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Training advanced skills for sustainable manufacturing: A digital serious game

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Abstract

With the rapid development of manufacturing towards the vision of Industry 4.0, considerable efforts should be done in order to improve the manufacturing skills of young generations and to prepare them to the challenges of the new industrial world. For this reason, the paper first analyzes the learning requirements for the education and training about advanced manufacturing topics and the most suitable educational approaches to satisfy them, identifying digital game-based learning (DGBL) as one of the most promising. On this basis, the Life Cycle Assessment (LCA) Game, a digital game (DG) aiming at supporting the comprehension of LCA for sustainable manufacturing, is presented. Thanks to its high scalability and focus on the practical implications of the use of LCA in an industrial context, the suitability of LCA Game for both universities and companies is shown. Finally, the potentialities of digital game-based learning applications for manufacturing are discussed.

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Keywords: Sustainable manufacturing; Education; Training; Skills; Serious games; Digital game-based learning (DGBL); Life cycle assessment (LCA); Co-design

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1. Introduction

Even though the latest advancements in both technologies and processes towards the vision of Industry 4.0, there is still at both European and global level a serious lack of skilled human resources able to foster the progress of manufacturing sector [1]. In particular, high skills are those most requested but at the same time most difficult to find and develop [2]. While the causes of the skill shortage have already been addressed in literature, and have been identified as an aging workforce, an outdated workforce planning, the limited education efficiency, the changing nature of work and a poor image of manufacturing among youngsters [3], the exploration of the possible solutions to the problem is still in its nascent phase. From the educational side, it is important first to identify the current learning requirements for the training of new generations about advanced manufacturing topics, and then understand the most suitable approaches able to satisfy those requirements. In addition, the educational solutions should be developed by directly involving the learners in the co-design process, in order to validate and enrich the requirements and improve the content provided. This way it will be possible to reach two main objectives. First of all, the new generations of university students could be trained about the emerging advanced skills requested by the industrial world in advance, being able to proactively support innovation once they have joined a company. Second of all, current manufacturing workers could be easily updated about the most recent developments of the sector.

In light of this, the paper presents first an analysis of the current manufacturing literature in order to identify the most relevant learning requirements for manufacturing education. On this basis, it goes through the different educational approaches proposed in the last years for the development of advanced manufacturing skills (as they have been classified by the ETA Industry Competency Initiative [4]), identifying digital game-based learning (DGBL) as one of the most promising. Afterwards, the Life Cycle Assessment (LCA) Game, a digital game (DG) aiming at supporting the comprehension of LCA for sustainable manufacturing, is presented together with the co-design process that was adopted in order to implement it. The suitability of the application developed to address the needs of both university education and industrial training is showed. Finally, limitations and suggestions for further research are provided.

2. Learning requirements for manufacturing education and training

Current manufacturing literature dealing with educational and training aspects was extensively analyzed, considering as *learning requirements* the conditions that facilitate the learning process [5]. For the research, all the main topics related to manufacturing according to [4] were taken into account, hence adopting a wide perspective. The main learning requirements that were found directly dealing with the ETA's advanced manufacturing skills are resumed in Table 1. For each learning requirement, the description and the related references are provided.

Table 1. Learning requirements for manufacturing education and training

Number	Learning Requirement	Description	References
1	Team work	Working in teams can support the learning of manufacturing subjects, with learners discussing with each other and solving problems together	[5] [6] [7] [8] [9] [10]
2	Collaboration and interaction among learners	The collaboration and interaction among learners discussing and working together can support the involvement in manufacturing subjects and the understanding of the concepts	[7] [10]
3	Active involvement of learners	Active participation of learners in the learning process, engaging them in the concepts and methods exposed	[5] [7] [11] [12]
4	Allow the improvement of learners' soft skills	Improvement not only of pure technical skills but also of the "soft" ones, allowing the development e.g. of discussion, presentation, communication and negotiation capabilities	[5] [10] [13]
5	Hands-on learning	Show the learners the effective operation of processes and systems	[5] [6] [8] [10] [14] [15]
6	"Live Case" approach	Learners working as consultants of companies facing an issue	[12] [16]
7	Role-playing games	Support of games (both IT and not) with learners playing and learning from different roles, in order to see different situations and understand the implications among the different activities	[6]
8	Real-time interaction with the events	Interaction of the learners with an environment where it is possible to have real-time feedbacks about their comprehension of the subject and about the quality of their work	[11]
9	Solution of real problems	Solution of real problems that manufacturing companies are facing can	[5] [14]

		reinforce the connection between theory and practice	
10	Visualization of real factories dynamics	Concretely see “how things work”, both directly on the field or also thanks to remote connections	[9]
11	Use of “visible” and “up-to-date” examples	The use of “visible” and “up-to-date” examples can support learning, e.g. the reference to sustainable manufacturing topics	[12] [14]
12	Variety of teaching strategies	Different teaching strategies used in an integrated way improve the attention and the application of learners (e.g. the combination of theory and practice, the work alone or in groups, the use of traditional methods and of specific learning technologies)	[8] [17]
13	Clear feedback on learners’ actions	Clear feedbacks to learners about what and how they effectively learned, in order to understand where and how they can improve	[18]
14	Class-to-teacher issue-based discussions	Importance of the class-teacher interaction in the learning process, with discussions and debates on specific issues	[8]
15	Innovative ways of gathering feedbacks	Importance of the way to interact with learners also when collecting feedbacks about the learning activities	[14]
16	Interdisciplinarity	Allow proper connections between the different disciplines of manufacturing	[5] [6]
17	Stimulation of exploration, problem solving and decision abilities	These elements promote the active interaction of learners with the subjects they are facing, improving the overall learning process	[5] [13]
18	Stimulate imagination, creativity and initiative	These elements support the interest of learners towards the subjects they are studying, improving the overall learning process	[5] [11]
19	Big challenges	Big challenges force learners to develop greater problem-solving skills	[5] [11] [13]
20	Reflective practice	Use of practical experiences but together with a structured reflection about their objectives and effectiveness	[8]

The twenty items identified can be further structured and grouped in a final list resuming the main learning requirements to be used in order to develop educational solutions for the training of advanced manufacturing skills. The final list was obtained through subsequent iterations of the grouping process of the initial twenty learning requirements until agreement among the authors was reached [20]:

- **Collaboration** ***(1, 2, 4)*****:** Development of educational solutions able to foster the interaction and the collaboration among learners, both during the activities themselves (i.e. in real time) and after thanks to the promotion of discussions and follow-ups.
- **Proactivity** ***(3, 5, 6, 7, 14, 17, 18, 19, 20)*****:** Development of educational solutions which guarantee a proactive involvement of the learners in order to understand the concepts addressed.
- **Feedbacks on learners’ actions** ***(8, 13, 15)*****:** Definition of clear interaction mechanisms between learners and their work, in terms of both feedbacks on their actions and subsequent evaluation. Innovative ways of gathering feedbacks should also be considered as well as proper mechanisms to assure the continuous real-time interaction of the learners with the educational activities.
- **Reality** ***(9, 10, 11)*****:** Establishment of the contact with reality, i.e. with real problems to be solved but also with the presentation of visible and up-to-date examples. Also the visualization of real factories dynamics should be allowed, by means of virtual applications and/or with an interaction with the shop-floor.
- **Variety** ***(12)*****:** Proposal of a variety of activities and approaches to be used. To this respect, innovative ways of delivering contents should also be integrated to more traditional ones.
- **Interdisciplinarity** ***(16)*****:** Provision of an interdisciplinary approach integrating different topics and hence allowing the learners to understand the interactions among the different manufacturing disciplines.

3. Digital game-based learning (DGBL) for manufacturing education and training

In the last years, many different educational approaches have been developed in order to update and improve the skills of young generations and to prepare them to the new challenges of the Fourth Industrial Revolution. Among them, those based on ICT technologies have the potential to support learners’ engagement and proactive interaction with the activity [19] allowing their personal exploration of manufacturing concepts. Therefore, several ICT-based educational solutions have been developed both for university students and workers in order to improve their learning of advanced manufacturing skills. For example, relevant works have addressed lab systems [6], mobile technologies for remote connection with the industrial plant [15], serious games [11], simulations [8], on-line distance learning [10], and virtual factory teaching systems [9].

Among those approaches, one of the most promising turned out to be the use of digital game-based learning (DGBL), which represents the combination of digital interaction with game-based learning. The advantages of this learning approach are several, e.g. the active participation of the learner [20], the sequencing of task and objectives [21], the provision of real-time feedbacks for self-assessment [22], the possibility for the learner to continuously test his/her own hypotheses [23]. Moreover, all these factors are then supported by the fun element, that is not used here for mere entertainment but to support the global motivation of the user [24], and therefore also his/her high order thinking skills, creativity and problem solving ability [25].

As can be noticed, the specific features of DGBL make it highly suitable to satisfy the learning requirements for manufacturing education and training. Indeed thanks to its high level of interaction, collaboration among learners can be enabled, by assigning different roles to users and making them work together to achieve a common goal. Proactivity is highly stimulated through the establishment of a set of final goals to be achieved by following a sequence of different tasks. Feedbacks on learners' actions are continuously provided by a real-time system of scoring and advisory, that allows the learner to reflect on his/her actions and immediately look for alternative solutions. Furthermore, the digital environment and the orientation to problem solving are ideal to propose realistic situations and up-to-date examples. In particular, the visualization of both complex shopfloor and system dynamics (e.g. logistics, operations management) otherwise difficult to be represented can be enabled. The variety of learning activities to be proposed is guaranteed by the high modularity of the learning objects that can be integrated in the virtual environment. For example, data collection and interpretation, development of solutions, testing and evaluation, writing of reports. Finally, as a result interdisciplinarity can be allowed, showing the learners the real connections among the different areas of manufacturing and the specific skills that are needed for each of them.

Unfortunately, despite its relevant features, the development and implementation of advanced game-based digital applications for manufacturing education and training is still scant, even though manufacturing students and workers could extremely benefit from such kind of educational approach. In order to show the particular suitability of DGBL to explain the complex concepts that will be more and more important for the future of manufacturing, the Life Cycle Assessment (LCA) Game was developed targeting the specific area of sustainable manufacturing.

4. The Life Cycle Assessment (LCA) Game

The LCA Game was developed in order to support the comprehension of the Life Cycle Assessment (LCA) tool for sustainable manufacturing by involving the learner in an industrial plant where a real LCA analysis on a coffee machine shall be performed. The LCA is a quantitative methodology, which quantifies the environmental impacts of a product, good or service, throughout its whole lifecycle. The LCA is standardized by ISO, in the 140404 and 14044 regulations [26], where a LCA framework is presented and the general guidelines are highlighted. The LCA Game is based on an online application which needs just a PC and an internet connection to be run. It can easily be played in an IT lab setting or directly by means of the personal laptops of the participants.

The LCA Game was developed through a co-design process that covered a period of two years from December 2013 to December 2015 involving a total of 265 university students as users. The process started with the testing of a first release of the game that was then improved after each of the six sessions run finally reaching the final version. The iterative co-design process was implemented by means of the systematic involvement of the users in the process. In particular, the steps of the process, inspired by the work of Hansen *et al.* [27], included the following:

1. Definition of the learning objectives
2. Validation of the learning requirements
3. Implementation of the learning requirements
4. Testing and collection of users' feedbacks
5. Analysis and elaboration of users' feedbacks

Each time users' feedbacks were elaborated, learning objectives were refined and learning requirements validated. The learning requirements were then implemented in the new release that was each time tested in a classroom setting through a pretest-posttest approach based on questionnaires. Finally the users' feedbacks collected during the testing were analysed and elaborated in order to provide new inputs for the first steps of the process.

Thanks to the systematic iteration of the co-design process, the final version of the LCA Game was obtained. In particular, the following learning objectives were identified:

- Understanding of LCA gathering process in a company
- Selection of relevant LCA data among possible mistakes and redundancies
- Elaboration of LCA data in an LCA report
- Provision of suggestion to the management of the company in order to improve the sustainability of the product

The main tasks of the LCA Game were defined in order to keep them coherent with the four main LCA phases defined by the ISO 14044. The tasks include goal and scope definition, where the problem and the objectives of the game are presented to the learner. In the inventory analysis, the simplified process tree of the product life cycle is defined and data shall be collected. In the impact assessment, the environmental load and impact are linked in order to provide a full report to the CEO. Finally, in the interpretation step, opportunities for improvement are identified and sent to the CEO.

The learner flow starts with the briefing of the game, where the coffee machine and the components and activities of the production system are described, in order to introduce him/her to the context. Before the game starts an introduction of the characters and of the goal of the LCA is also provided. In particular, the learner takes the role of a new-hired sustainability manager that has to evaluate the life-cycle environmental performance of the product. By starting the game, the learner has immediately at his/her disposal different windows (Figure 1):

- LCA Toolbox: A tablet where the player finds different apps in order to implement the LCA, i.e. boundaries selection, flowcharts, data entry, impact charts, and recommendations. In addition, the player can find the briefing with all the explanation and the app “my notes” with all the dialogues.
- Personal Computer: The player can consult the ERP System (where info about the BoM is stored) and the Coffee Machine Instructions (where info about Middle of Life and Recycling is stored).
- Books: This are can contain information regarding other lifecycle phases not directly related to the company.

Figure 1. Beginning of the LCA Game

The game starts with the system boundaries definition. A picture describing the main steps of coffee machine lifecycle allow the player to select the system boundaries he/she wants to include into the analysis (Figure 2).

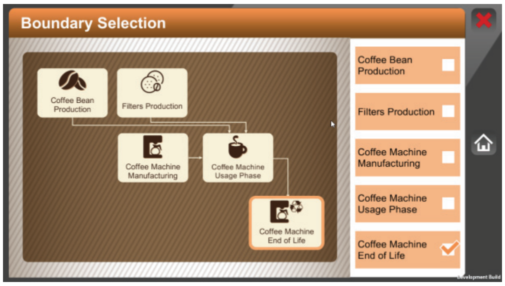

Figure 2. LCA Game – Boundary selection

The boundary conditions have information on the upstream processes, considering information about the coffee, with the coffee bean production, and the filter production used for the coffee maker under analysis. The core process is the coffee machine manufacturing directly related to the company. Finally, the downstream processes after the gate are related to the coffee machine usage and the final disposal.

Once the system boundaries are defined, the flowchart highlights the lifecycle steps with the related input and output included in the system boundaries. In this case the player can see the information regarding input and output not available or not useful for the analysis. Indeed one of the challenge of the game is to understand which data are necessary for the assessment.

The core of the game is the data collection step, where the list of input and output shall be filled in the data entry sheet. When the mark on the right is red it means that the player has not found that specific data yet, while when the mark is orange the player can insert the value (Figure 3).

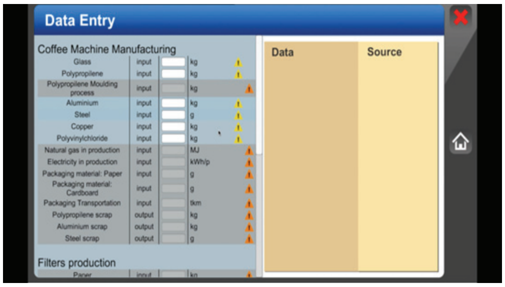

Figure 3. LCA Game – Data entry

In order to collect the data and understand the correct system boundaries selection and functional unit the player has the opportunity to ask four different characters, i.e. the CEO, the Production Manager, the Shift Manager and the R&D Manager, who all have different useful information for the achievement of the abovementioned goals. The player can interact with them and also look at his/her own computer and at the plant's PLCs to get important information for the LCA. Indeed the player can walk in the company's facilities and use the lift to go downstairs on the shop floor (Figure 4).

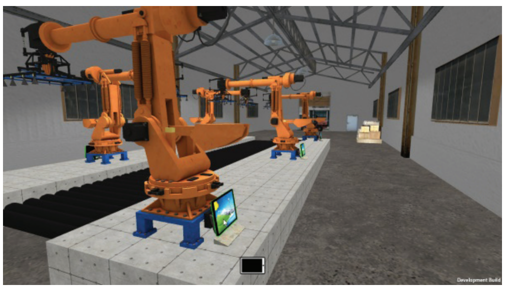
Figure 4. LCA Game – The shop floor

Once data entry is completed, the player shall complete the environmental impact assessment report in order to understand which are the relevant environmental indicators and the related justifications. The player has four sentences to analyse and for each sentence he/she has to define the impact category and one correct justification which describes the reason why that specific impact category is the highest or the lowest (Figure 5).

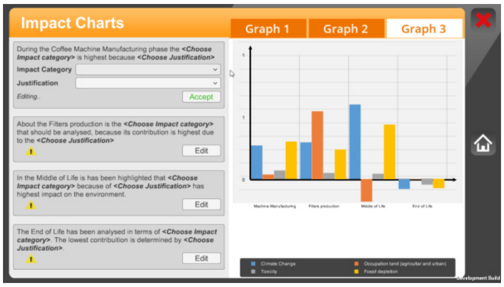

Figure 5. LCA Game – Impact charts

Eventually, the player has to send a suggestion for improvement to the CEO, choosing among five different options made available by the system. The game ends when the player submits the LCA Report to the CEO by clicking the Submit button in the LCA Tool. After that, an email from the CEO provides the player with the final score and an individual evaluation of his/her work. The player will hence discover if he/she will be confirmed or not as the sustainability manager of the company.

5. Conclusions

In order to sustain the rapid development of manufacturing according to the Industry 4.0 paradigm and to fill the increasing skills gap that the sector is facing, several efforts on the education and training of both university students and current employees should be done. Among the different solutions that can be adopted, it is hence important from the educational side to identify the learning requirements for the training about advanced manufacturing topics and the most effective educational approaches able to satisfy those needs, finally proposing concrete solutions. For this reason, in the current paper first the most relevant learning requirements for manufacturing education have been identified through a review of the existing literature. Afterwards, the different educational solutions explored so far in the sector have been discussed, identifying DGBL approach as one of the most effective in addressing all the six classes of learning requirements identified (i.e. collaboration, proactivity, feedbacks on learners' actions, reality, variety, interdisciplinarity). In particular, collaboration among learners is enabled thanks to the high level of interaction, while proactivity is made possible through the establishment of a set of final goals to be achieved by following a sequence of different tasks. Feedbacks on learners' actions are provided in real time by means of the scoring and advisory system, and the presentation of realistic and up-to-date situations provides the necessary link with reality. Eventually, the high modularity of the learning objects embedded in the virtual environment can guarantee the variety of the learning activities and the connections among the different areas of manufacturing by showing from time to time their own specific features and issues. As a concrete solution able to satisfy the learning requirements presented, the paper describes the LCA Game, a DG aiming at explaining the application of LCA to sustainable manufacturing. The main steps of the co-design process that was adopted in order to develop it are also illustrated, showing the importance of implementing educational solutions on the basis of the continuous interaction with the final users in order to validate and specify the learning requirements.

The LCA Game is an educational solution highly suitable for both university students and employees, thanks to its high scalability and its focus on the practical implications of the use of LCA in an industrial context. As a consequence, it is evident how this kind of virtual applications can give a relevant contribution in the necessary process of update of the manufacturing skills at different educational levels. They could be integrated in a systematic way in the current university curricula as well as in the corporate training programmes, enabling the development of applicative skills that would be otherwise hardly to train through traditional learning approaches. However, despite the evident benefits, the development and implementation of advanced game-based digital applications is still scant.

Therefore, future research should address the systematic evaluation of those educational solutions according to the specific manufacturing topic addressed, in order to provide both universities and companies with sound indications about the context in which these applications have the maximum effectiveness.

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