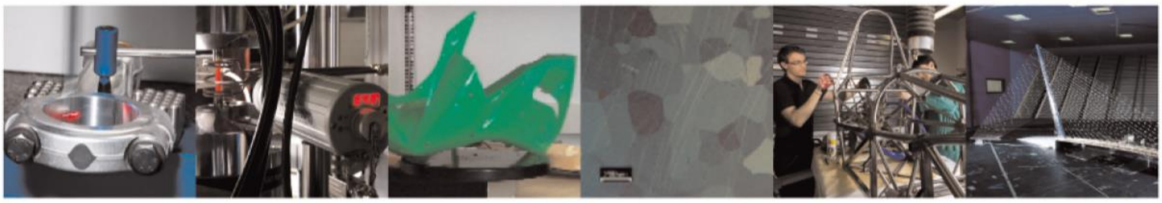

Design of serious games in engineering education: An application to the configuration and analysis of manufacturing systems

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Design of Serious Games in Engineering Education: an Application to the Configuration and Analysis of Manufacturing Systems

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Abstract

Higher education has to cope with current trends in digital technologies, in particular in the field of industrial engineering, where digital competencies are required more and more. Digital technologies, combined with serious gaming, offer new opportunities for teaching engineering in higher education, with a twofold objective: 1) offering students a rich and realistic experience exploiting advanced digital tools; 2) supporting and complementing traditional education schemes by increasing participation and involvement via serious gaming, enhanced by digital/virtual technologies. Herein, we present a framework for the design of serious games in engineering education, with a specific focus on the definition of intended learning outcomes and the development of the corresponding game activities. This framework was applied to develop a serious game application for the design and analysis of manufacturing systems. The approach was tested thanks to the cooperation of 60 bachelor engineering students and the results extensively analyzed in both quantitative and qualitative terms.

Keywords: Serious Game, Manufacturing Engineering, Higher Education

1. Introduction

Although the use of gaming techniques for non-entertainment purposes has been already addressed in the last years [1], this trend is further emerging thanks to the popularity of video games, even if often limited to early adopters [2]. The concept of gamification defines the use of game design, game thinking and game mechanics techniques applied in non-playful contexts, in particular in the field of education [3, 4], aiming to increase participation and involvement of users in situations usually considered as not entertaining [5, 6].

The rationale of gamification is exploiting playful elements to make learning more effective, through intrinsic and extrinsic mechanisms by increasing its attractiveness for the users [3]. Recreational elements, such as prizes or points, favor extrinsic motivation, while facing a challenge increases intrinsic motivation [7].

The use of gamification through digital game-based learning (DGBL) and Serious Games has rapidly grown in the educational field to support the understanding of theoretical notions and their applications [8, 9, 10]. This approach is especially promising in engineering education, to make engineering subjects more attractive, attract a larger number of students, as well as simplifying and contextualizing complex and abstract concepts [9, 11, 12, 13]. Nevertheless, the adoption of these approaches in the academic community is not widespread putting serious gaming in the area of emerging trends in engineering education [14, 15].

Indeed, serious gaming offers the opportunity to experience a simulated environment, representing concrete and realistic engineering problems with the appropriate level of details, where it is possible to train, apply and assess engineering skills and methodologies, such as the identification of relevant objects and their organization in systems, making hypotheses based on observations, searching for information and collecting data. These skills are fundamental to solve engineering problems, but can be hardly addressed in traditional learning approaches because of the impossibility to decouple the learning process of students from the necessary mediation of the teacher, who defines use cases or targeted exercises. At the same time, up-to-date engineering tools, devices and approaches are often expensive and complex, and requires the supervision of an expert operator. Acting in a simulated environment enables students to operate freely and safely on complex engineering problems, as well as to learn from their mistakes, thanks to punctual feedback and the availability of multiple attempts [16].

These considerations are especially applicable to the area of industrial engineering, where students have to learn concepts, methodologies and tools to analyze, design and manage manufacturing systems and processes. Education 4.0 is a new educational paradigm aimed at responding to the needs and potential of the fourth industrial revolution [17, 18, 19] by including digital twin [20], intelligent technologies, artificial intelligence and robotics in university curricula. The applicability of serious gaming in industrial engineering courses necessarily depends on the availability of industrial cases that are sufficiently large and complex to be exploited in simulated environments for the definition of meaningful and realistic engineering problems [21].

In this paper, a general framework is proposed to support the use of serious games in industrial engineering education, to identify and classify the intended learning outcomes and guide the design of a serious game (Sect.3). This general approach is exploited to develop a serious game for learning, addressing the design and analysis of a manufacturing system (Sect.4). The serious game has been implemented and been tested involving industrial engineering students (Sect.5) and the results analyzed (Sect.6) to draw conclusions with respect to its utilization in engineering education (Sect.7).

2. Related Works

This section provides a review of the frameworks that have been proposed to support the design and classification of games, in particular serious games (Sect.2.1). Then examples of serious game in the field of industrial engineering are analyzed by highlighting their strengths and limitations (Sect.2.2).

2.1. Frameworks for Game Design

As the complexity and richness of games has increased, many frameworks have been proposed to support their structured design. One of these is the Mechanics Dynamics Aesthetics (MDA) framework [22], that identifies three fundamental components of games, i.e., rules, system, and "fun", associated with the design of mechanics, dynamics, and aesthetics respectively. MDA can support the game design process by specifying data, processes and actions that are available in the game (*mechanics*), dynamics of actions and run-time behavior (*dynamics*), and the desirable emotional responses of the player (*aesthetics*). All these are strictly linked aspects, requiring to take in due consideration the perspectives of both designers and players.

The Design, Play and Experience (DPE) framework [23] extends MDA after highlighting the need of a pedagogical point of view, specific for serious games, including characters, settings and narratives of the story. The design of a serious game involves heterogeneous stakeholders: 1) academics for educational pedagogy and communication theory, 2) experts in the specific topic addressed by the game, 3) game designers. Defining the goals of the game is a fundamental step for the effective design of a serious game. The DPE framework identifies four subcomponents of the design phase, i.e., Learning, Storytelling, Gameplay, User Experience, that must be instantiated with respect to three main aspects: Design, Play and Experience. Moreover, DPE explicitly considers Technology as a transversal layer.

Other frameworks have been proposed in the literature, such as the Design, Dynamics and Experience (DDE) framework [24] and the Learning Game Design Model (LGDM) [25] as well a structured comparison of them [26].

2.2. *Serious Games in industrial engineering*

The state of the art of serious games in the engineering and industrial area is broad, with more than 20 serious games developed during the first decade of the millennium [27, 28], even though not all of them were successful [1]. *COSIGA* is a team player game entailing parallel and cooperative working in a distributed and concurrent engineering (CE) environment [29, 30]. The authors' goal is to obtain learning goals and qualitative data on the subjective experience during the game. Each student plays a role in the product development process and works collaboratively to manufacture the final product - a type of truck. The product is finally tested in the simulated factory. The awareness about the context, through the exchange of information and decision-making, is underlined. The strength of the work is the in-depth analysis of the end-users, leading to positive feedback by the participants. On the other hand, the needs are customized and limited to a very specific experience.

Beware [31] is a multiplayer online game to make people aware of risks within an industrial. The user has to design a simple product and detect risks that could arise during its processing. Players collaborate during the game, to find adequate solutions to overcome barriers. The importance of the feedback provided to the students on the results obtained is also highlighted [32]. Researchers conclude that the primary learning mechanism happens without the support of gamification techniques but the latter contributes to a successful learning experience by providing a stimulating experience, especially if the user has already basic knowledge of the topics.

Serious games have been also developed in the design area [33], to let the students experience the difference between *set-based* concurrent engineering (SBCE) and *point-based* concurrent engineering' (PBCE) methods. Users must design a simplified airplane structure with LEGO bricks, using the two different design strategies. In this team game each player represents a department focused on a subsystem of the plane, e.g., body, wings, cockpit and tail. This work has been proposed to a small set of users without a control group, thus the effectiveness of the learning was not tested.

Li et al. [34] present *CADament*, a gamified multiplayer tutorial system for learning AutoCAD where players solve a drawing task in rounds that come in rapid succession. This fast-repeating round format would allow students to practice the same tasks multiple times, facing different opponents. In addition to autonomous learning, students also learn by observing the opponent strategies. According to authors', this game improves learning performance, motivation and knowledge transfer; however, a comparison with a control group is missing, as well as a long-term study on the impact of the serious game on the acquired skills.

The simulation of the production of a specific part is addressed by the *Workshop Game* [35]. Students must obtain the necessary documentation for the production, explore different workshops and use different machines to process the part. The game does not provide real levels but is organized in sub-missions.

An example of an environment for remote training of high-precision production is presented in [36]. However, no experiments has been done to collect objective and subjective data.

A serious game simulating an assembly line in the automotive industry, *Muscle Car*, has been shown in a training event [37]. Workers have to assemble as many cars as possible while keeping the inventory cost as low as possible. Players, divided into two teams, had to evaluate different organization paradigms: traditional, self optimized and lean.

Product life-cycle management (PLM) is the subject of *PEGASE* [38]. The authors use a case study from the plastic industry, asking the students to identify the differences between running a process traditionally or using a PLM approach. The strength of this work is a very large cohort of users observed (more than 200). The results show a limited effectiveness, and the authors only highlight an increased motivation of the students.

An emerging area for serious games is the use of virtual reality environments wearing head-mounted displays [39]. *Be-Ware of the Robot* is a highly interactive and immersive virtual reality training system that simulates the co-operation between industrial robots and humans while executing manufacturing tasks using a head-mounted display [40]. The authors emphasize the sense of presence and realism experienced by students, and judge the virtual reality system to be efficient for the purpose. Nevertheless, the evaluation is focused on the degree of immersion in the game rather than on the effectiveness of the learning experience.

Through the analysis of the cited works, some common limitations emerged:

1. Some serious games have not been designed with an incremental level of difficulty. A general rule is designing the difficulty of the challenge at an intermediate level [41]. A difficulty too high would demotivate the player, vice versa it would make the game less interesting.

2. Very few works use a rewarding scheme to motivate the users. This option can also be used to provide players feedback, a very common approach in successful commercial games and good pedagogical practice [42].

3. A player guide is not always available, even though it would facilitate a meaningful experience, especially at the beginning of the game and with inexperienced players [10].

4. The possibility to play collaboratively is not always present. This option, although more difficult to implement, is often recommended [41].

Finally, most of the described approaches miss in giving due importance to the design of *Intended Learning Outcomes*, making it difficult to evaluate and asses the results obtained.

3. A Framework for the Design of Serious Games in Industrial Engineering Education

The analysis of the state of the art helps to identify a list of requirements for the design of a serious game aimed at engineering education:

Req.1 Follow a structured approach to define goals, contents and mechanisms of the serious game.

Req.2 Explicitly define Intended Learning Outcomes (ILOs).

Req.3 Provide the experience of a realistic (simulated) environment.

Req.4 Apply and assess engineering skills and methodologies.

Req.5 Challenge the user with an incremental level of difficulty.

Req.6 Give feedback and rewards to motivate the users.

Req.7 Guide the user before and during the game to enhance the experience.

Req.8 Stimulate the interaction and collaboration among users.

The first requirement (*Req.1*) is met by adopting a general framework to support the design of a serious game for engineering education. The proposed framework (Figure 1) is a specialization of the DPE framework [23] for Industrial Engineering applications (DPE-IE). Although it has been developed with respect to industrial engineering, it is general enough to be applied also in other domains.

The following subsections delve into four design layers of the framework (i.e., *Learning, Storytelling, Gameplay, User Experience*) and the related *Technology*. The coherent and connected design of the layers is addressed, enriching the indication of the DPE framework with a higher level of details, thus supporting the concrete design of a serious game. In addition, it will be shown how the requirements *Req.2*-*Req.8* can be met.

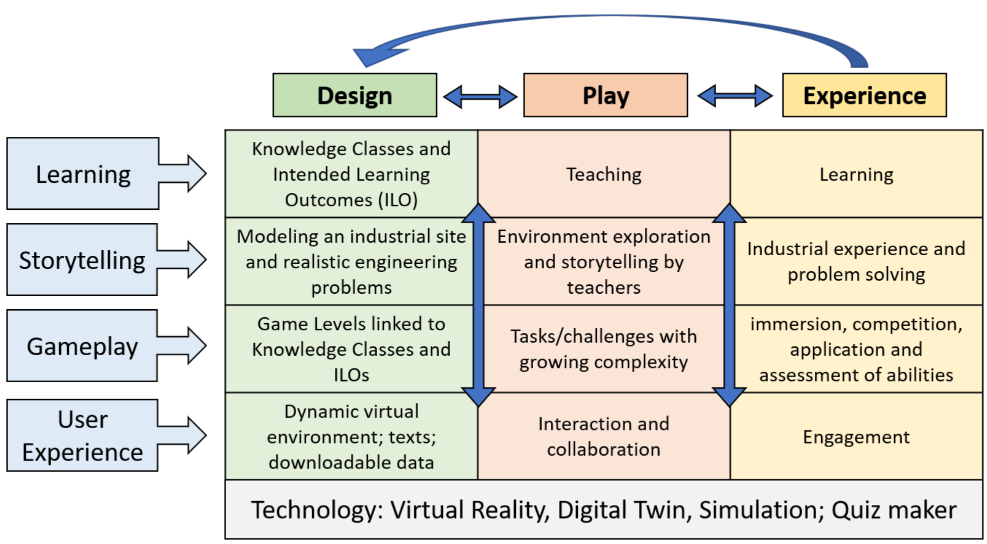

Figure 1: *Design-Play-Experience for Industrial Engineering (DPE-IE) framework.*

3.1. Learning Layer

The Learning Layer defines the content and pedagogy, together with the learning outcomes. Herein, we proposed to design the learning layer in terms of ILOs (*Req.2*), commonly used to describe and declare what the students are going to learn and what they will know or be able to do after the learning experience [43]. ILOs are defined assuming the point of view of the student and also including a declaration of the knowledge or performance indicator that should be met. The definition of ILOs is based on a set of keywords organized according to different types and degrees of learning [44, 45].

ILOs are grouped into four different classes of knowledge, while adopting the scheme proposed by Anderson et al. [45]:

A. **Factual Knowledge**: the basic elements that the learners must know to be acquainted with the discipline or problem under study.

B. **Conceptual knowledge**: the framing of the basic elements in a theory or a system and their relations.

C. **Procedural knowledge**: the capability to do something, e.g. apply an algorithm, a technique, a method, etc.

D. **Metacognitive knowledge**: the knowledge of cognition and awareness of one's own cognition.

3.2. Storytelling Layer

The Storytelling Layer deals with the story used to set the stage, provide purpose and engagement, and convey content. The setting, character design, and narrative are the primary elements defined by the game designer.

Herein, the setting is a real industrial site where the user is an engineering student. The narrative revolves around the need of analyzing, designing, installing or managing an industrial facility that is represented in a realistic environment (*Req.3*). The story will guide the user to explore the game environment in an autonomous way while facing challenges that ask to apply engineering methodologies (*Req.7*). Most of the tools and methodologies used in industrial engineering ground on more or less strict hypotheses. The text of an exercise typically provides the hypotheses that are needed in a traditional classwork, whereas the observation of the operating production system in the game environment provides stimuli to infer hypotheses by matching the characteristics of the system with the methodologies to be used. Nevertheless, the storytelling layer can help students to identify relevant pieces of information leading to proper hypotheses and, hence, driving the selection of viable methodologies and tools. The result of the application of these methodologies and tools will help to assess skills and competences (*Req.4*).

In addition to the main user, a teacher participates in the game to give feedback (*Req.6*) or provide additional information, thanks to the direct and visible connection between what the teacher is saying and the reference to a specific object, areas, process or event in the game environment. This type of advanced interaction is beneficial for both the students and the teacher (*Req.8*).

3.3. Gameplay Layer

The Gameplay Layer tackles what players will be able to do in the game environment and what will be they asked to do. This layer is decomposed into mechanics (e.g., rules, challenges, goals of the game), dynamics (i.e., the behavior and interaction of the different parts of the game with each other and with the player), and affects (i.e., resulting experiences and emotions of the player) [23]. The gameplay is organized into Game Levels, i.e., stages where a player grows abilities. Levels consist of tasks/challenges with growing complexity according to the type of knowledge (*Req.5*). Each game level contributes to reach specific ILOs and must be associated with an assessment. The initial levels of the game will be mainly aimed at providing fundamental knowledge, while the higher ones build up on the existing knowledge to achieve higher learning objectives. A key issue is balancing the difficulty of the game, i.e. finding the right balance between challenges and the (increasing) abilities of the player. Completing levels with increasing difficulty functions also as a reward system (*Req.6*).

Mechanics and dynamics must be designed while considering relevant affective goals such as immersion, intellectual problem-solving, competition, creation, discovery, advancement and completion, application of an ability, and learning. In addition, it may be valuable to let students participate in the game in teams, in order to stimulate social interaction, collaboration, and team working attitude (*Req.8*).

3.4. User Experience Layer

The User Experience Layer deals with the design of interfaces that define everything that the user can see and hear. The aim of the game is providing the students with an industry-related experience, e.g., visiting a construction site or watching a manufacturing process. The realism must be guaranteed in terms of both quality and dimension, thus the environment must resemble a real industrial site operating a process in terms of details, dynamism, and functionalities. The complexity of the environment must be comparable with the real one (*Req.3*).

The serious game environment must be able to provide additional information (e.g., texts, graphs, data) that students must find in an autonomous way or assisted by a teacher that asks and replies to questions and stimulate the discussion in a spoken or written form. This helps to guide the user through the serious game and enhance the experience (*Req.7*).

3.5. Technology Layer

The Technology Layer defines how the game is implemented. Appropriate technologies must be selected for an effective serious game and to enable the other layers, in particular the gameplay and the user experience. Herein, it is recommended the use of Virtual Reality [46, 47, 48] to enhance the realism of the experience (*Req.3*).

Since the modeling of the industrial environment and the related business processes can be complex, the use of digital twin technologies and simulation [20, 49] can help to provide meaningful contents and boost the relevance of the experience from an engineering perspective.

Finally, the assessment of skills and competences ask for the management of questions/challenges (e.g., a quiz) with the related data processing and feedback (*Req.4*). Questions and answers can be given either via the user interface of the game or using an external form. The former option requires a more complex implementation, but it enables students to be completely immersed in the game environment and makes it possible to reply through the interaction with objects, e.g., clicking on a station to be identified. The latter option can take advantage of existing Learning Management Systems (LMS) [50] to easily create forms and administer replies in a reconfigurable and modifiable way without changing the game environment.

4. A Serious Game for the Design and Analysis of Manufacturing Systems

The serious game design framework presented in the previous section has been exploited for the design and analysis of manufacturing systems (*Req.1*). This is typically a complex engineering problem requiring multidisciplinary knowledge to achieve the production goal. Firstly, manufacturing systems consist of production resources with specific functionalities and capabilities, depending on their characteristics. Nevertheless, the way they are combined also impacts on the capability that can be provided. The manufacturing system design process is driven by key performance indicators asking specific approaches and tools for their assessment. The following subsections detail how the design framework was applied by specifying the contents for each layer.

4.1. Learning Layer

Taking as a reference the taxonomy proposed by Anderson et al. [45] (Sect.3.1), Table 1 instantiates the types of knowledge that are relevant for manufacturing system design and analysis. *Factual knowledge* is related to understanding the specific characteristics and functionalities of production equipment. *Conceptual knowledge* deals with capturing the role of production resources (e.g., machine tools, transporters, buffers) in a given system configuration, identifying specific functions derived from general modeling approaches that must be related to the system under study. Once a manufacturing system has been formally described and modeled, *Procedural knowledge* consists in the applications of specific methodologies, techniques, and tools that are needed for the analysis of its performance. Finally, *Metacognitive knowledge* is related to the ability of self-assessing the knowledge and understanding of manufacturing systems design and analysis.

After the specification of knowledge types, the design of a learning approach passes through the definition of ILOs and activities (*Req.2*). Each activity

Table 1: Taxonomy of knowledge types [45].

A. Factual Knowledge

- AA. **Knowledge of terminology.** Ability to identify different types of equipment.
- AB. **Knowledge of specific details and elements.** Ability to identify properties of an object in the virtual environment.

B. Conceptual Knowledge

- BA. **Knowledge of classifications and categories.** Ability to classify pieces of equipment according to their class, namely production resources and/or transportation resources and/or buffers.
- BB. **Knowledge of principles and generalizations.** Ability to understand the flow of parts within the manufacturing cells in the virtual environment.
- BC. **Knowledge of theories, models, and structures.** Ability to identify different types of manufacturing system architecture, e.g., flow shop, job shop, etc.

C. Procedural Knowledge

- CA. **Knowledge of subject-specific skills and algorithms.** Ability to use performance evaluation techniques (e.g., discrete event simulation) to model a manufacturing system and assess its performance.
- CB. **Knowledge of subject-specific techniques and methods.**
  - CB.1. Ability to analyze the behavior of manufacturing systems and assess functional parameters.
  - CB.2. Ability to develop a performance evaluation model grounding on a conceptual model of the manufacturing system.
- CC. **Knowledge of criteria for determining when to use appropriate procedures.** Ability to make proper hypotheses and generate a conceptual model of the manufacturing system under study.

D. Metacognitive Knowledge

- DC. **Self-knowledge** Ability to self-assess the confidence associated with replies to questions or solution to exercises.

asks students to accomplish specific tasks, designed to foster the acquisition of the associated ILO. In some cases, students will just need to learn what are the elements in a manufacturing system and recognize them, learn where to look for specific information and what it means. ILOs related to procedural knowledge will ask to use tools that are external to the game environment, e.g., for the assessment of manufacturing system performance. The detailed learning activities associated to specific ILOs are reported in Table 2.

Table 2: ILOs, type of knowledge and game activities.

ILO	Type	Description of the ILO and the associated activities
I1	AA	*Identify the different types of equipment.* Students have to identify all the instances of a given type of equipment (e.g. a pick-and-place unit, a workstation, a conveyor, etc.), by checking if a piece of equipment is installed, counting how many are located in the industrial plant.
I2	AA	*Identify the product undergoing the manufacturing process and its components.* Students have to identify the specific products being processed and/or assembled together with their components.
I3	AB	*Identify the attributes of an object in the virtual environment.* Students will get acquainted with properties associated with each object (e.g. a workstation, a conveyor) in the virtual scene, in terms of ID, position and orientation, dimensions (length, width, height).
I4	BA	*Classify the pieces of equipment according to their class.* Students will be asked to label the equipment in the game environment according to their class. Exemplary classes are: transportation/handling device, buffer, workstation, parts, etc. The assessment can be done by asking to tag objeects with predefined labels.
I5	BB	*Identify the flow of parts within the manufacturing system in the virtual environment.* Students will be asked to list the stations visited to process a given part type. To complete this assessment they will look at the parts moving in the virtual environment and take note of the IDs of the stations visited.
I6	BC	*Identify the type of manufacturing system architecture.* Students will be asked to identify the type of architecture of a given sub-system. To this aim they must observe the routing in the system for a reasonable time and identify the routes that are actually used.
I7	CB.1	*Analyse the behaviour of manufacturing systems and assess functional parameters.* Students will be asked to assess the value of some system parameters, e.g., the processing time of a station, the number of parts in a buffer, the failure rate and repair time of a machine. This assessment will be done through the observation of the system working in the game environment or by providing logs of events.
I8	CC	*Make proper hypotheses and generate a conceptual model of the manufacturing system under study.* Grounding on the observation of the system and the assessment of its characteristics, students will be asked to provide the hypotheses required to build a model (e.g., simplification hypotheses to apply an analytical method).
I9	CB.2	*Develop a performance evaluation model based on a conceptual model of the manufacturing system.* Students will be asked to develop a performance evaluation model grounding on knowledge and skills they already have, e.g., an analytical model (addressed through CC) or a discrete simulation event (DES) model. The model will be validated against the data and behaviour of the manufacturing system.
I10	CA	*Evaluate the performance of a manufacturing system.* Students must use a performance evaluation model and assess the system performance in terms of key performance indicators (KPIs). The model can be provided or they could be asked to build a model themselves (addressing other ILOs). They must be able to collect data provided by the performance evaluation model and assess the KPIs.
I11	DC	*Self-assess their replies.* Students will be asked to provide an estimation of the confidence they have with respect to their replies and numerical solutions provided.

4.2. Storytelling Layer

The general design of this layer is framed around students playing the role of a professional engineer performing an analysis or investigation in a real manufacturing system, e.g., the identification of the bottleneck and the associated root cause analysis (failures, inadequate buffer space, high setup times, etc.), and proposal of a possible solution to improve the performance. The narrative scheme entails a description of the part type(s) processed, information related to the demanded production volumes over time, the pieces of equipment installed and their role to operate the process, possible constraints (e.g., floor space available). Therefore, students can experience what professional engineers are supposed to do and how the acquired knowledge can be used to address a manufacturing problem. The soundness of the storytelling layer and the realism of the game environment is fundamental for the students to feel as they are interacting with a real system.

Herein, an assembly line[1] producing a hinge for the furniture market has been considered as a real industrial case (*Req.3*). Students are requested to analyze aspects related to products, processes, and the system. With respect to products, the assembly is detailed in terms of its components. In the virtual environment, students can click on the product (the hinge) or one of its components, and retrieve basic information (e.g., name, class and relative position). With respect to processes, different types of operations are considered, e.g, pick-and-place, handling, joining, quality control. In pick-and-place operations, the component is placed onto the product being assembled, thus the students can observe its actual execution. The same applies for handling operations, where the assembly is moved from one station to the other by rotating tables and conveyors. For joining operations, the operating parts of the stations are modelled (e.g., riveting) while aspects related to process simulation are not considered. The assembly line consists of 19 workstations operating pick-and-place, pin insertion and riveting operations. The analysis of the system entails the identification of the pieces of equipment, together with their role in the assembly process, characteristics, and parameters (e.g., processing time, buffer capacity, etc.).

As mentioned in Sect.3.2, storytelling can give hints for the application of tools and methodologies. As an example, while providing description of the production line, the storytelling layer can be used to underline that parts are mounted onto pallets, and that the number of pallets is given. This will likely drive students to assume a constant population in the system and use a compatible class of methods (e.g. closed queuing networks).

4.3. Gameplay Layer

The gameplay layer (Sect.3.3) is organized into three game levels (*Req.5*):

[1] `https://virtualfactory.gitbook.io/vlft/use-cases/assembly-line`

1. **What is a factory made of?** Players are introduced to the factory environment and get acquainted with its objects and the related terminology, e.g., equipment, parts (Factual Knowledge). The manufacturing system in the factory environment does not need to be animated.

2. **How a factory works.** This level is aimed at providing information related to products and processes (Conceptual Knowledge). The manufacturing system must be animated to let the player observe the routing of parts and the manufacturing processes taking place in the workstations.

3. **Performance of a factory** This level asks the player to recognize specific situations or verify hypotheses to select a proper modeling approach (Procedural Knowledge). Finally, it also entails a quantitative estimation of the performance indicators. The manufacturing system must be animated and additional data (e.g., log files) could be provided to support the analysis.

The definition of game challenges is implemented in terms of a set of questions. These questions and their replies enable the assessment of the students taking part in the serious game (*Req.6*). Moreover, they also provide the possibility to pursue Metacognitive Knowledge by asking students to self-assess their confidence with respect to the replies (*Req.4*).

The detailed design of game levels grounds on the definition of classes of challenges and questions to be implemented in the game, as reported in Table 3.

4.4. User Experience Layer

The player must be able to freely navigate in the industrial environment and explore the production systems, while having access to additional data that are useful to address the challenges (*Req.7*). In particular, the graphical user interface enables to:

- click on the objects in the game environment and retrieve data like the name and ID of the object, its dimensions and position in the factory, its description and relations with other objects.

- get links to files attached to the objects in the virtual environment. Thus, students will be able to download slides, data sheets, 3D files, or data related to the pieces of equipment or products, e.g, the log of failures or processing times for a workstation.

The game environment can be enhanced if different game modes are selectable, e.g., single/multiplayer and teacher/student mode (*Req.8*). The multiplayer mode can take advantage of avatars that show the position and point of view of each player. The teacher mode can offer additional functionalities to support the interaction with the students, e.g.:

- Students are forced to assume the same point of view of the teacher while explaining concepts that are shown in the virtual environment.

Table 3: Game Levels and associated ILOs.

ID	Challenge	Question	ILO
1.1	Count pieces of equipment	The player is asked to count the instances of a piece of equipment that is shown in a picture (e.g., rotary table, robot, conveyor) together with useful information (e.g., name, class, functionalities).	I1
1.2	Search for a piece of equipment	Similar to Challenge 1.1 but just asking to check whether at least one item of the piece of equipment exists in the environment. It is intended to pursue the same learning objective in a less pedantic way.	I1
1.3	Identify factory objects	A view of the factory is shown together with a set of labels, asking to drop the correct label onto the specific piece of equipment.	I1
1.4	Properties of factory objects	Report the value of properties of an object or a derived measure (e.g., the distance between two stations). Properties are retrieved via the user interface.	I3
2.1	Processed parts	Identify the type of part processed in the system and, in case of assembly process, also its components.	I2
2.2	Classify factory objects	Classify factory objects grounding on the interaction with parts selecting from a list of options, i.e., buffering, transporting, processing.	I4
2.3	Routing of parts	Identify the routing of parts in the system, e.g., choose between clockwise or counterclockwise directions, find the path of a part in the system, check for the last visited station.	I5
2.4	Routing of parts	Identify where a part and a component are assembled together.	I2, I5
2.5	Architecture	Identify the type of manufacturing system architecture, e.g., flow shop, job shop, etc.	I6
2.6	Workstations	List the workstations in a manufacturing system.	I5, I6
3.1	Processing times	Estimate the processing time of a station by timing it while animated or by downloading and analyzing additional data, e.g., a log file.	I7
3.2	Failures	Estimate failure parameters (MTTF, MTTR) of a workstation by analyzing additional data (log files).	I7
3.3	Check hypotheses	An hypothesis is enunciated and must be assessed as true or false.	I8
3.4	Method selection	The player has to select among a set of proposed tools/methods applicable to the system under study.	I8
3.5	Estimate model parameters	Given the selection of a tool/methodology, estimate a set of model parameters (e.g., the number of servers in a queue, the dimension of a buffer, routing probabilities).	I9
3.6	Performance evaluation	Use a tool/methodology to evaluate the performance and draw conclusions, e.g., the maximum daily throughput, the minimum number of pallets or buffer capacity needed to satisfy the demand, etc.	I10
S	Self assessment	Players have to declare their confidence about the correctness of the reply to a given question.	I11

- The teacher monitors the students playing in the virtual environment by identifying their position and assuming their point of view.

4.5. Technology Layer

As recommended in Sect.3.5, virtual reality (VR) technology has been chosen to provide the required level of realism so that students entering the scene can experience a virtual walk in the factory to mimic a visit in a real factory (*Req.3*). The proposed serious game can be experienced with two different applications:

- Gamification app based on ApertusVR, a platform-independent C++11 virtual and augmented reality engine[2] [51].
- Virtual Environment based on Babylon.js (VEB.js) [52], a JavaScript framework and graphics engine for HTML5 and WebGL[3].

Figure 2 shows how the industrial environment that includes the assembly line (Sect.4.2) is rendered in VEB.js.

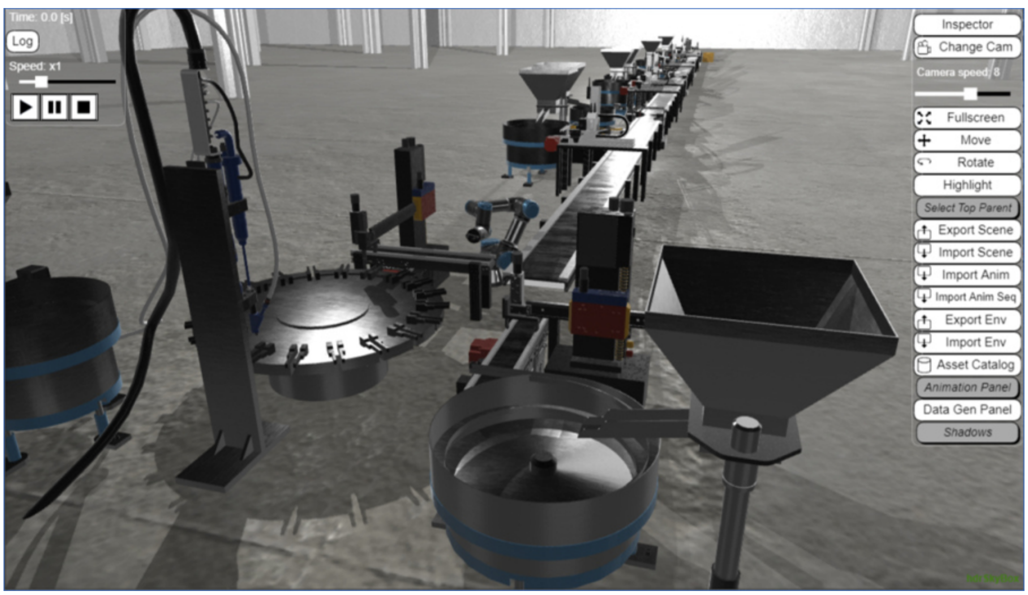

Figure 2: *Screenshot of the VR application based on Babylon.js.*

The presentation of the game challenges and the derived assessment have been implemented taking advantage of the Moodle platform [53], an online learning management system providing a wide range of tools for the definition of forms and the associated assessment (*Req.4*). Different classes of questions

[2]`https://apertus.gitbook.io/vr/`
[3]`https://www.babylonjs.com/`

have been used, e.g., numerical, multiple-choice, assign labels in a picture, select right words in a sentence. In addition, a conferencing platform can be employed during the game to give lectures, provided online support or let the players collaborate in case of multiplayer mode (*Req.8*).

Besides the front-end VR application, a set of tools have been used to support the modeling of the industrial case represented in the virtual environment. Specifically, factory objects, their placement in the virtual scene, their three-dimensional representation and attributes have been defined thanks to OntoGui [54], a graphical user interface to instantiate a factory model based on an ontology data model [55]. The generation of events supporting the animation of the virtual scene has taken advantage of Java Modelling Tools (JMT), a comprehensive framework for performance evaluation, system modeling with analytical and simulation techniques [56, 57]. The proposed game environment has been developed within the Virtual Learning Factory Toolkit (VLFT) Erasmus+ project[4] focused on integrating a set of digital tools for engineering learning [58].

5. Testing the serious game approach

An assessment of the proposed serious game approach has been carried out by involving 60 students from the third year of the Bachelor Degree in Management Engineering of Politecnico di Milano, specifically from the course Integrated Production Systems (SIP), addressing basic methodologies to analyze and evaluate the performance of a manufacturing system. Within the course, two classes of manufacturing systems have been analyzed: Flexible Manufacturing Systems (FMS) [59] and production lines [60]. A traditional teaching approach has been pursued for FMS, using slides to support lectures and exercise sessions. On the contrary, the serious game approach has been used for production lines, through a single long session of about three hours.

This section presents the setup of the test, whereas Sect.6 reports the results. The test has been organized on a completely remote basis due to the limitations imposed by the Covid-19 pandemics in the year 2020. The students involved can be considered a homogeneous sample, since all of them have been attending the same course at the same phase of their learning path, with similar access to the digital environment used for the serious game. All students voluntarily performed the test and the result of the assessment has not been used for grading but as a self-assessment exercise.

5.1. Equipment and Procedure

The serious game application (Sect.4.5) was run on the personal computers of each student, while the questionnaire has been served on the Moodle platform and accessed through browser. The serious game session was organized according to the following steps:

[4] `https://vlft.eu/`

1. The day before the session, students were provided with a detailed explanation of the game environment and its functionalities (graphical user interface, game levels) and the procedure for the assessment (platform used, classes of questions, required feedback, etc.).

2. A troubleshooting session was organized to address possible installation and technical issues.

3. The day of the game session, students were given the assessment questionnaire to be filled individually. During the whole session, a tutor was available on a video-conference platform to address specific questions or issues (e.g., bugs in the application or form) but not to provide any support with respect to the assessment.

5.2. Measures for the assessment

The validation and testing was aimed to collect objective and subjective information related to both the assessment of the student knowledge and the serious game experience.

1. **Feedback on the serious game approach as a learning tool.** Students were asked to compare the serious game with a traditional learning approach in terms of their agreement on a 5-point Likert scale (1 "not at all" - 5 "very much") to the following questions:

    - *Involvement* - Would you say that you felt more involved in the learning experience than in the traditional approach?
    - *Attention* - Would you say that your attention and concentration were better than with a traditional approach?
    - *Retrieve information* - Would you say that looking for relevant information was easier than in the traditional approach?

2. **Grade.** The questionnaire was organized according to the game levels and associated challenges described in Table 3, together with an assessment of the knowledge and skills of the students automatically calculated through the Moodle platform.

3. **Feedback on the serious game as an assessment tool.** After communicating the grade for each game level, students were asked their judgement on the effectiveness of the serious gaming in assessing their knowledge and skills.

    - *Suitability* - Grounding on the grade you just received, do you think this is a suitable approach to assess your learning?
    - *Expectation* - Does the grade fit your expectation?

4. **Perceived knowledge.** Report possible improvements of the knowledge perceived by students as a result of the serious game experience.

5. **Serious game approach as a self-learning tool.** Preference for this type of approach for self-learning and frequency of use. Replies had to be further motivated by highlighting any problem with this teaching method compared to traditional ones, and possibly considering advantages and disadvantages of both approaches based on the specific topics.

6. **Preference for the serious game approach.** Preference for the use of a serious game with respect to a traditional learning approach.

7. **Feedback provided through open-ended questions.** Optional open-ended questions were also proposed to collect specific feedback related to the grade obtained and to collect suggestions for improvement, both in terms of the game environment and assessment methodology.

6. Results

The results of the serious game test are reported according to the measures described in Sect.5.2. Whenever applicable, the results are detailed for each of the three game levels, referenced as *Level 1...3* (Sect.4.3). The number of replies collected decreases as the game levels progress because some students did not complete the game.

6.1. Serious game approach as a learning tool

Figure 3 reports the feedback of students with respect to their degree of involvement, attention, and ease of retrieving relevant information, while using the serious game as a learning tool.

The majority of users agree on the benefits of the proposed approach with respect to the involvement (1), as well as for attention and concentration (2). Thus, it can be stated that the serious game approach was effective in improving the engagement of students in the learning experience. Negative scores are a small percentage, increasing as the game level advances, probably also because of the increasing difficulty of the challenges to be addressed

A less positive feedback was given to the easiness of retrieving information to accomplish the proposed challenges (3) and this can be at least partially explained by the type of activities that students were asked to accomplish in the various game levels (Table 3). *Level 1* was focused on learning concepts and terminology, therefore students had to search information attached to factory objects. The aim was to push students to explore the environment to retrieve relevant information and concepts, but the distribution of data across multiple objects was judged not sufficiently clear by some students. *Level 3* purposely asked students to search data that were needed to derive proper hypotheses and select a performance evaluation method. However, also in this case, the objective of pushing students to observe the system was perceived as a not clear delivering of information by some of them. More details and considerations are discussed in Sect.6.7.

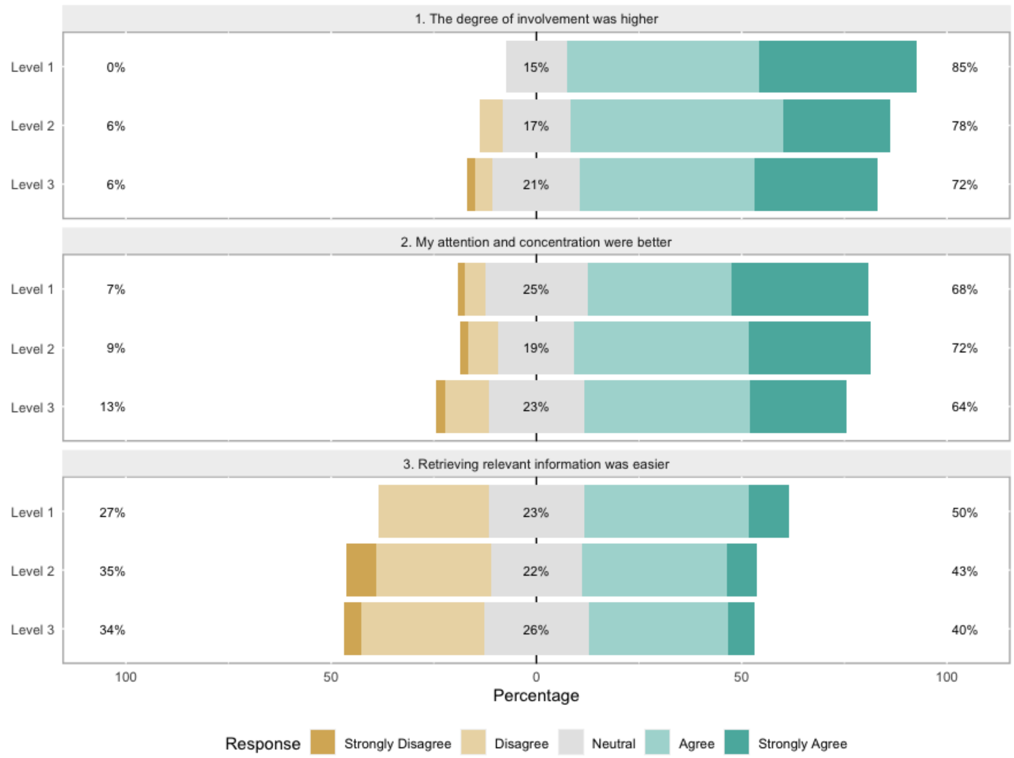

Figure 3: Feedback on serious game as a learning approach

6.2. Grade

The answers to the questions in each level were automatically collected by the Moodle platform. The results are reported in Figure 4 in terms of the grade obtained and the number of students that completed the level. For all the levels, about 70% of the students received a grade between A and C, even though the number of not sufficient evaluations is higher for *Level 2 and 3*. It must be noted that, since the experiment was organized as a single long session, many students stopped the serious game before completing *Level 3*. Thus, the different distribution of grades for higher game levels is due to two factors: 1) the increasing difficulty of the questions and exercises, 2) a decreasing participation of students.

6.3. Serious game as an assessment tool

After being informed about the grade obtained in each game level, students were asked to give feedback about the serious game as an assessment tool. The first question was aimed at evaluating the assessment approach, i.e., the relevance of questions to assess the knowledge gained by students. The results reported in Figure 5 show a largely positive feedback, even though a slightly

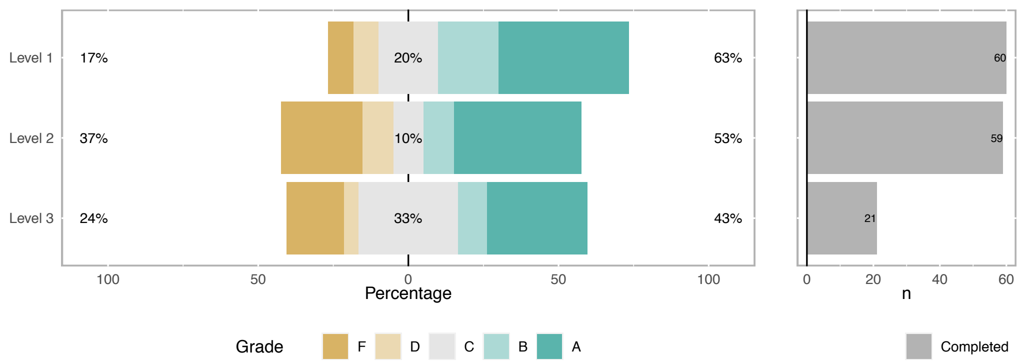

Figure 4: Grades obtained per level.

lower score was reported for *Level 3*, probably because questions were more difficult to solve and required more time. However, the effectiveness of the serious game approach was less convincing for students when considering the matching between the grade and their expectation, as shown in Figure 6. In *Level 1* most of the questions were closed-ended, thus possibly causing a polarization of results. Questions in *Level 3* where increasingly difficult and this had a negative impact on the final grade.

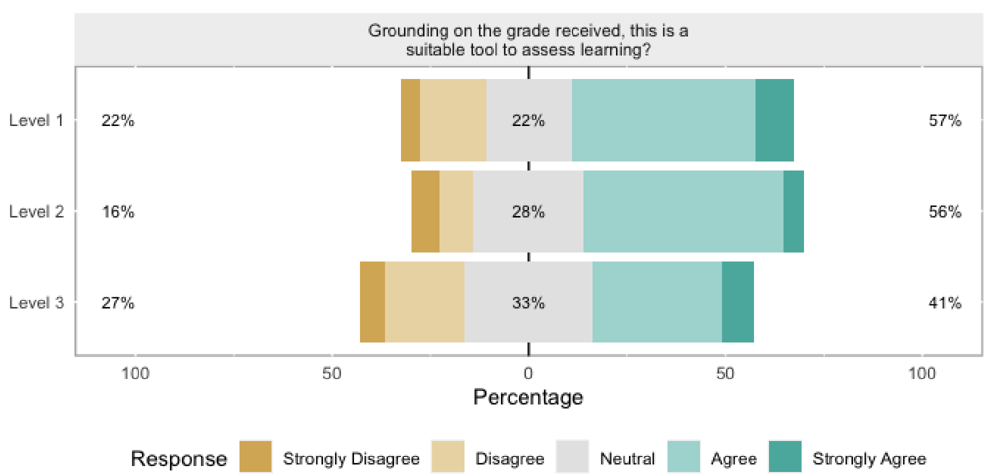

Figure 5: Feedback on serious game as a learning assessment tool

6.4. Perceived knowledge

Students have been also asked to assess whether their knowledge on the topic had improved through the serious game experience. The results are reported in Figure 7, showing that the majority declared an improved knowledge for *Levels*

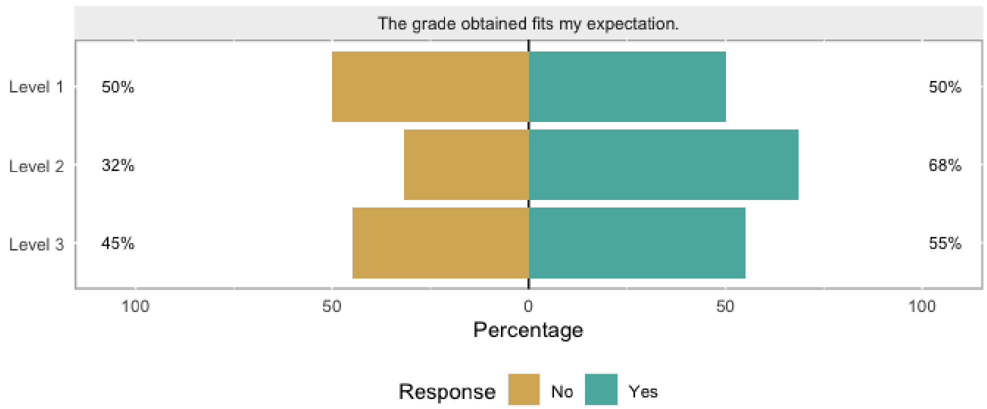

Figure 6: Matching between the grade and the expectation

1 and 2. This value is slightly less than 50% for *Level 3*, where 53% of the students did not confirm the statement.

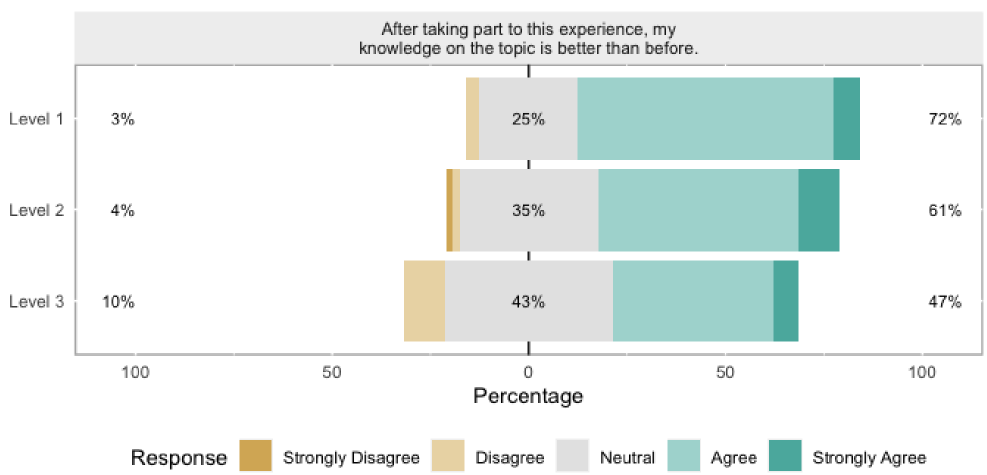

Figure 7: Feedback on perceived knowledge

6.5. Use of the serious game approach as a self-learning tool

Serious games can be used also to support self-learning, thus students were asked how frequently they would use the tool in this way. The results are reported in Figure 8 and show that, although 64% of the students are inclined to use it, nobody expects to use it often. The replies to the open-ended questions reported in Sect.6.7 provide further considerations for a better interpretation of these results.

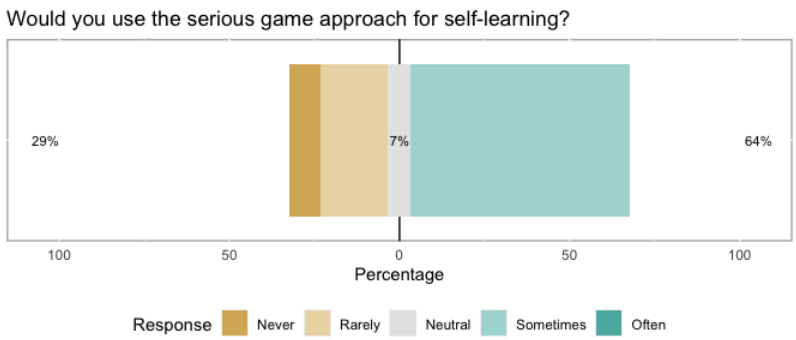

Figure 8: Intention to use the serious game approach for self-learning.

6.6. Preference for the serious game approach

At the end of each game level, students were asked if they prefer the serious game over a traditional learning with lectures and classwork while considering the specific addressed topics. The results (Figure 9) demonstrate that the majority of students would prefer the serious game. A small difference emerges between the levels, but it may be not significant because of heterogeneous number of replies and the influence of enthusiasm for the first level and weariness for the last one.

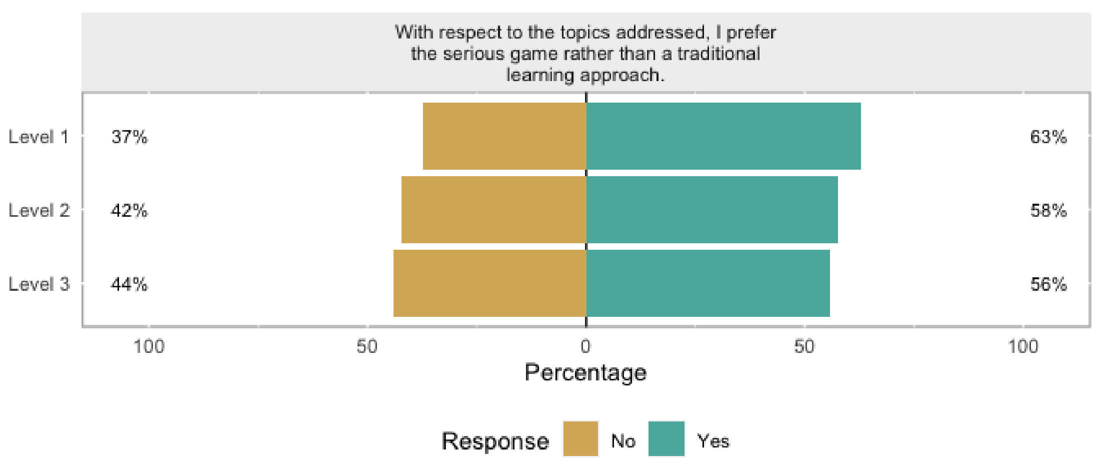

Figure 9: Preference for the serious game with respect to the topics addressed.

A similar question was asked at the end of the game considering the experience as a whole. The results show a perfect balance between the two learning approaches.

6.7. Feedback provided through open-ended questions

Finally, students were given an open-ended question to motivate their preference and suggest directions for improvement. The vast majority of students agreed that the serious game experience entailed many positive aspects, but the traditional approach is still preferable in many cases. Specifically, the traditional approach is preferred when learning new concepts because it has the advantage of clearly defining what must be learnt and to what extent. Indeed, textbooks, slides and notes from the lectures define a clear border between what must be studied and what is out of scope. The serious game enforced a different scenario where students had to look themselves for relevant information to address a challenge. Many students appreciated that the realistic environment of the serious game enables to put together and experience what they had already studied. Thus, they suggested using the serious game to test abilities and understanding of the subjects, linking together in a holistic way different pieces of knowledge, skills, methodologies and tools to address an industrial case. More than half of students appreciated the interactivity and novelty of the serious game, as well as the opportunity to work on a realistic and concrete industrial case, especially when a visit to the real factory is not possible.

7. Conclusions

Grounding on the experience reported in this work, we derived practical recommendations to support the effective and successful adoption of a serious game approach for higher education in industrial engineering.

7.1. Lesson learnt about ILOs

As stated in Sect.3.1 and 4.1, particular attention must be paid to the design of ILOs and related challenges. Although serious gaming emerged as a promising learning approach, traditional lectures are still considered the best approach for learning theoretical aspects. For instance, the results of the experiment and the comments by students give evidence that traditional learning approaches are preferred for acquiring the knowledge of terminology (*Factual Knowledge*, Aa in Table 1). Indeed, traditional learning approaches are typically based on well-structured textbooks representing an explicit and stable reference to key concepts and expected outcomes. However, pieces of information were spread over several elements in the environment of the proposed serious game. Some students complained that it was not possible to know if they had collected or checked everything.

Furthermore, attempts aimed at forcing students to look for specific pieces of information (e.g., asking specific object properties or the number of objects of a type) were unwelcome by some participants. Firstly because the task was considered as repetitive, trivial and tedious, secondly because possible errors and the consequent lower grades were not accepted as a fair evaluation of the acquired knowledge.

On the contrary, students appreciated how a realistic representation of a manufacturing system in the game environment is much more effective to address activities designed for *conceptual knowledge* (Table 1). Walking virtually around the manufacturing system, looking at specific pieces of equipment while working, observing the flow of parts, etc. provide a deeper understanding compared to pictures with written information in a textbook.

The analysis of the activities related to *procedural knowledge* can be split into two parts:

a) data search and check of specific hypotheses, aimed at guiding the student towards the selection of a set of applicable methods;

b) application of methodologies to evaluate the performance of the manufacturing system.

With respect to the first part (a), the considerations are similar to those related to *factual knowledge*, i.e., traditional learning approaches are preferred to understand and recognize hypotheses and characteristics supporting the application of specific methodologies. Facing a realistic use case of relevant dimension (e.g, number of stations) puts the student in an unfamiliar situation. Thus, it is recommended to use the serious game as a companion to traditional learning approaches and materials also for knowledge of type Cc (Table 1).

A different opinion emerged with respect to the application of methodologies (b), even though it is necessary to note the smaller sample size and the likely better preparation of students completing the associated activities. Almost all students appreciated operating with tools and methodologies in a realistic case, both in terms of dimensions and complexity. Similar considerations apply to *metacognitive knowledge* (Table 1), since students appreciated the opportunity to apply knowledge and tools in an integrated and holistic way to support the analysis of a manufacturing system from different perspectives.

7.2. Recommendations for the design and integration of a serious game

After the experimental activity, we conclude that traditional learning approaches and serious game have complementary strengths:

1. Traditional learning approaches are perceived as more effective for learning fundamental knowledge (in particular factual and conceptual), since they provide a clear and explicit knowledge to be acquired together with the related material.

2. Traditional approaches are also preferred for small examples and exercises finalized at a first understanding of theoretical knowledge applied to a concrete case.

3. A serious game supports the motivation of students by making the activities more interesting and challenging, thanks to the possibility to operate in an environment where practical and theoretical aspects are jointly experienced.

4. A serious game is the best tool to provide students realistic and complex cases to analyze, that cannot be addressed too frequently due to the impossibility of making multiple visits to real plants, collect and use real data, etc.

Therefore, while organizing learning activities related to the design and analysis of manufacturing system, we recommend exploiting serious games for:

- complementing traditional learning approaches to provide concrete examples (e.g., an example of a piece of equipment, of a process, of a workstation, of a production system, etc.).
- providing an environment to carry out advanced practical sessions where students are expected to exploit and apply the concepts learnt in an integrated way, facing a realistic industrial problem.

7.3. Technical recommendations

Finally, comments and suggestions provided through open-ended questions have been useful to identify technical requirements related to the software application and the design of activities to make the learning experience more effective and enjoyable.

- *Virtual environment.* Moving in the virtual environment has to be fluid and easy. Limitations due to a low performance computer and difficult interactions because of interfaces (keyboard, mouse, track-pad) can seriously hinder the sentiment of the users.
- *Realism and details.* Students entering a serious game environment are expecting to make an experience that is comparable with typical video games, thus attention must be paid to graphical details. Users expect to have a realistic experience and would be disappointed if a stretch of imagination is needed to overcome missing details. This also apply to animated objects and their trajectories.
- *User interface.* Students will be asked to look for specific pieces of information embedded in the game environment. The medium is the user interface that must be designed meticulously. Easiness in interacting with the information associated to objects, selecting the right objects without troubles and navigating through the user interface must be as smooth and responsive as possible.
- *Fun.* A game, although serious, must be enjoyable. Thus, activities must be fun and engaging. Repetitive or trivial questions and activities should be avoided. Finally, gaming sessions must be limited to a reasonable duration to remain entertaining.

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