virtual menu, and training with holograms.

Figure 7: Example of the overall view of the subline in the internal environment created by the VR scene.

(a) (b) (c)

Figure 8: Examples of scene creation results. Details of rotor press-fitting tool with 26 DOP (Discrete Oriented Polytope) Simplified Collision (a), and rotor press-fitting tool with Complex Collision (b). Detail of the press-fitting station showing the touching and grabbing of the rotor press-fitting tool (c).

Virtual Golden zone - The manikin and golden zone model were considered for ergonomics assessment. A Blueprint was implemented, based on the visibility interaction, connected with the static mesh of the manikin and of the golden zone. To manage the manikin and/or golden zone visibility (input and output action) the blueprint was associated with the button ”X” on the left-hand controller.

Virtual menu - Another important interaction task was the creation of a virtual menu to control the e-axle box rotation on the cart and mimic the dressing operations. Three faces of the e-axle box (called A, B, and C) were identified to set the machine cycle and optimize the equipment positioning by the worker and obtain the e-axle dressing.

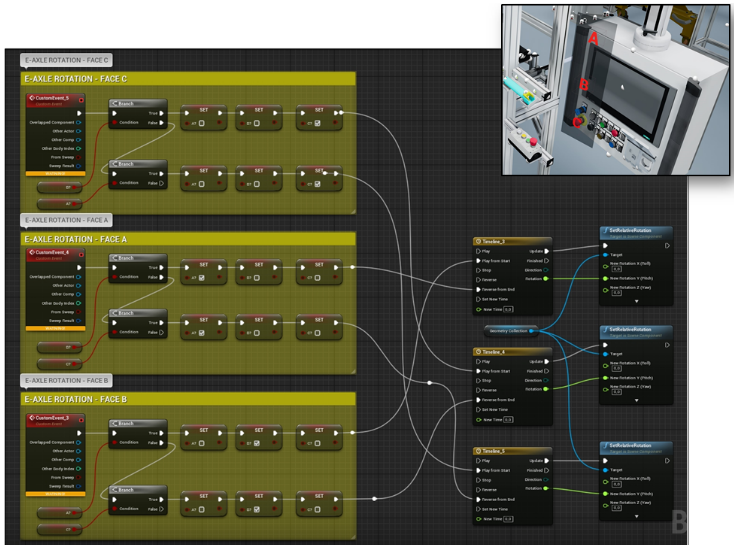

Figure 9: Event graph of the blueprint specifying the e-axle box virtual rotation. The subplot at the top right corner shows the interactive menu in the VR environment

.

To generate the rotation, a custom visual scripting was developed, connected with a virtual menu including the related three buttons (A, B, and C). The visual scripting was created using the Event Graph option available in the blueprint of the Unreal scene project. The blueprint was organized with three custom events blocks to activate the required face, three timelines blocks to manage the start and end positioning, three blocks to set the rotation of the e-axle relative to the environment, and one geometry represented by the e-axle model, all connected to each other. The rotation interaction allowed users to choose the preferred box face without order limitations (as shown in Figure 9).

Training with holograms - Finally, to mimic the e-axle dressing procedure as a training method, the ”hologram” function was implemented. It was created the hologram for each component that took part in the machine’s cycle. The blueprint contained a dressing sequence that brightened step by step the areas of the objects to give the order of the operation.

VR Review

After the VR environment setting, the VR Review phase was conducted. The VR sessions lasted from 1 to 4 hours for each session and involved about 20 people. The first VR sessions were organized to visualize singularly each station (i.e., the mainline, the subline, and the loading and unloading area), while the final VR sessions addressed the scene with all modules representing the overall e-axle production layout (reported in Figure 5).

Among the different scenarios, one was considered particularly useful for the company: the evaluation of the ergonomics of the operator. Usually, during the traditional design phase, the company already used import that manikin and golden zone in the software CAD to set the heights; differently, in the VR sessions the scenarios were centered around evaluating the visibility of a worker given a particular setting or posture. In addition, to design an efficient and safe workplace and avoid ergonomics risks due to material handling (e.g., back injuries), the company team analyzed all the stations using the virtual golden zone. Indeed, in order to analyze the worker activities, the manikin and virtual golden zone visibility were managed by the Oculus controllers. The obtained result, shown in Figure 10, was a semi-transparent volume with different colors around the Manikin to point out the safety areas within which the operators are able to comfortably perform the tasks. For example, comparing the manikin golden zones placement with the gravity rack location, allows the ”spectators” to check whether the highest boxes are located in the correct position. Moreover, the users inside the VR scene were able to mimic the operation and check if the arms movement were in the golden zone.

Finally, one of the VR review sessions was focused on checking the e-axle box rotation on the cart and mimicking the dressing operations based on the previously created interaction (see Figure 11). During the ergonomic evaluation, three cart configurations were defined and compared before identifying the final version that ensures the worker tasks to be in the golden zone due to the e-axle dimensions.

4.3. Outcomes and Implications

In this subsection, we debate the VR approach usability and advantages reporting the outcomes and implications derived from the analyzed case study.

As a first outcome, we highlight that, differently from similar approaches [32], the defined VR approach is not limited to laboratory tests: in particular, the conducted case study in a real industrial setting shows that VR can be effectively integrated in a company process by our standard methodology with well defined phases. Based on the lessons learnt from the presented case study, the company decided to implement the defined VR procedure as a standard enterprise policy to be followed in the design of CMSs by the different involved departments and in the relationship with customers and suppliers.

Second, we remark that the conducted VR reviews lead to tangible and relevant results. The comparison with traditional methods employed by the company shows that the 2D interfaces of CAD platforms have limits when bringing out the right impressions of the dimensions and proportions and reaching issues in 3D space. Conversely, by using the VR environment the whole e-axle assembly process was successfully analyzed, and various design issues were detected fast as shown in Table 3. In particular, ergonomics and visibility are the two main sources of issues that professionals appreciated throughout the VR scene navigation. During the VR reviews, the professionals were able to use the VR scene to effectively design the equipment and tool positioning as if it were a traditional project CAD. For instance, to design a safety picking by the operators, they determined the optimal equipment position and orientation of the cart near the machine. Moreover, they mimicked the operator task to verify if the picking operation is conducted in a ergonomically correct fashion (i.e., without turning the wrist or the torso).

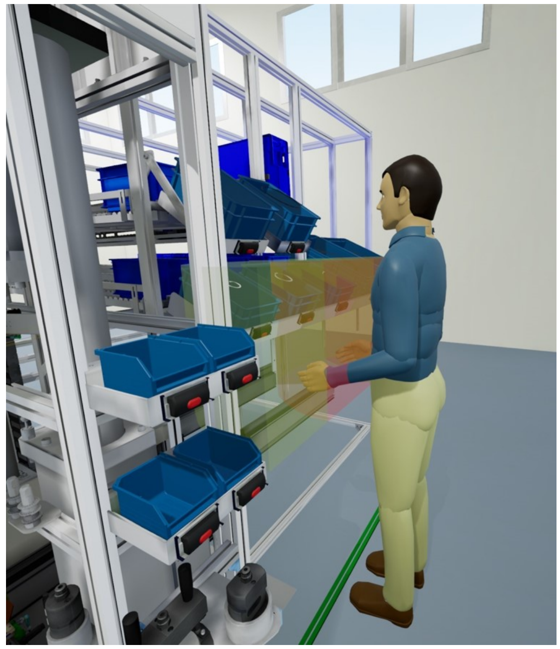

Figure 10: Example of the Golden zone method for the ergonomic assessment of the Gravity Rack in the e-axle CMS design.

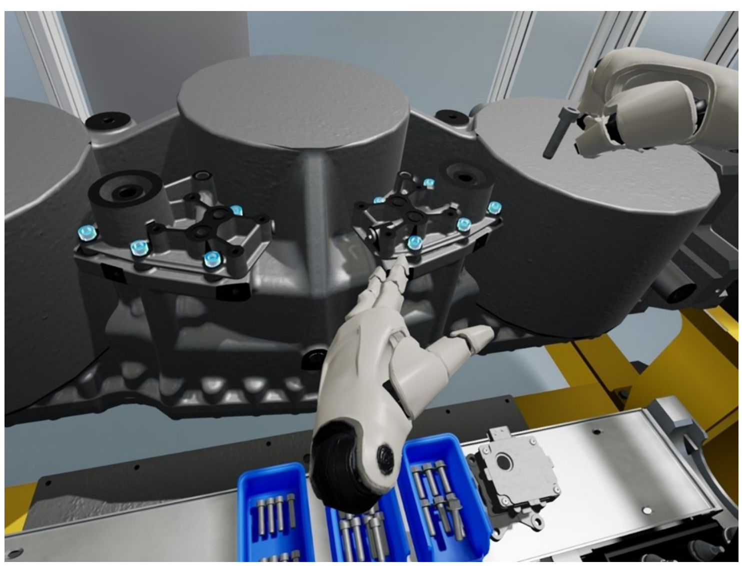

Figure 11: Example of touching/grabbing and assembly training tasks in the e-axle CMS design: details of the specific interaction using the light blue hologram to show the worker tasks step by step.

Table 3: Example of design issues related to ergonomics and visibility evaluation.

Design Issues	Ergonomics	Visibility
Gravity rack and box positioning	X	X
Press fitting tools positioning	X	
E-axle equipment positioning for kitting	X	
Powered driver positioning/handling	X	X
Tube oil orientations	X	
Ring nut screwing		X
Press fitting tool installation	X	X
Top bracket placement	X	
Return flow filter positioning	X	X
E-axle rotational displacement from cart	X	X
Box's cover handling/positioning		X
Space between cart handles	X	
The machine structure dimensions	X	
Special areas for maintenance operations	X	X
Distance between operator and HMI		X
Rotor and transmission inserting into the e-axle box		X
Stop-pallet sensors		X
PLC positioning		X
Dynamic leak test	X	X

The last outcome concerns the virtual commissioning of the CMSs. As shown in the case study, virtual commissioning, above all in the automotive field, requires that well-defined phases are conducted by various tasks and responsibilities. As matter of fact, the concept, design, and project finalization phases are indeed strictly connected, with continuous information exchange. In this context, the proposed approach aims at achieving great advantages in terms of cost and time savings due to the correction of eventual design flaws. Time-saving represents the common goal of different similar methodologies (e.g., [36]). However, other methods are available focusing on a specific topic, for instance, using VR to address the ergonomics evaluation only [36]. Instead, as shown in the case study, the proposed VR approach can be implemented in the whole design phase to achieve findings from a wider engineering perspective. Moreover, the case study finalization highlighted that time savings were earned during the assembly phase, since typical design issues were in advance fixed in the early phase thanks to the use of VR tools in the company CMS development process. Such time savings were estimated by the company based on the comparison with similar projects that were conducted through with traditional methodologies not relying on VR, experimenting several design issues until the production phase. Conversely, the e-axle project realized using the proposed VR approach layer was finalized with no open points reported through the CMS actual commissioning.

Summing up, the analyzed case study demonstrates that the VR technology plays a crucial role in virtual commissioning and supports the engineering process development from the concept to the design phase, while monitoring performance and provid-

Table 4: Questionnaire results related to the interviewed participants' level of familiarity with interface tools.

	No knowledge	Slight knowledge	Some knowledge	Moderate knowledge	Extreme knowledge	Total replies
CAD	1	3	3	4	12	23
VR	5	4	6	6	2	23
GUI	7	5	2	4	5	23

ing optimised design solutions thanks to VR review session.

5. Evaluation of the proposed VR Approach from the Users' Perspective

For the sake of evaluating the acceptance by professionals of the proposed VR approach, in the framework of the e-axle CMS design project, the proposed VR approach was evaluated through a questionnaire. In particular, 23 selected users involved in the VR reviews were asked to fill a questionnaire using Microsoft Forms. Participants, of an average age of 36 years and ranging from 23 and 60 years, include: 2 Competence Leaders, 2 Project Managers, 1 Project Engineer, 2 Technical Leaders, 7 Designers, 2 Assembly Leaders, and 7 others. The gender division was unbalanced (namely, 2 females and 21 males), but was considered as representative of the workforce in this kind of industry.

Apart from open-ended questions, the proposed questionnaire comprises three sections: familiarity with CAD-VR-GUI, workload, and VR usefulness and integration.

In the first section, participants were asked about their familiarity with CAD, Graphical User Interfaces (GUI), and VR using a 5-point Likert scale (1, No knowledge - 2, Slight knowledge - 3, Some knowledge - 4, Moderate knowledge -5, Extreme knowledge). In addition, participants were asked to indicate how many times (namely, one, two, or more than three times) they used VR tools during the session reviews.

In the second section, the well-know NASA Task Load Index (TLX) [61, 62] was used to assess the mental demand, physical demand, temporal demand, performance, effort, and frustration using a 20-point Likert scale (ranging from 1 - Very Low to 20 - Very High). The workload assessment was based on two hypotheses: the work is less than the critical value of 50, and the workload is not affected by the frequency of VR use.

In the third section, users were asked to answer to specific questions aimed at investigating the level of ”VR usefulness and VR integration” in the CMS design process of the company. In this case a 5-point Likert scale was employed including the following values: 1 - Strongly disagree, 2 - Disagree, 3 - Neither agree nor disagree, 4 - Agree, and 5 - Strongly agree.

5.1. Questionnaire Results

As shown in Table 4, only few participants declared a low level of familiarity with CAD: this is not surprising, because the CAD software knowledge in the automotive sector is a required digital skill. Conversely, as for the familiarity with VR and GUI,

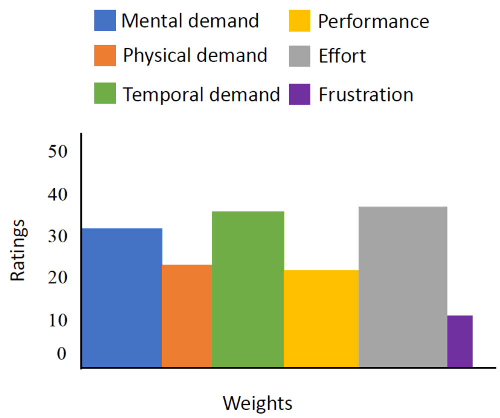

Figure 12: Graphical representation of the results of weighted subscale ratings for the VR approach workload using the standard NASA-TLX assessment tool.

only a range between 2 and 7 people declared a high level of knowledge on these technologies.

To study how the so-called initial ”wow” effect may have influenced the workload, a preliminary workload analysis was performed, focused on a comparison between two categories of users (i.e., ”beginner” and ”advanced” users). The group of beginners was composed of 11 people who used the VR device only once or twice during the VR sessions, because they used to participate in the design by watching from on a large screen. The group of advanced users was composed of 12 people who used the VR device more than three times. The Shapiro-Wilk normality test (AS R94 algorithm) [63] revealed that the data from both samples followed a normal distribution. Thus, we compared them as two unpaired samples. The unpaired t-test revealed that there was no statistically significant difference in the workload between the two groups [64] Subsequently, since the two groups belong to the same population, we performed the NASA TLX analysis of all users' responses. The obtained results for ratings and weights related to the six NASA TLX dimensions (namely, Ratings: Mental Demand 29.6, Physical demand 21.1, Temporal demand 35.0, Performance 20.4, Effort 35.9, Frustration 9.8; Weights: Mental Demand 3.17, Physical demand 1.74, Temporal demand 2.83, Performance 3.04, Effort 3.70, Frustration 0.52) are shown in Figure 12). The weights were derived for each participant by requiring simple decisions about which member of each paired combination of the six dimensions is more related to her/his definition of workload. For each participant, the rating sub-scale was then multiplied by the appropriate weight, developing a composite tailored to individual workload definition. The overall workload of the proposed VR approach is represented in Figure 12, with the average value of 30.14, which thus belongs to an intermediate workload range [62, 61] and is below the critical value of 50. Note that a high value of workload means high work stress producing decreased motivation, low morale and discipline, and poor work performance [65]; conversely, to reach the production target and compete with other companies, the employees must have good work performance in the work [66].

As summarized in Table 5, reporting the questionnaire results, we remark that users

Table 5: Questionnaire results related to the VR usefulness and VR integration (1 - Strongly disagree, 2 - Disagree, 3 - Neither agree nor disagree, 4 - Agree, 5 - Strongly agree)

Questions	Median Score
VR can help through the product life cycle.	5
VR has a positive effect on communication between departments.	4
VR enables me to see ergonomics flaws.	5
VR enables me to see design flaws.	4
VR enables me to see logical flaws.	4
Interacting with the components is fun.	5
Wearing the device is comfortable.	4
The interaction approach is intuitive.	4
I have been able to easily select and move parts of the power unit.	4
After removing the headset I felt dizzy.	2
Using VR I felt isolated from my team.	3

strongly agreed that the presented VR approach supports the design of a CMS through its whole product life cycle (the median score is 5 of 5 in the Likert scale), and it has a positive effect on communication between the company departments (the median score is 4 of 5 in the Likert scale). Similarly, most users strongly agreed that VR enables users to detect ergonomics (the median score is 5 of 5 in the Likert scale) and logical (the median score is 4 of 5 in the Likert scale) flaws during the project review using the VR device. In addition, a relevant 74% of users strongly agreed that the interaction with system components in the VR environment is fun (the median score is 5 of 5 in the Likert scale), and they agreed that the interaction approach is intuitive allowing to easily select and move parts of the power unit (the median score is 4 of 5 in the Likert scale). Moreover, two surprising results appear noting that wearing the device is almost comfortable (4 of 5 Likert scale), and most users on the fact disagree that after removing the headset they felt dizzy (2 of 5 Likert scale). Finally, the users neither agree nor disagree to feel isolated from the team while wearing the device during the VR review (3 of 5 Likert scale).

5.2. Discussion

As a first finding, we remark that the questionnaire supports the answers to RQ1 (Does the presented VR approach support the CMS design process?) and RQ2 (Which steps of the CMS process can benefit from the use of VR?), showing that the presented VR approach significantly helped the development of CMS, especially during the design phase. In fact, the VR approach was evaluated positively: in particular, interviews indicated that VR can help the CMS development throughout the product life cycle, identifying and addressing ergonomics, design, and logical issues before the assembly phase. Therefore, the VR technology plays an important role as a support tool in the design phase.

Another finding from the questionnaire results is related to the comparison between the use of the VR approach by beginner and advanced users. Such an analysis showed that in the presented case study there was no statistically significant difference in the workload at the end of the VR review between beginner and advanced users. It is worthwhile to highlight that the reported task workload was equal for both user groups; hence, also people using the VR tool for the first time are not significantly impacted by the corresponding workload.

Since all the team members obtained the same workload level that was also under the critical value of 50, we deduce that the proposed approach overcomes traditional methods thanks to the VR methodology integration acceptance by the users. Finally, we remark that the questionnaire analysis supports also the answer to the RQ3 (What is the professionals' acceptance of the VR approach for CMS design?): in fact, the findings obtained from the second part of the "usefulness and integration" questions highlighted that that the interaction with the system component is fun and intuitive and wearing the device is comfortable.

6. Conclusions and Future Works

The design of complex manufacturing systems (CMSs) is increasingly characterized by the need for co-design tools aimed at achieving product innovation as well as manufacturing efficiency and effectiveness, while minimizing risks and maximizing performance.

In this context, this paper presents a novel procedure for the use of virtual reality (VR) as a virtual commissioning design tool for CMS industrial practice. Relying on a real case study regarding an electric axle production line, the proposed VR design approach demonstrated to be effective in the CMS design, especially from the perspective of critical design aspects such as ergonomics and visibility. With respect to traditional 2D tools, VR allowed a better organization of stations equipment and an improved manual object picking for different worker heights. VR also demonstrated its advantages in improving project decision timing and communications between professionals of different sectors and skills, thanks to the new and visual language.

The presented case study was enriched by the analysis of a questionnaire aimed at assessing the users' workload during the VR sessions and their corresponding technology acceptance, as well as evaluating how and how much this innovative technology can provide a helpful contribution to the design of CMSs. The questionnaire results showed a general appreciation of the VR approach, a non-critical workload even for beginners, positive usability, and ease of user feedback. This is an important result that highlights the usefulness of integrating VR tools in the company process also for beginner users.

Although the obtained findings cannot be considered conclusive, this manuscript provides some interesting directions for future work. Having established that VR provides considerable technical support to the design of CMSs, it would be interesting to investigate extending the use of VR to the commercial proposal phase and the concept phase, for instance generating a draft preliminary model aimed at showing the expected result early and making important decisions on time. Moreover, it would be interesting compare the approach with alternatives from in the related literature. Another aspect to be addressed is the application of VR to other steps of the CMS life cycle, such as training and maintenance application, and its integration with discrete-event simulation models of CMS, aimed at optimizing their design and operation (e.g., layout of the plant, performance of the production lines, routes of AGVs).

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