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Simulations and serious games for the transition towards Industry 4.0 – An action research on the development of serious virtual game in an academic environment

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Simulations and serious games for the transition towards Industry 4.0 – An action research on the development of serious virtual game in an academic environment

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Summary

Resumo

Chaim O.C. (2022) – *Simulação e jogos sérios para a transição rumo a indústria 4.0 – Uma pesquisa-ação sobre o desenvolvimento de jogos sérios no ambiente acadêmico* (Tese de Doutorado), Escola de Engenharia de São Carlos – Universidade de São Paulo, São Carlos, SP, Brazil

Os avanços recentes nos campos de inteligencia embarcada, conectividade, softwares e maquinário de produção são parcialmente responsáveis por mudanças sociais e de produção significativas. Esta tese trata aspectos relacionados a dois frutos diferentes destes avanços: a necessidade de treinamento e informação gerada pelas mudanças produtivas relaciadas ao fenômeno da indústria 4.0 e as oportunidades relacionadas ao desenvolvimento de aplicações de aprendizagem possibilitadas pelo avanço de softwares abertos e comunidades de desenvolvimento de jogos. Tem-se como objetivo relatar o desenvolvimento de um *serious game* utilizando softwares e plataformas abertas e/ou gratuitas para possibilitar a criação de novas ferramentas educacionais com princípios de aprendizagem ativa e voltadas para a mediação de conhecimentos relacionado transià indústria 4.0. Para tanto, como parte de um projeto binacional de pesquisa firmado entre o Brasil e Alemanha, foi desenvolvido um jogo com objetivos de aprendizagem relacionados a indústria 4.0 onde o jogador assume uma fábrica e toma decisões de produção e melhorias para atingir um objetivo pré-estabelecido. Além do desenvolvimento da ferramenta e das observações e conclusões decorrentes da pesquisa-ação, são apresentados os resultados das aplicações e das respostas dos usuários e a teoria desenvolvida referente ao jogos sérios e indústria 4.0. Como resultado, embora os custos de desenvolvimento e barreiras de entrada é ainda necessária a participação de programadores capacitados para criar este tipo de ferramenta, sendo o custo de tempo de desenvolvido e a variedade de habilidades técnicas necessárias uma das principais barreiras para a ampliação da criação e uso de jogos sérios computacionais. Além disso, a comunicação entre membros da equipe com diferentes fluências em conteúdos digitais e jogos se provou um desafio maior do que esperado.

Palavras-chave: Jogos Sérios. Indústria 4.0. Desenvolvimento de Competências.

Abstract

Chaim O.C. (2022) – *Simulations and serious games for the transition towards Industry 4.0 – An action research on the development of serious virtual game in an academic environment* (Doctoral Dissertation) Escola de Engenharia de São Carlos – Universidade de São Paulo, São Carlos, SP, Brazil

The advances of the last decades in the fields of embedded intelligence, connectivity, production software and machinery are partially responsible for significant social and production changes. This thesis deals with aspects related to two different results of these advances: the need for training and information generated by productive changes related to the phenomenon of industry 4.0 and the opportunities related to the development of virtual learning applications made possible by the advancement of open software and development communities. This work reports the development of a serious game using free and/or open software and platforms to enable the creation of new educational tools with active learning principles and aimed at mediating knowledge for the transition towards industry 4.0. Therefore, as part of a binational research project signed between Brazil and Germany, a serious game was developed with learning objectives related to industry 4.0 where the player takes over a factory and makes production and improvement decisions to achieve a pre-defined objective. In addition to the development of the tool and the observations and conclusions resulting from the action research, the results of the applications and user responses conclusions, the theory developed regarding serious games, education and industry 4.0 are presented. As a result, although development costs and entry barriers have reduced recent developments, the participation of skilled programmers is still required to create this type of tool, with the cost of development time and the variety of technical skills required being one of the main barriers to scaling up. the creation and use of serious computer games. Besides that, the communication among members with different digital and gaming literacy has proven a greater challenge than it was initially expected.

Keywords: Serious Games. Industry 4.0. Competency Development.

1 INTRODUCTION

In the interest of developing new learning methods to meet the changing needs of industry, a project was approved to create a learnstrument for industry 4.0. This PhD work is closely related to a binational project between Brazil and Germany, funded by CAPES and DFG, throught the cooperation initiative BRAGECRIM. As such, many of the applications proposed and the research performed will be applied to the development of content and material regarding this industrial changing process and how it changes the way industry works, the human-machine interactions in industry, the transformation towards service, the digital presence in industry and other relevant factors that this international process can lead to. This leads to a work that is mostly dedicated to exemplifying the development of serious games in an academic context with its costs, decision making methodologies, and skills demands, while exploring the educational opportunities of interactive games and simulations in the context of technical education in the for the transition towards industry 4.0 and its implications.

1.1 Context

The lack of skilled workers specially in technical fields is a well documented worldwide problem (I.E.E.E, 2022). The need to modernize educational systems is an international issue and one of the most pressing matters in the XXI century. To do so, not only the update of tools is required, but also a change on the goals and justification of education itself to answer to the anxieties of a distintic reality. Be it in elementary, high, superior or informal education, the technological advantages are providing many opportunities for educators to seize, such as the creation and use of learning games, virtual reality applications and directed computer simulations.

Currently the overall costs for developing more interactive computer based learning tools is decreasing, and with this, the range of possible application increases. In this context, investiments and research are needed to allow the development of new types of tools and accelerate their usage and spread in order to address the growing needs for capacitation, training and, in a broader and deeper sense, education.

Adding to this opportunity, the increasingly connected work environment and the online distance working opportunities can lead to the need of a more distributed training and capacitation environment, specially in the context of the fourth industrial revolution (MULYADI; HUDA; GUSMIAN, 2022).

The competency development and training of skilled workers is a shared responsibility of the formal educational systems, the industry and the workers themselves (GOLDBERG; SOMERVILLE, 2015). Self-learning tools such as online courses, course libraries and digital learning tools have great potential to address the accelerated capacition needs by being able to attend to either group, being accessible both to individuals and organizations. Serious games can fit well for industry, university and for self-learning.

One of the most marked recent developments of the world´s economy is the industrial digitalization phenomenon (GEISSBAUER; VEDSO; SCHRAUF, 2016; STOCK; SELIGER, 2016), be it called Industry 4.0, industrial internet or smart industry (HERMANN, M.; PENTEK, 2015). No matter the terminology adopted, the changes caused by the interconnectivity of industrial elements and increased affordability and capacity of distributed intelligence are affecting the workplace and productity of industries significantly (GHOBAKHLOO et al., 2021). These developments changes what it means to manage and work in industrial environments, requiring professionals and students to prepare and adapt or fail realizing the potential benefits of the digitalized industry. This thesis has adopted the industry 4.0 term to address these changes due to both its impact and spreadth as well as the project connections to the German industrial terminology.

Based on the needs for capacitating people in the transition companies are experiencing towards industry 4.0 and the opportunities made available by the decreasing development costs of virtual learning tools, the BRAGECRIM team saw an opportunity to develop a virtual serious game to put users in contact with concepts and technologies related to the industry 4.0. In this context, the concepts of educational changes, engineering education, serious games and industry 4.0 are explored as a basis for this thesis research-action methodology on the development of the virtual prototype and game on the transition towards industry 4.0.

1.1.1 The Project

The project aims to create a serious game to address topics regarding industry 4.0. As such, it is expected to provide results both in terms of research and products, the serious games themselves. To deliver and produce the games in an easier and timely way, an intermediate development platform is developed. Funded by CAPES and DFG, this project is binational project run by the *Escola de Engenharia de São Carlos – Universidade de São Paulo* (EESC- USP), the *Universidade Federal de São Carlos* (UFSCAR) and the *Technische Universität Berlin - Institut für Werkzeugmaschinen und Fabrikbetrieb* (TUB-IWF).

In the first funding period, of which the majority of the works described in this thesis are part of, the main objective was the creation of learnstruments for students and employees on the design principles of industry 4.0 in relation to changes caused by the emergent technologies in factory layout and production planning.

Regarding the research, the two main fronts are interactive self-learning tools and industry 4.0. The objective of the first in the project is to understand the current practices and preferences through feedback forms, questionnaires or surveys, explore the best practices through literature review and propose a methodology for the development of the learning tools.

While the serious game itself is a deliverable, the development platform was not considered a deliverable by itself in the project description, however given the opportunity and relatively low marginal cost of developing an open solution, the researchers have decided to make it as accessible and flexible as possible. To be able to focus the effort on the devopment of the serious game, a game development engine, called Unity (UNITY TECHNOLOGIES, 2022), has been chosen as the development platform. The final engine consists of the implementation of codes, behaviors, 3d models and other premade elements designed to be rearrangeble, with as little programing as possible, to create the final learning tools. Within Unity 3d, this platform is a factory simulation learning engine with a set of parametric behaviors and industrial game mechanics already implemented.

The learning tools developed are virtual spaces, interactive videos and explanations, a serious game and challenges used to promote learning for different audiences. The main deliverable are the challenges and the serious games, with the others being smaller parallel developments.

Overall the project was renewed for a second funding period with a slightly different scope which result in the development release of a Board Game (PARAVIZO, 2021).

1.1.2 The working group

As stated in the funding document, the project would be divided in several workpackages, each led by a professor. In practice, this model was used for responsibilities and accountability, but the linear structure represented in Figure 1 was not followed, as the group opted for a non linear iterational approach.

Figure 1 - Work Packages and Professors. Source: Bragecrim Funding Proposal

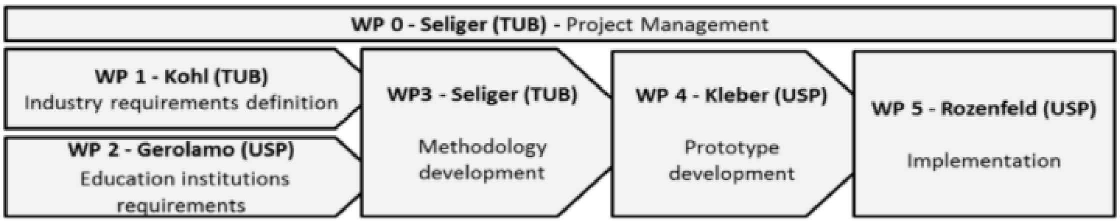


Table 1 lists the members for the first funding period of the BRAGECRIM project.

Participant	Occupation - Advisor	Insttution
Prof. Dr.-Ing. Holger Kohl	Professor	TUB - IWF
Prof. Dr.-Ing. Günther Seliger	Professor	TUB - IWF
Dipl.-Ing. Bernd Muschard	PhD Candidate	TUB - IWF
Diplo. Wirtsch Ing Tim Stock	PhD Candidate	TUB - IWF
Prof. Dr.-Ing. Henrique Rozenfeld	Professor	EESC - USP
Prof. Dr Daniel Braatz	Professor	Ufscar
Prof. Dr Mateus Cecílio Gerolamo	Professor	EESC - USP
Prof. Dr Edson Walmir Cazarini	Professor	EESC - USP
Prof. Dr Kleber Francisco Esposto	Professor	EESC - USP
Omar Cheidde Chaim	PhD Student - Cazarini	EESC - USP
Núbia Carvalho	Master Student - Cazarini	EESC - USP
Ana Carolina de Arruda Falcão	Master Student - Gerolamo	EESC - USP
Esdras Paravizo	Undergraduate Student - Braatz	Ufscar

Table 1 - BRAGECRIM team members

On the implementation side, while the members reviewed and complemented each other work, four distinct groups of activities happened in practice: Feedback and surveys, literature research, game design and game implementation.

1.1.3 Action Researcher point of view - My position in the project

Since it is relevant for the characterization of my role in the project as the action research observer, in this section I describe my participation in the implemented activities. To do so properly, I consulted the many meeting proceedings available in the project folders as well as the authorship of the documents produced during the project. Since the professors were involved in the overseeing, evaluating and feedback of the works in our biweekly meetings, their participation is a given.

Acting at first as the Brazilian side student manager, I was involved in the four implementation groups however my share of work and influence on each of them was distinct. For the feedback and survey I mostly reviewed and made suggestions on the proposals without getting involved in their research and creation. In the literature research, with the professors help for determining the methodologies, I worked in equal share with the other students, and we decided our responsibilities as group in our weekly meeting. On the game-design front, I worked in close relation to Esdras Paravizo, with Núbia Carvalho jointly contributing with the scripts and as a lead for the User Intefaces. In the last segment, Game implementation, I worked mostly alone since the programming skills for the development of the serious games was not shared by the other participants.

As part of the implementation of the serious game itself and of the action research methodology, after the final presentation of a prototype, a new revision cycle started, normally in the next biweekly meeting with the start of the next implementation.

1.2 Objectives

This research projects aims to develop the theory on serious game usage and devolopment for engineering and technical learning by studying and putting to use the best practices while creating the learning tools, analyzing the results and feedback on the resulting solutions through the research action methodology.

1.3 Objectives

The main research questions were defined about halfway in the development of the first prototype (Haifa), being at the point three:

- What are the main challenges on developing serious games in an academic environment?
- Is it already possible to create tools for non-programmers to create their virtual serious game?
- How viable is the creation of serious games within research projects?

1.4 Parts of the document

After the introduction, the next session contains an overview of the literature research on the most relevant topics. The third session contains an overview of the research methodology of action research. The fourth session reports the methodology framework from its literary base to the actual implementation in the serious games. The fifth section describes the action revision cycles of the implementation of the prototypes and serious games. The sixth section describes the achieved results of the developed serious game, the factory game engine that was created for the serious game development, and a list of the published/submitted articles related to the project. The last section contains the conclusion that arose from the project and this thesis research action.

The annexes were developed by the BRAGECRIM project team and are included in this thesis to allow for the visualization and discussion on the actual implementation of the steps. This document contains the following annexes:

- Annex 1– First Game concept presentation
- Annex 2 – Haifa Prototype Dialog Script
- Annex 3 - Principle Cards for Haifa
- Annex 4– 3D Models Link Library
- Annex 5 – Relation of Industrial Scenes and Industry 4.0

- Annex 6 – Second Prototype Game Script – Recycled for use in the bicycle factory 4.0
- Annex 7 – Selection of product to create the learning virtual factory
- Annex 8 - Developed Challenges based on the Industrial Examples (Media/Marketing)
- Annex 8 – Bicycle Factory 4.0 form feedback

To maintain the transparency on what the group worked with during the project, the annexes are presented as they were with the occasional omission of unnecessary or repetitive text. Notes and comments were also removed as they do not contribute to the comprehension of the delivarables presented. Some of the formats had to be changed, specially when the actual development document was a presentation file or a large table. Overall, the attempt was to strike a balance between usability in the format of a thesis and transparency on reporting the works presented.

All annexes were developed by the group to be used for research and divulgation purposes.

2 LITERATURE REVIEW

To understand the overall context and in which state is the current development of the studied areas, a literature review is presented on the educational changes related to active practices, possibilities in the context of the application and development of Serious Games and an industry 4.0.

The literature review was done differently for the education and gamification sections and the industry 4.0 section.

For the first eduction and gamification topics, the review was less structured and started by the most cited papers on both topics in the google scholar, web of science and scopus databases, followed by the inclusion of the papers cited within the most cited that were deemed relevant. Throughout the research, new papers were included while searching for emerging question and as recommendation from professors, by peers in conferences and other project members.

For the industry 4.0 section the review was more structured. Using the same three databases, all articles regarding industry 4.0, smart factories, digital transformation, smart industries and industrial Internet of things were filtered by title. Then they were prioritized and selected based on their summaries. In the end 62 articles were included as resources for the project. This review is further detailed in section 5.1.2.3. as it was part of the development of the main prototype. As the project continued, new articles were found and added in a less structured form from recommendations and updates to the review.

2.1 Application contextualization in education

The most common tools for education regard mainly the transmission of knowledge, such as reading materials, textbooks, lectures and videos, even in this context however, active projects are available e.g. exercises, projects-based-learning, student-lecturing. What technology can change is the availability of active learning practices, just as it has done by making the aforementioned materials widely accessible, and their capacity to adapt to the learners needs (ZAPALSKA; BROZIK; RUDD, 2012).

Parting from traditional practices, some of the most accessed language courses are actually active-learning based. One of the main examples of this is the multiplatform app Duolingo (DUOLINGO, 2017) with 120 million total users and over 1 billion exercises done monthly, it uses some gamification principles coupled with exercise-based learning to accelerate and improve language learning. Another example more focused on the gamification side of learning is MindSnacks (MIND SNACKS, 2017) where the learner is exposed to a many different games focused on different compentences of language learning, such as reading, writing, vocabulary and so on. A third active based app of note is HelloTalk (HELLO TALK, 2017) which puts learners in direct contact with natives and mediates the process, best case scenario being two people trying to learn each other native languages. Despite their limitations, these examples provide evidence of the potential of active learning practices.

In the formal education context, the dominance of text books and digital presentations is connected to the initial investiment on their development in comparison with the significantly higher budgets and time expenses of more interactive alternatives (BAARTMAN; DE BRUIJN, 2011; D’ANGELO et al., 2014). While both books and presentations are mostly created by a single or small teams of experts with experience who have known and used presentations and books for years, the development of games and simulations for learning require a larger set of abilities beyond the core educational objectives. Coupled with the lack of experience that most professors have with games in general, and more drastically with serious games, this presents a significant barrier to overcome in developing this kind of learning instruments (AHMAD; RAHIM; ARSHAD, 2015).

2.1.1.1 Serious Games and their characteristics

Games and the usage of gamification theories have been around since the second half of the XX century but despite the elapsed time and increase in the total market value of the gaming industry, the games for learning are still scarce (BOYLE et al., 2015). To describe games that are not developed with the end-goal of entertainment but rather that of education and training are called serious games (DJAOUTI; ALVAREZ; JESSEL, 2008)

While the aforementioned barriers are present, the technical difficulty of developing games in general has dropped in the last decade (MITGUTSCH; ALVARADO, 2012; SILVA, 2020). The increase in the size of Indie games industry and the appearance of free and/or affordable game engines and asset bases are responsible for a significant decrease on the effort and cost of game development in general (WESTERA, 2019).

Given the increased cost to create serious games in comparison to more traditional methods, some advantages or positive points must exist in order to justify the investment. Some of the key advantages are mentioned below:

Opportunities for on-demand and adaptative learning: Due to their capacity to incorporate many different types of media, well-designed serious games can be backed up by an available body of knowledge. As an example, the learner may be asked to perform a task that requires a certain knowledge: if the players succeds directly, there is no reexplain the topic. If the players feels lost about how to proceed, help can be built-in the game and accessed while she or he is trying to solve the challenge. In case the player fails, the game might offer him insight on what went wrong and guide her or him towards the built-in help (ALDRICH, 2009; KHAN, 2011). This flexibility is but one example on the potentials of adaptability that serious games provide:

Interactive assessment of and for learning: serious games can be used within their development context to assess from a player personality and favored tactics to ability to complete simulated tasks (BELLOTTI; KAPRALOS; LEE, 2013; DELACRUZ, 2011; HARTEVELD; SUTHERLAND, 2015).

Motivation for learning: The practice of gamification in schools, online courses and universities is closely related to the impact that games have on motivation. Many practices present in entertainment games have been studied for adaptation in non-game environments with positive impacts , this can also be applied to serious games with even less adaptation. While increased motivation can lead to improved learning, this may not always be the case, a balance has to be achieved in regard to serious games so that the motivation impact contributes to the learning process, and not only on the interest on the game itself (WESTERHOLT; LOREI; HÖFLE, 2020; WOUTERS et al., 2013).

Training through process simulation: Games can also be used to promote through scoring and rewarding positive practices better practices in simulated processes (HAUGE; RIEDEL, 2012).

Competency development: Depending on their development, these tools can facilitate competency development. Since games have more tools available to represent the different realities, they can be used to create a more immersive experience that is more closely related to the usage of the developed knowledge (NADOLSKI et al., 2008). If the concept of the serious game is extended to adapted input, it can contribute even to the development of motor abilities.

Self and tutored learning tool: Another interesting topic to explore on the usage of serious games is their ambivalence for self and tutored learning. While games can be developed as self-contained learning packages, they can also be used in a classroom context (DELACRUZ, 2011; TANG; HANNEGHAN, 2011). Professors and tutors can use them both as a learning tool as well as a follow-up and feedback one. This significantly increases the feedback potential of such games and allows the professor to see how the students are using their knowledge to solve the proposed challenges and help them improve their practice and mature their line of reasoning. For games to provide this capacity properly they have to be developed with that in mind.

In the context of engineering they can lead to a closer relation with market practices (HAUGE; RIEDEL, 2012). While conventional exercises and materials frequently have to break down a concept in order to be functional, a virtual scenario can deal with a set of intertwined concepts simultaneously in a manner where the learner has to direct his or her own view. This is a distintic characteristic of simulations and games, the impacts of action can be felt in the next steps, something that is quite difficult to achieve even to a lesser degree, regarding educational practices, without the aid of a computer. As an example, if a student is required to buy a set materials for a production challenge but buys more than is needed, he or she will not face an immeadiate failure, as would happen in a traditional exercise, but will have less resources or inventory space to work with for the remainder of the challenge, and will end it with or lower score. This idea of a multitude of results for a given action in contrast with either a right or wrong is one of the key advantages, if not the, of this type of tool(HAUGE; RIEDEL, 2012; ZHONGGEN, 2019).

The new potential benefits that interactive active learning tools provide, is in many situations more than sufficient to justify their implementation and the increased costs. This can be even further developed when considering the case of technical education.

2.2 Towards industry 4.0.

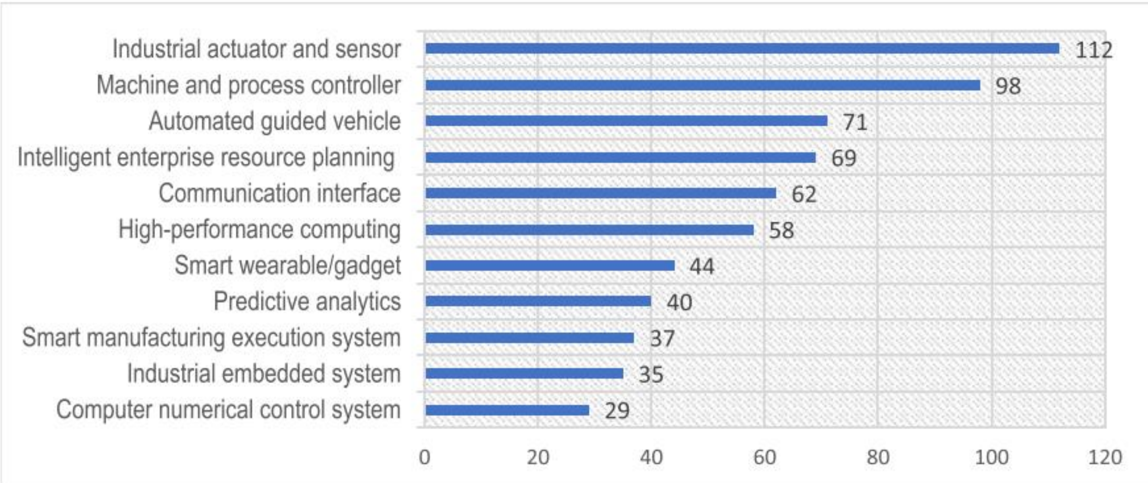
Industry 4.0 is a name created in Germany, first presented in 2011 (KAGERMANN; LUKAS; WAHLSTER, 2011), for the changes seen in industry due to the industrial large-scale implementation of technological advances that configures a change that is large enough to be separate from the automation of industrial lines, also known as the 3rd industrial revolution (ALMADA-LOBO, 2015). These changes transcend the industrial to process themselves to incorporate the intelligence from different sources to understand and monitor the entire product/service timeline, creating a closer relation to users while changing business models (HERMANN, M.; PENTEK, 2015). The term has been actively promoted by the German government through financial incentives, funding and creation of practical research material (KAGERMANN, 2013).

It is relevant to point that the German terminology of Industry 4.0 is not the only used to define these set of changes, other names related or directly connected to the process are: Industrial internet, Advanced manufacturing, Smart Factories, Industrial IoT (Internet of Things) (GHOBAKHLOO et al., 2021). While there some diferences in the scope of these terms, they are attempts to undestand and describe a similar phenomenon. In this work the focus will be given to the discussion on industry 4.0 without ignoring the discussions and literature presented by the other terminologies.

Among the definitions of industry 4.0, and the similar terms described previously, (BEIER et al., 2020), two key elements can be identified: Connectivity (machines and systems capacity to connect among themselves, to other databases and even to people) and intelligence (decision making based on data received data to adapt to changes). It is important to notice that the term does not describe, as usually reported by the media, the simple implementation of “plug and play” technologies, but instead a process of organizational practices and complementary innovations to achieve its potentials (CULOT et al., 2020).

Another key aspect of industry 4.0 is the technological components that have enabled its occurrence and that make a phenomenon tied with emerging technologies. On that front, much research has been conducted (CULOT et al., 2020; QIN; LIU; GROSVENOR, 2016), with for instance a over a hundred articles connecting sensor and actuators to industry 4.0. Figure 2 summarizes the main technologies related to industry 4.0 with their respective citation count out of 745 related articles (GHOBAKHLOO et al., 2021):

Figure 2 - Main tecnological terms related to industry 4.0 and their mention count out of 745 analyzed articles (GHOBAKHLOO et al., 2021)



One of the main topics of discussion of this concept regards the role of human beings in these processes (BONEKAMP; SURE, 2015; PFEIFFER, 2016; REUTER et al., 2017). While there is much interest in the topic which changes are going to happen are not as clear and how fast are not as clear (BONEKAMP; SURE, 2015). Of the main aspects of changes in industrial working realities, some factors are prominent (BEIER et al., 2020): decreased participation of lower skilled workers, development of new training technology (SACKEY; BESTER; ADAMS, 2017; STOCK; SELIGER, 2016), continuation of maintenance workers employment, increased need for technically trained workers, increased cooperation with heavy industrial machinery, overall increase in productivity.

Of the researched literature, the framework selected to be used as standard for the initial development of the learning game was that proposed by Herman and Pentek (HERMANN, M.; PENTEK, 2015). This article was selected for the actionable proposed design principles (which attempt to differentiate the design thinking on production systems in industry 4.0 to that used before), its high importance in literature (this article was among the most cited at the time) and the quality and clarity of the research. The six design principles definition on industry 4.0 selected as a framework included: Interoperability, Decentralization; Virtualization; Real Time Capability; Modularity; Service Orientation.

Among these principles, the decentralization, virtualization, real time capability and service orientation drive the need for new educational tools and methods. The velocity of changes and requalification of workforce is said to be accelerated even further (BAUER et al., 2015; DEMARTINI; BENUSSI, 2017) making it more difficult for companies and industries to stop periodically to requalify professionals and strengthening the need for on-demand direct qualification. These changes also remove a significant amount of the workforce from operational industrial tasks, directing human labour towards activities that cannot be performed by machines (DEMARTINI; BENUSSI, 2017). Other than these general notices on the impact of these changes, some of the aforementioned design principles lead to other consequences regarding education.

Virtualization when thoroughly applied implies a profound overhaul of the communication between humans and machines. On one hand it means that the physical world, concerning the industry, will be somehow modeled in a virtual self (KELLER et al., 2014), making information and responses less location dependent and given a proper analisys system, providing insigths in the production process that are still to be developed (LEE; KAO; YANG, 2014b; SALDIVAR et al., 2015). On the other hand it means that machines will be able to use a digital avatar, for lack of a better word, of themselves to communicate to other machines and human workers, meaning that the machine will possibly be able to guide maintenance workers performing its own maintenance through augmented reality or teach an operator how to work with it, meaning that machines in this context may capacitate human workers on the run (STOCK; SELIGER, 2016). This is one of the key points for the development of learnstruments, capacitate workers based the reality they are immersed in, taking into account their learning needs, when that capacity is needed (BONEKAMP; SURE, 2015; SONY et al., 2021).

Decentralization leads to a distribution of decision making to a higher numbers of employees, machines and stakeholders involved in the production processes, requiring not only empowerment of those involved, but also an increased responsibility and understanding of the big picture where the decion making is made, a better understanding and usage of decision making support systems and accountability and communication to align the general strategy (CARVALHO et al., 2018; KELLER et al., 2014). This is a reality where a overly divided structure and responsibility silos are specially dangerous. In terms of education, a distributed decision making process require a more holistic understanding not only of one´s own responsibility, but also the industry and business as whole .

Real time capability highlights the need for fast and efficient communication systems as well as the constant usage of systems to support decision making (KELLER et al., 2014). This design principle focus on avoiding the creation of system that require human authorization or consultation in their overall framework, attempting to maintain whenever possible a faster connection through the strategy-tactics-operation chain of decision.

Service Orientation is a topic more related to the very financial sustainability of companies and is a tendency that transcends industrial practices. Many examples of service oriented products are appearing in many different markets, ranging from car manufacturers that are switching from selling cars (Product) to selling the usage of cars (services) to companies that are competing with razor blade manufacturers by offering a subscription services where every month all the apparatus required to shave is delivered. Regarding the less physical products, such as music, series and movies, the change is even more drastic. Overall, this is one of the design principles that is easier to notice, but certainly one that we are still to see the deepest impacts (HERMANN, M.; PENTEK, 2015; LEE; KAO; YANG, 2014a). On educational needs, it can be argued that this will lead to even more demand for qualified work-force since the very industrial production is a plausible service to be offered, creating many opportunities for many professionals to create new products and solutions without the need to set up a plant (BAUER et al., 2015; VIGNAESVARAN JEYANDRAN., 2017).

Modularity deals with the ability of constitute production system of modular parts, increasing the flexibility of new production systems (HERMANN, M.; PENTEK, 2015). This is to be achieved by improvements in machine to machine communication and the emergence and decrease in cost of autonomous movers.

Interoperabiity deals with the capacity for machines of different makes, fabrication dates and manufacturers to work with each other and also with humans (HERMANN, M.; PENTEK, 2015). This intends to deal with current wastes by allowing different machines to communicate with one another through the creation of standardized protocols. Another aspect of this design principle, is the attempt to allow safer operation while humans and machines work together through the use of intelligent interpretative analysis of risk, such as used by autonomous cars, decreasing risks and allowing for a better use of space (GHOBAKHLOO et al., 2021; KELLER et al., 2014).

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3 METHODOLOGIES

Given the scope of the international product from which this PhD work is part of, at least three methodologies will be used. To create learning materials and further the understanding on the topics related to tools as well as to define the best tools and implementation practices, literature reviews will be used. To assess the functionality and validate the learning tools results surveys and questionnaries of both qualitate and quantitave nature will be used. To contribute to the under-development theory of creating serious games, the main focus of the thesis, the proposal is to use a research-action methodology, for both the interest on these topic and the contributions that can arise for the international nature of this project.

Since both the methodologies of literature review and surveys suit more the articles and research byproducts of this project, the main methodology is the only briefly reviewed in this document.

3.1 Research Action

Overall research action offers an opportunity to perform research while performing work. It is most suitable when dealing with areas of theory development that are less mature (COUGHLAN; COGHLAN, 2001).

Lewin's article that originated the term action-research (LEWIN, 1946) calls for a research that directly helps the practitioner, transforming goodwill in organized practice understand the current situation, the risks and mainly, what to do. According to Coughlan (COUGHLAN; COGHLAN, 2001) "Action research has been traditionally defined as an approach to research that is based on a collaborative problem-solving relationship between researcher and client, which aims at both solving a problem and generating new knowledge" and consists of the steps a diagnosing, planning, gathering data, taking action and analizyng the results to plan further action (BASKERVILLE; HARPER, 1996; COGHLAN, 2007, 2008).

This methodology suits this project as the working group, in this case a research group, is expected at the same time to solve the problem and develop the solution at hand while building theory and reflecting on how to do it. In the wrestle between using the best approach described and solving the problem and maintaining a healthy project, a balance has to be found.

As a key indicator of quality action research is its transparency and clarity, including when describing less than optimal choices during practice, the section on the developed instruments includes the reasoning behind the most relevant choices, the limitations faced at the time and the perceiveid results of the practice. Since a total of three serious games reached a testable prototype phase, each will be considered as a cycle regarding the action research methodology, having a development description, a feedback collection step and ending in a reflection/learned lessons.

3.2 In Project implementation

During the development within the BRAGECRIM project, the documentation of the steps towards the implementation of the serious games were often more detailed than required for the needs of the proposed research action methodology. Since the biweekly meetings had meetings procedures and the development advances were often presented and explained to the project members in Brazil and Germany, the reasoning behind much of the decision making was already being recorded. These meetings reinforced the implementation of the methodology, by promoting accountability and clarity.

Adding to the supported documentation, as described in the Development Methodology section, the game components deliverables such as scripts, challenges descriptions, interface art among others were also used as sources. To complement the meeting presentations, development documents and proceedings, I started creating annotations of the programming development and challenges faced through the implementation.

Among the most valuable resources for the action revision cycles, the feedbacks of the tools on the testing of the developed learning tools were used extensively and are perhaps the most influential element in the revision phase and planning for the continuation of the development.

The action-revision actual descriptions are embedded in the descriptions of the Serious Game development, with each prototype roughly representation a cycle.

4 DEVELOPMENT FRAMEWORK

This chapter describes the methodologies used for the development of the actual learnstruments, and is divided in two main sections. The first gives an overview of the game development technologies implemented. The second describes the actual methodology used and the elements that were considered while developing the tool.

4.1 Game design framework

This work started with the selection of a development framework. Barbosa et. Al (BARBOSA et al., 2014) justified the creation of a new methodology for developing serious games due to the scarcity of such methods a view shared in a latter literature review utilized for this development in the year it was published (AVILA-PESÁNTEZ; RIVERA; ALBAN, 2017).

Some frameworks directly related to serious games differ significantly in their proposed implementation, some opted for a more formal approach considering even its inclusion criteria in university (NADOLSKI et al., 2008) while others focused more on specific implementations of serious games (BARBOSA et al., 2014). Mitgutsch and Alvarado (MITGUTSCH; ALVARADO, 2012) provides an assessment framework to be used during development to evaluate the consistency of the game components.

In their review on available serious game development frameworks, the authors (AHMAD; RAHIM; ARSHAD, 2015) identified four sequential movements for game design, the first focused on listing the required elements of a game, the second frameworks centered around learning theories and their relation to games, the third incorporating game-based learning in formal environment and the fourth changing from a learning centric framework to a development centric. The authors state the while there are frameworks for the development of educational games, "[…] *research in the design of educational games is still in its infancy level."*(AHMAD; RAHIM; ARSHAD, 2015, p 23) and point to the need of developing further research, specially on the communication between stakeholders, proper modelling and traceability of requirements and testing methods of games. These points of inquiry are shared by other authors. The communication between stakeholders is a topic also discussed by Braad et.al (BRAAD; SANDOVAR; ŽAVCER, 2016) and Frutuoso (SILVA, 2020) who proposes a series of model to facilitate communication.

Despite their publication dates, these two articles (BARBOSA et al., 2014; NADOLSKI et al., 2008) are still the most cited articles in related to development methodology for serious games, however neither of them fit the project needs directly.

To mitigate that we started working inspired by the framework overview provided by Avila et. Al. (AVILA-PESÁNTEZ; RIVERA; ALBAN, 2017) formalized in Table 2, combined with the recommendations present in the “Art of Game Design: a book of lenses” (SCHELL, 2008).

Table 2 - Phase/Stages of the approaches for serious game design. Source:(AVILA-PESÁNTEZ; RIVERA; ALBAN, 2017)

Phases	Stages	E01	E02	E03	E04	E05	E06	E07	E08	E09	E10	E11
Analysis	Identification of the problem	–	√	√	√	√	–	–	√	√	√	√
	Teaching Objectives	√	√	√	√	√	√	√	√	√	√	–
	Teaching Competence	–	–	–	–	–	–	√	–	–	–	–
	Learning Tools	–	–	–	–	–	–	–	–	√	–	√
	User / Player Profile	√	–	–	√	√	√	–	–	√	√	–
	User Experience	√	√	–	–	–	–	√	–	–	√	–
	Quality assurance	–	–	–	–	√	–	–	–	–	–	–
	Specification document	√	–	–	–	√	–	–	–	–	–	–
	Therapeutic techniques	–	–	–	–	–	–	–	√	–	–	–
	Instructional activities	–	–	–	–	–	–	–	–	√	–	–
Design	Patterns Design	√	–	–	–	–	–	–	–	–	–	–
	Narrative	√	–	–	√	√	√	√	√	√	√	√
	Game Mechanisms	√	√	√	√	√	√	–	√	–	√	√
	Requirements Specification	–	√	–	–	√	–	–	–	–	√	√
	Architecture	–	–	√	–	√	–	√	√	√	–	–
	Design Prototype	√	–		–	√	–	–	–	–	–	–
	Quality assurance	–	–	–	–	√	–	–	–	–	–	–
	Document Specification	√	–	–	–	–	–	√	–	–	√	–
	Evaluation Design	–	–	–	–	√	–	–	–	–	–	–
	Risk analysis	–	–	–	–	√	–	–	–	–	–	–
Development	Game Programming	√	–	√	–	√	–	√	–	–	–	–
	Application prototype	√	–	–	–	√	–	√	–	–	–	–
	Quality assurance	–	–	–	–	√	–	–	–	–	–	–
	Specification document	√	–	–	–	–	–	√	–	–	–	–
	Game integration	–	–	–	–	√	√	–	–	–	√	–
Evaluation	Goal Validation	√	–	√	–	√	–	–	–	√	–	–
	Quality assurance	√	–	–	–	√	–	√	–	–	–	–
	Testing	–	–	–	–	–	–	√	–	–	√	√
	Feedback	–	–	–	√	√	–	–	–	√	–	–
	Maintenance	–	–	–	–	√	–	√	–	–	–	–
	Continuous Improvement Plan	–	–	–	–	–	–	√	–	–	–	–

In practice, the following steps were followed during the development of the first learnstrument, with the adaptations being described in each of the prototype´s sections in Chapter 5 – Serious Games Development.

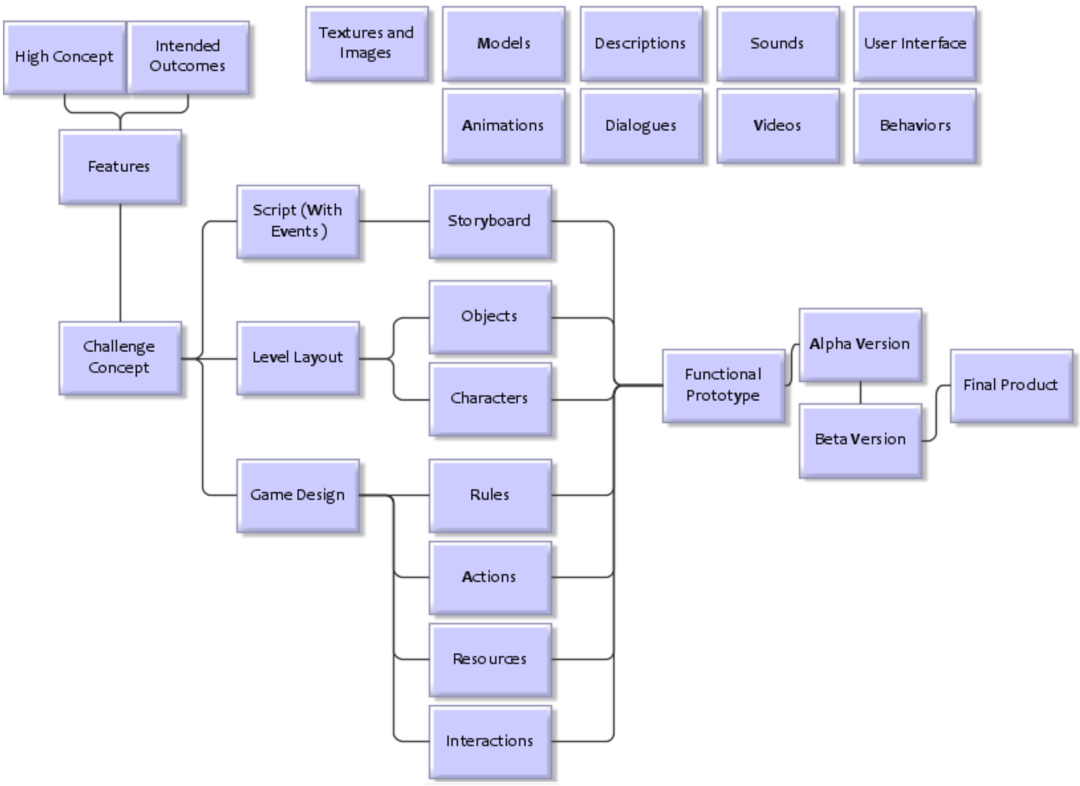
1. Determination of the learning goals
2. Proposition, presentation and approval of a high concept
3. Creation of narrative related to the researched literature
4. Creation of the main game mechanics and continous relation to the literature base
5. Creation of the scenario
6. Creation of the User Interface
7. Testing the new prototypes
8. Feedback implementation and change towards next prototype

4.2 An overview of the game development components

As the development of the serious game would be made from scratch, determining what would be the manageable deliverables and the sequence for the development became a management necessity.

Based on the works described in the serious game design review section and in the ontology provided by Tang and Hanneghan (2011), a set of deliverable elements adapted for the development reality of our project was designed as presented inFigure 3. Following are the descriptions of the main deliverables focusing on the development of the virtual factory and the learning challenges with their usual delivery format.

Figure 3 - Deliverable Game Development Elements



4.2.1 Main deliverable components

High Concept – text document

Contains a short description (normally limited to two or three lines) of the challenge or virtual factory concept. In this project, this deliverable should be brainstormed based on the literature and key examples of 4.0 industry concepts implementation.

E.g. “Students will make decisions on the placement of sensors and communication devices in a virtual factory to improve defined KPIs on orders with increasingly varying batches.

Intended Outcomes – text document

To accompany the High Concept, a set of intended outcomes should be provided in order to make clear what the objectives of the challenge are. They are directly to the learning requirements and are defined by industry, university and technical school needs.

E.g. “Understanding how interconnection despite higher investments can lead to better results. Raising awareness of the potential of localized factory decisions. Learning how to deal with constraints. Understanding the conditions that make these implementations more and less feasible. …”

Features – text document

Describe the main features of the challenge in a topic list. These are the main characteristics of the game and is similar to brainstorming how to achieve the high concept

E.g: An bird view on a 3d factory that looks both futuristic and simple

A User Interface that collapses and presents information like a set of augmented reality glasses. It shows both the resources and the period outcomes

The game runs in turns of hours, days, weeks or months. The student makes a decision and then hits play for the turns to run.

Clicking on each machine shows up its description and an upgrade panel where students can buy and set up new sensors and communication devices. Information on time wasted:idle (waiting for the next part), setting up changes; under maintenance or waiting for supplies is also shown in percentages or regarding KPIs.

The same can be done with employees that may receive training or technological devices to improve their performance.

Talking to characters in scene provides help, hints and more information.

The game finishes when KPIs reach a level that is too low (lose), hit the challenge target (for instance a set profit or waste reduction level), or hits a time limit.

Challenge Concept – text document

Includes the key concepts of how the challenge unfolds. It consists in the application of the features for the specific scenario that is under development.

E.g. In this challenge the player will try to maximize profit in three months, having three machines to manage and dealing with relatively big batch sizes. This is the learning challenge, so the conversations will not be optional.

Script (With Events) – text document

The script normally includes dialogs trees and sequential events. Since games are an open loop, the script is less structured containing with the usual sequential events game loops, optional events, possible actions-consequence pairs among others.

Storyboard – Image or PDF

Graphic representation of the script and events. Used to convey layout, style and movement. For this project there were only two developed project story boards.

Level Layout – 3d Model, CAD file

The layout positioning the objects and characters in the virtual environment. While it could be done in either 2 or 3D, given the game requirements, a 3D standard was set.

Objects – Engine Object

The functioning objects, which may include 3D models, textures, animations, audio, video, behaviors and description texts. For this project, since the Unity plataform has been selected, the objects were included in game as the development progressed. They are still a deliverable, as their quantity and quality affects the reach, flexibility and quality of the final factory game engine and serious game.

Characters – Engine Object

The functioning characters, which may include 3D models, textures, animations, audio, video, behaviors, dialogues and description texts. A specific type of object as described above, only distinct due to its abstraction and implementation characteristics.

Game Design - Text

The game design contains the game documentation and includes decisions on all the challenge parameters, including the rules of the challenge, what actions can the student do, what resources he or she is to manage and the objects and characters that can be interacted with.

This deliverable should be kept updated with the documentation of rules, actions, resources and interactions that are implemented in the game engine. This document should be understandable by all project members since the actual rules, actions, resources and interactions become programming scripts.

Rules – Code

The rules of a challenge are implemented in the game engine through a programing code (in this case C#) that follows the definition of the game design.

Actions – Code

The actions that the player can perform are also coded.

E.g: “Buying equipment, upgrading them, setting communications, responding to variable…”

Resources – Code

The resources that the player manages must be kept as variables and recorded in order to provide information on their usage and determine successes and failures.

Interactions - Code

The response of objects and characters to interaction.

Functional Prototype – Serious Game Version

The first version of the challenge that is usable. The aesthetic elements may not be in place.

Alpha Version – Serious Game Version

A more complete prototype for the involved in the project to test. The main focus of this version is to detect improvement points.

Beta Version – Serious Game Version

The test field version. It is not yet stable and ready to release, but it is functional enough for external testing.

Final Product – Serious Game Version

The compiled challenge able to run on different OS. The actual product.

4.2.2 Pre-requisite deliverables

These deliverables compose others in the development structure.

- Models – 3D Model
- Animations – Engine implementation
- Descriptions – Text
- Dialogues– Text And Code
- Sounds – Audio Files
- Videos – Video Files

- User Interface – Images and UI Engine Implementation
- Behavior - Code
- Images and Textures – Image Files

4.2.3 Programming the tool

To accelerate development considering the skillset of the project members and the time available, the decision for the usage of a game engine was optimal. This allowed the development to focus more on the idea implementation instead of spending resources programming a physics and graphical engine from the start. Among the available game-engines at the time, two main alternatives were considered, Unity (UNITY TECHNOLOGIES, 2022) and Unreal 5 (GAMES, 2022). In the scope of the project, the main reason for the selection of Unity were its multiplatform capabilities and the quality and availability of its support materials and tutorials.

The justification for the selection of the main tools is listed in Table 3

Table 3 - Development Justication – own production

Parameter	**Choice**	**Justification**
Development Platform	Unity 3D	One of the biggest available and best supported game engine available. In comparison with the main alternative (Unreal V), it allows for easier implementation in multiple platforms
Programming Language	C#	Due to the larger availability of support in the Unity community and sheer quantity of examples and training tutorials. For this platform, javascript was also available when the development started.
Paradigm	Event-Oriented Programming and Unity Best Practices	Large community usage, allows for organized code, makes overall solutions easier and emphasizes adaptability and development speed.

The main criteria for this decision is to provide fast-to-develop, reliable and adaptable platform as opened to external usage as possible. This led to the selection of Unity as the platform, with the programming language and paradigm being consequences, as they are among the best fits for Unity.

While there are many possible design patterns and programming paradigms that can be successfully implement in the development of virtual serious game, the selection of Unity as the development engine promotes the use of and object oriented component based design pattern. This usage favours composition instead of inheritance where each functional object (called game object in Unity) being made up of smaller components.

A components represent actions or capabilities that an object might have as distinct components. A factory worker for example might have a moving component, that enables walking, that is the same as the one used by an automated mover. This allows for versatile behaviours that can be used in a variety of contexts.

5 SERIOUS GAME DEVELOPMENT

In this chapter the development of the prototypes and serious games is described. The first prototype coincides with the first action/revision cycle and concludes with the review of the Haifa conference workshop. The second prototype and the first student proof of concept were made simultaneously, with the action revision cycle ending with the presentation of the prototype. The second student proof of concept was implemented simultaneously with the bicycle factory. The third and final cycle coincides with the development of the bicycle factory learning tool.

The following sections describe the development of these tools.

5.1 Prototype 1 - Haifa Workshop Prototype

5.1.1 Overview

The first prototype consisted of a dialogue heavy generic factory prototype. In this version, the player had limited actions and had to chose a single improvement project at the end of an iteration to then see the results of that choice. While the iteration was happening, the players had to keep the machines working, representing the role of factory operators, as at first there was no indication of failure besides the unusable products, select quotes of orders to accept and create a production order.

5.1.2 Development Phase

The development of this prototype started soon after the kickstart meeting of the project.

5.1.2.1 Determination of the Learning goals

Of the official projects Learning Goals, the first learnstrument focused on the relation between technology implementation and their relation with production order and self-made decisions. As such the learning goals ended up as:

1. Understand what is industry 4.0

2. Experience how some technologies may affect the production order, sales and factory floor operation
3. Understand how these technologies can relate to industry 4.0 design principles and improve outcomes.

These goals changed many times during the development process, more often then not decreasing in scope. For the entirety of the development however, the concept of industry 4.0 and the relation between technology implementation, design principles and actual industrial benefits remained constant.

5.1.2.2 Proposition, presentation and approval of a high concept

Before discussing the overall prototype concept with the project group, we prepared and presented a document to inform the group on game development methodologies as presented in Annex 1– First Game concept presentation.

At this point we also attempted to implement a agile project management framework, but it soon became just a formality, as I was the only programmer responsible for the development and consequently the vast majority of bottlenecks. Most of the activities were reported from me to myself, and since the effort to benefit ratio of the attempt was not paying off, I discontinued the attempt. I believe however this framework would become more valuable if there were more programmers working together.

On the high concept, the following proposition was accepted:

“In an industrial environment with coworkers to speak to, the player has to accept and order production orders, keep machines working and avoid waste while the factory runs in real time. Between running turns, the player can improve the factory with industry 4.0 related projects and experience.the changes. The order of the improvements matter. ” – source: created by the project work group.

Regarding the learning goals, this high concept uses dialogue to address the overall understanding of industry 4.0 and the projects and the experiencing of their results with the second and third aforementioned learning goal.

5.1.2.3 Creation of a narrative related to the researched literature

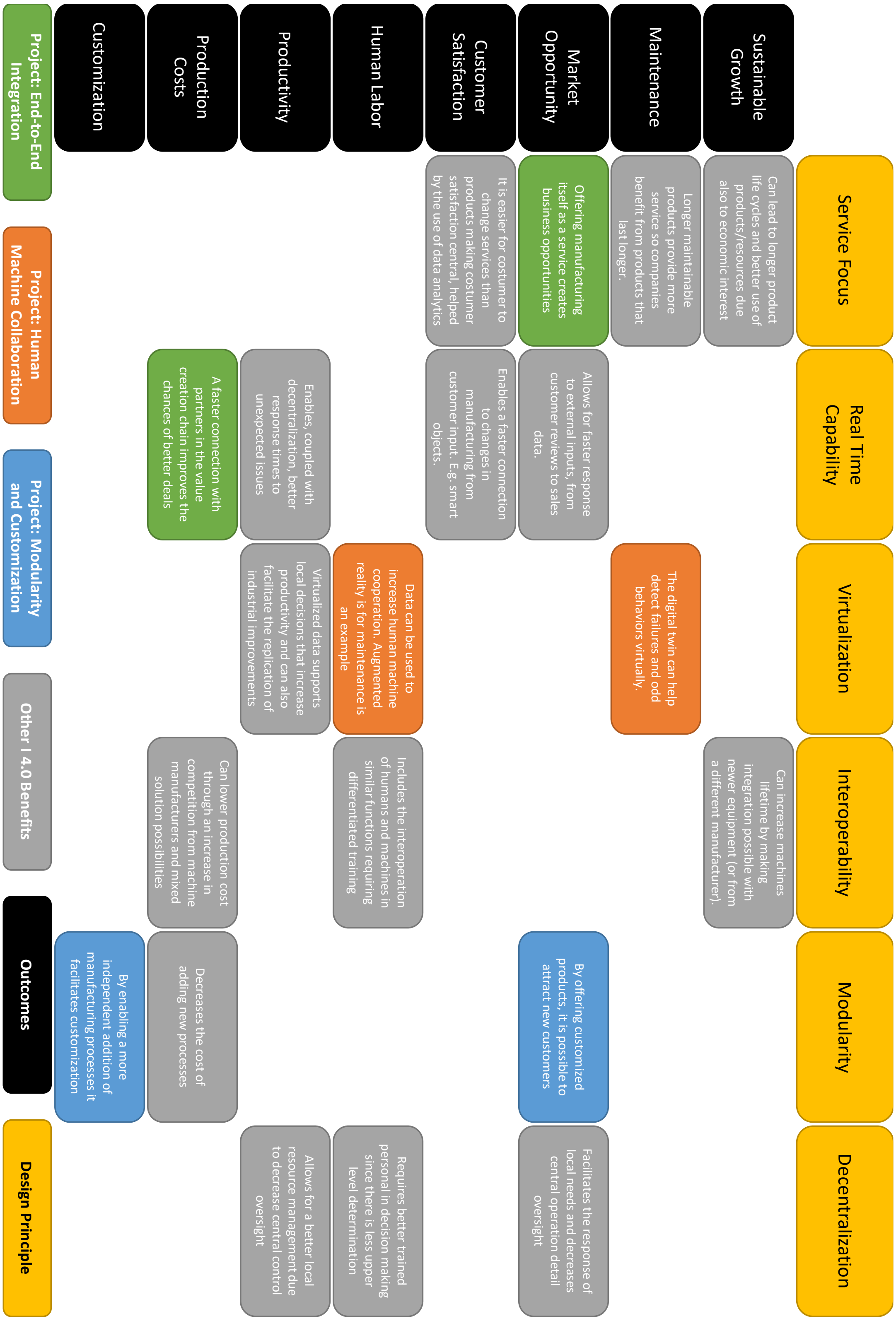
To ensure the connection between the presented narrative and the actual research on the topic, a total of 350 articles from the scopus, web of science and google scholar data bases were analised by the knowledge base team. Of those, we had access to 324 which were prioritized based on wether or not they dealt with design principles (or proposed best practices, model and other prescriptive recommendations related to I 4.0), related technologies and industrial outcomes. This priorization was based only on summaries and resulted in 62 articles. These were read and analised to compile a relational lists between design principles, technologies and industrial outcomes. This research was led by Ana Carolina and is part of her master dissertation.

Ten of these articles were selected to compose the main basis of the relations presented in the first prototype as shown in Table 4, eliminating repetitions of proposed relations, and selecting the broadest scoped articles, most impactful articles. For the development of the prototype, Figure 4 presents a matrix of the relations found between the design principles and desired industrial outcomes. Note the specific technogies that were part of the original literature selection criteria, were not included at this point, but were used in later prototypes.

Table 4 - References used to connect design principles to industrial outcomes. Source: own creation

Article Name	Reference	Design Principle	Outcome
Opportunities of Sustainable Manufacturing in Industry 4.0	(STOCK; SELIGER, 2016)	Interoperability	Human Labor
		Decentralization	Human Labor
		Decentralization	Productivity
		Service Focus	Sustainability
		Interoperability	Sustainability
		Service Focus	Maintenance
		Virtualization	Human Labor
		Real Time Capability	Production Costs
		Real Time Capability	Productivity
Industry 4.0 - Potentials for Creating Smart Products: Empirical Research Results	(SCHMIDT et al., 2015)	Real Time Capability	Productivity
Service innovation and smart analytics for Industry 4.0 and big data environment	(LEE; KAO; YANG, 2014a)	Virtualization	Maintenance
		Service Focus	Market Opportunity
How Virtualization, Decentralization and Network Building Change the Manufacturing Landscape: An Industry 4.0 Perspective	(KELLER et al., 2014)	Modularity	Market Opportunity
		Modularity	Production Costs
		Modularity	Customization
		Virtualization	Productivity
		Service Focus	Market Opportunity
		Service Focus	Customer Satisfaction
		Real Time Capability	Market Opportunity
Industry 4.0. The Future of Productivity and Growth in Manufacturing	(RÜSSMANN et al., 2015)	Virtualization	Human Labor
		Real Time Capability	Customer Satisfaction
Industry 4.0 with cyber-physical integration: A design and manufacture perspective	(SALDIVAR et al., 2015)	Decentralization	Market Opportunity
		Decentralization	Productivity
		Real Time Capability	Market Opportunity
		Real Time Capability	Production Costs
		Virtualization	Productivity
		Real Time Capability	Productivity
Collaboration mechanisms to increase productivity in the context of industrie 4.0	(SCHUH et al., 2014)	Decentralization	Human Labor
		Decentralization	Productivity
		Virtualization	Productivity
		Real Time Capability	Market Opportunity
		Real Time Capability	Productivity
		Real Time Capability	Production Costs
Transforming to a Hyper-connected Society and Economy – Towards an “Industry 4.0”	(BAUER et al., 2015)	Decentralization	Human Labor
		Interoperability	Human Labor
		Virtualization	Human Labor
		Real Time Capability	Market Opportunity
Robots, Industry 4.0 and Humans, or Why Assembly Work Is More than Routine Work	(PFEIFFER, 2016)	Decentralization	Human Labor
Consequences of Industry 4 .0 on Human Labour and Work Organisation	(BONEKAMP; SURE, 2015)	Decentralization	Human Labor

Figure 4 - Design Principle to Industrial Outcome relation matrix. Source: project group creation



On the narrative, we decided to place the player as the new production manager of the factory as a character in this role has to understand and deal with challenges that directly relate to the learning goals. The narrative itself has two interconnected parts, the dialogue present in Annex 2 - Haifa Prototype Dialogue Script and the improvement projects.

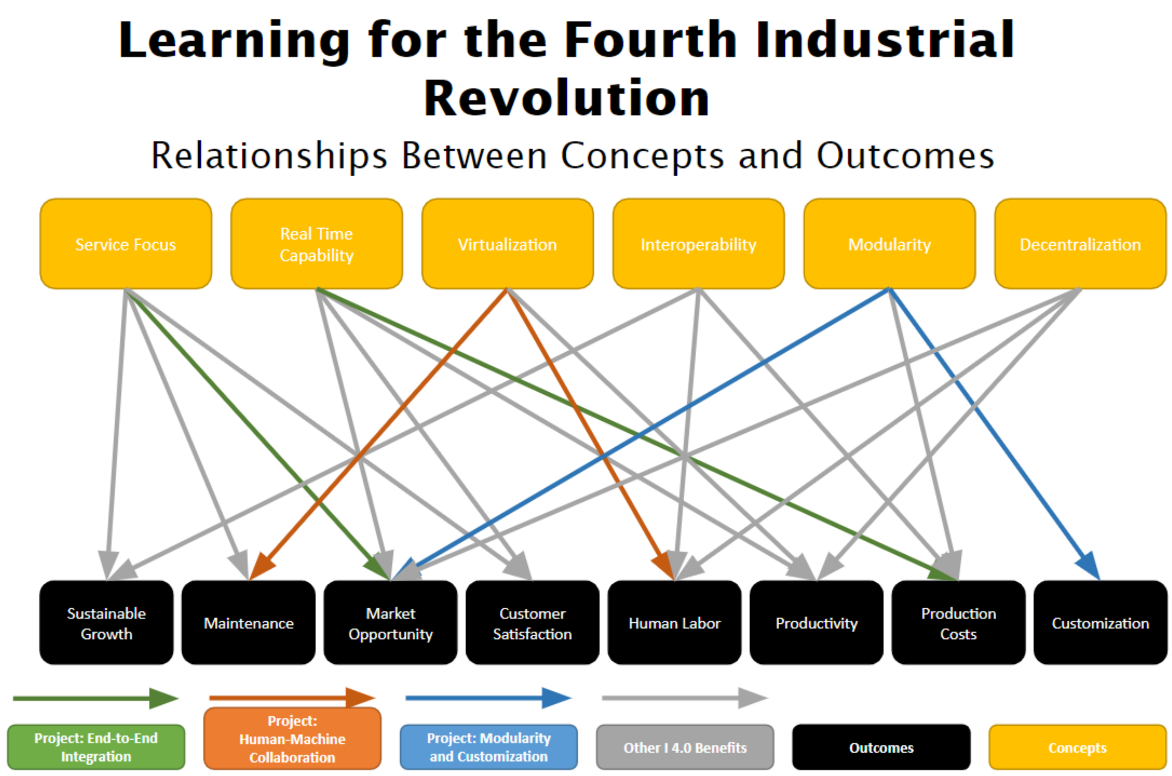
Intenting to present the industry related development projects, characters were created each leading the implementation of a different improvement. First the improvement projects were selected, then the character and dialogue. The following improvements, as shown in Figure 5, were present in the prototype presentation:

End-to-End integration

Human Machine Collaboration

Modularity and Customization

Figure 5 - Relationships between concepts and outcomes. Source: project group creation



To introduce each of them, a character was added to the introduction. The areas of each character and how they explain each of their projects is presented in Annex 2 - Haifa Prototype Dialogue Script on the prototype dialogue.

After the knowledge exposition via dialogue, the player is moved to a factory to experience the production reality and select in which order to implement the improvements. To keep it generic, the “product” presented was a transparent plaque where the characters “I 4.0” were put one at a time.

5.1.2.4 Creation of the main game mechanics and continous relation to the literature base

Beyond the dialogue exposition, the game is to be played in a very simple simulation of factory. The attempt was the creation of the simplest factory that could be used to mediate the learning goals and exemplify the impact of the improvement projects. As a result the factory was limited to a 3d printer, four robot arms (with a fifth being added with an improvement project), one conveyor belt, a representative delivery passage and a waste passage.

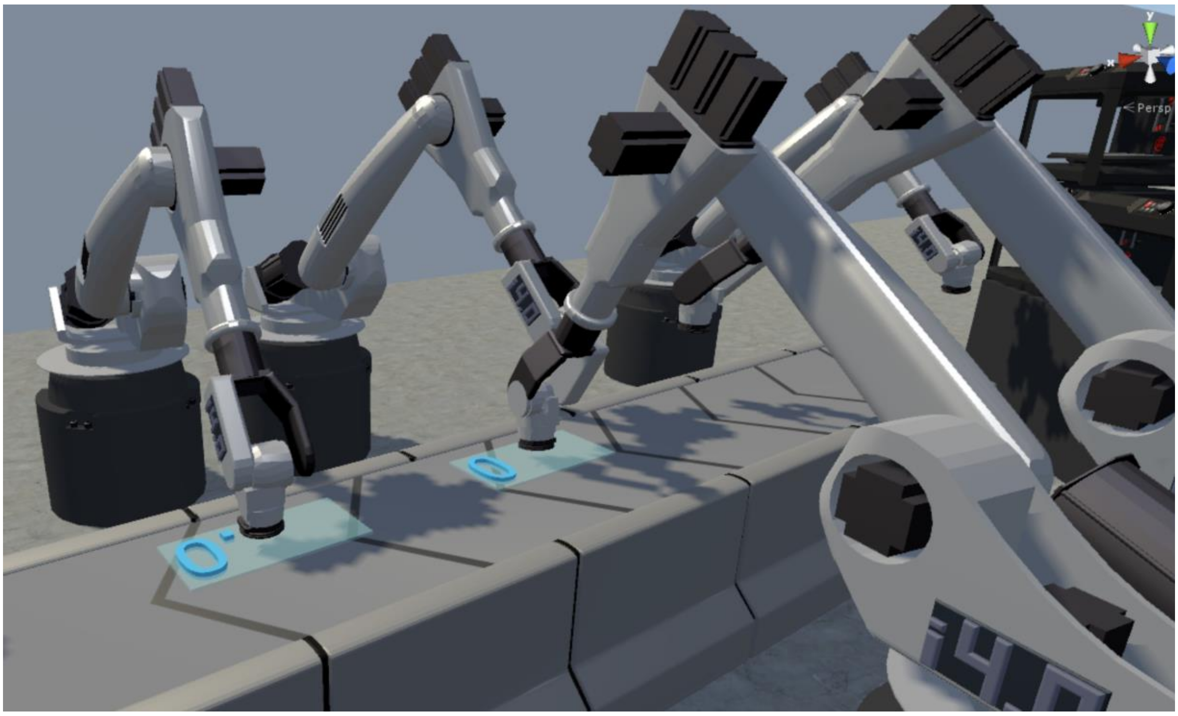
For the game mechanics, the following actions were made available to players:

On the production planning side, the player had control on which quotes to take or not, and the order in which they should happen. This created a trade-off since changing product types would lead to set-up times while batching too much might end up causing delayed deliveries. Since one of the key arguments of industry 4.0 the increased flexibility, two of the improvement projects changed the time cost of set-ups, making changes easier, the more “4.0” the industry became. This mechanic was meant to be the key balancing factor of the game, but implementation issues, specially our failure in clearly communicating what was actually happening to the player.

The replacement of tools and maintenance also led to a core mechanic. Aiming to show the intelligent production sensorization and decision making taking over ordinary human operational chores, at first the player had to manually request maintenance for defective or poorly calibrated machines, but after advancing in the improvement projects, the machine would detect its own failure and call maintenance by itself.

The last mechanic was the selection of an improvement project at the end of an iteration. The idea was for the player to think on the issues faced on the last iteration and which of the proposed projects would bring the most benefit. By design machines were overly defective at first and often players would waste products and consequently lose money. Of the three projects, one helped with maintenance, detecting defects and automatically pausing production for repairs while the other two would bring more orders either through customization or by renting factory capacity.

Figure 6 – Haifa Prototype Assembly Line View



These three mechanics would interact and the player would have three success indicators: total profit, total waste and production efficiency. In this game there was no fail clause, the player would be able to attempt as many times as desired and use the experience from previous attempt to understand what was going on and take a better course of action latter.

5.1.2.5 Creation of the scenario

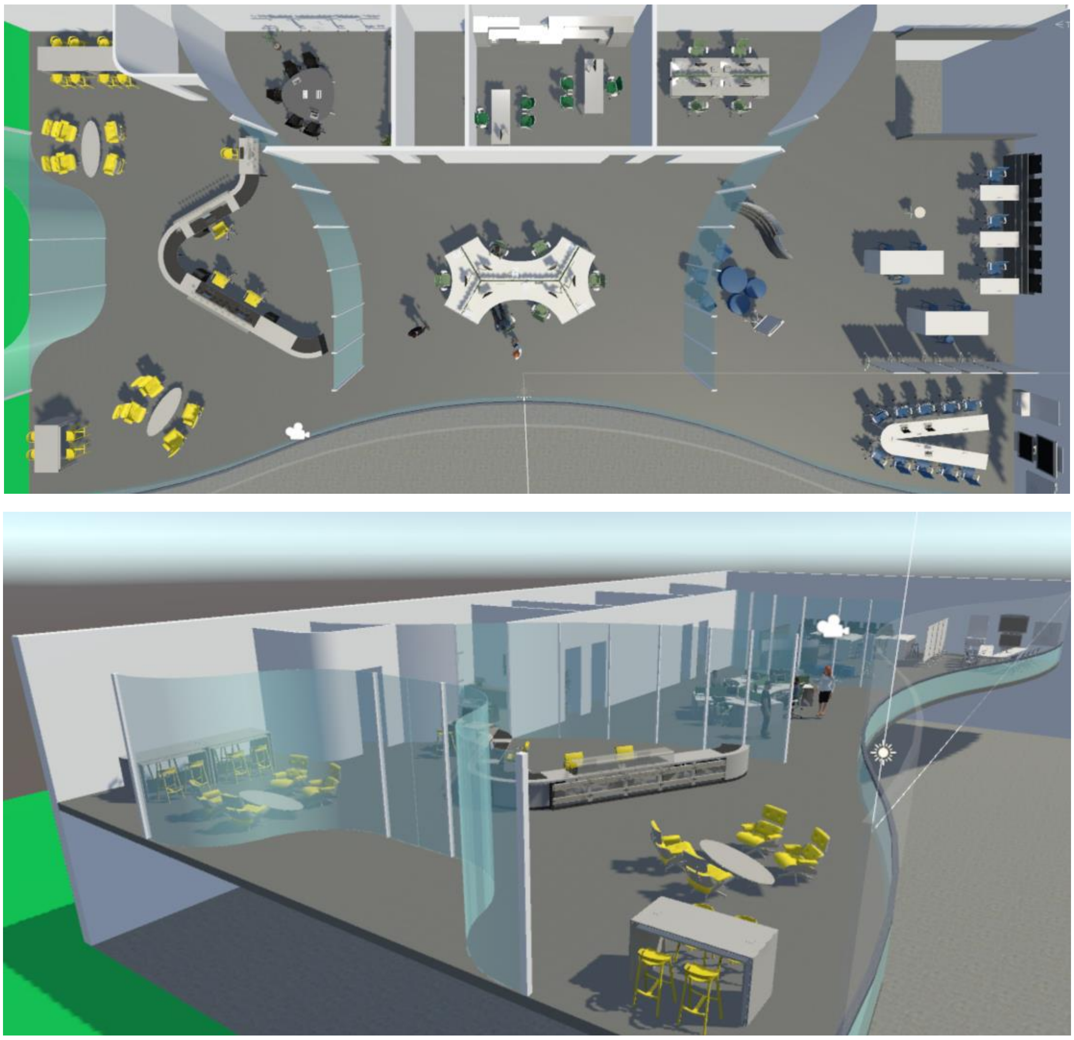
There were many challenges in the decision of a factory scenario. The group wanted to keep it simple, with limited or no camera movement during production, there was interest in making the equipments visually interesting with a ultra modern look, and the insertion of the perceived industry 4.0 equipment. For these reasons, a 3d printer was selected as the main production equipment, robot arms did all the work, and the conveyor had a futuristic look.

In contrast with the ultra modern production floor, the office space was meant to be a more relatable and cooperative environment were people near the production. For that, each character was given a specific sector to occupy with color coded furniture and the office environment would oversee the production floor. To facilitate the development, free to use pre-created rooms were used as a base, most of them design by the company Hermann Miller and provided freely at the Sketch up 3D warehouse (HERMANN MILLER, 2018).

After extensive search of ready to use industrial equipment, the team decided to develop our own machines. There were three main reasons for this: lack of models, uniformity of styles and recognizable products.

When first considering the resources to be allocated for the project and after doing an preliminar search of available models, we could easily find most of what we believed we needed, however when the overall style was determined and the requirements set, the few items we could find were provided by specific manufacturers. Even when the use was allowed, we considered the possible recognition of the equipment and its manufacturer troublesome, since the project was publically funded and the company may have legal issue with the implemented game behavior for their equipment (e.g. the machine breaking or being placed as not industry 4.0). Annex 4– 3D Models Link Library contains the pages link to the sources of the 3D models used in game. It was kept updated for all the developed prototypes and serious games.

Figure 7 – Upper floor layout screenshoot from the virtual game presented in the GCSM 15th Workshop.



Regarding the uniformity of styles, the models that could be found were developed by different people with different levels of skill and commitment, as such they had great variability in number of polygons (level of detail), dimensional accuracy and ease of implementation. Some models were almost as easy to redo than to adapt and others had their physical elements organized in such a way that time consuming modification, the entire model would have a single material (color).

The recognizable product issue became more evident when considering the most elaborate product parts, such as the robotic arms. The two models we deemed plausible for use were made by manufacturers who were market leaders, and had very recognizable shape and pattern, and had their logo stamped in the machine body. To avoid copyright and ethical issues, we decided to create our own based on their design.

This limitation was incorporated in the design and we limited ourselves to two elements, a conveyor belt and a robotic arm:

5.1.2.6 Creation of the User Interface

For this prototype, the development of the User interface was based mainly aesthetic and simplicity, both for the user and for development. Since the prototype had to be tested after less than six months after the start of the implementation, there was little time to polish the UI. Figure 8 shows the dialog interface while Figure 9 shows the factory management interface.

Figure 8 - Dialog Example

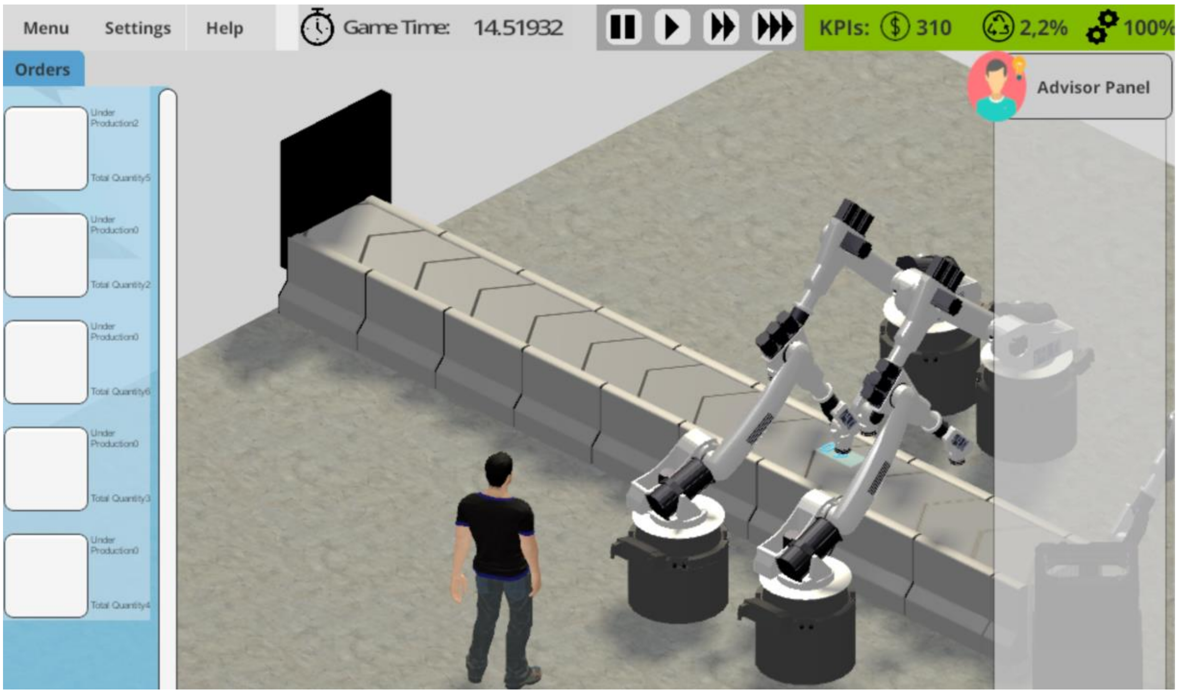


Figure 9 - UI View

When considering the development time needed for the interface, the effort was understimated by a significant margin, having thought that the design would be the main time consumer. In reality, its implementation proved a challenge, as creating behavior for its elements required a distinct skillset that had less relation than I thought to the 3d environment and factory behavior. The tree nested dialogue system took as much time of work as the factory behavior. This resulted in an underdeveloped UI where much of what was happening was not properly communicated to the player and where some parts did not work as intended.

5.1.2.7 Actual test – Haifa GCSM workshop

The first prototype had a clear deadline, the 15th Global Conference on Sustainable Manufacturing in Haifa – Israel. About a month before the presentation, Prof. Dr. Henrique Rozenfeld, the project manager, decided to incorporate physical elements to the presentation of the virtual game intending to make it accessible to a wider audience and to decrease the shortcomings of the game interface. To do so, while I continued the development of the tool, the other members of the implementation team went on to develop a set of cards containing the definitions of the industry 4.0, and a booklet (led by Esdras Paravizo). The cards are presented in the Annex 3 - Principle Cards for Haifa.

The test workshop, which happened on the 25th of September 2017 in Haifa Israel, had a total of 12 participants. The workshop started with a presentation containing information about the partnership and the BRAGECRIM Project and a quick overview of industry 4.0 followed by playing the prototype and discussing the changes. After the test, the participants filled an evaluation sheet. Figure 10 shows the collection of material given to the participants.

Figure 10 - Haifa workshop cards and materials.

5.1.2.8 Feedback implementation and change towards next prototype

Of the 12 participants, 8 responded the questionnaire with three of them not responding every question. From the questionnaire developed by Ana Carolina de Arruda Falcão, these were the compiled “lessons learned” for the development of the next prototype:

- The environment, layout and ease of use were considered good by more than Half the repondents. Only one considered it excelent.
- The level of attention required was considered sufficient by all participants.
- Dialogue and user interface need improvement.
- Two respondent requested a better representation of what was happening in the factory.
- Two respondents requested more interaction possibilities and direct consequences for the actions.
- One respondent asked for a more progressive learning curve

While conversing with the participants, the following suggestion were noted:

- Consider order of names in menus, order people to meet, dialogues
- Add gamification aspects and motivation aspects – medals, stories and so on.
- Do not divide in project levels but use projects to improve and buy them with earned money. Add requirements.
- People want to do and not to read
- Don´t scroll through answers
- Show in the answers what happen when you click them

5.1.3 Reflection

The first prototype was develop over the course of six months and in the end it did not deliver what was expected. Organization issues, unequal concentration of tasks and skills, the difficulties of doing research while developing a product and the communication barrier regarding game development literacy were some of the main challenges that explain the limitations of the first prototype.

My lack of experience in game development and the bottleneck caused by the need to program behaviors, coupled with other responsibilities in the project (such as literature research, creation of art assets and so on) led to a underestimation of the required resources. Due to the lack of polish of the prototype, obvious flaws and shorcomings were prominent in the responses and the overall game concept was less scrutinized. The conclusions were in line with literature as the first prototype was negatively affect by known issues of underestimating effort and exaggerating scope (AHMAD; RAHIM; ARSHAD, 2015),. The problems that arose from programming the software were also not ordinary, with two weeks being spent only on inverse cinematic calculations for the approximate positioning of the mechanical arm on the product.

After the Haifa workshop, the group decided to change the core game loop (in line with the answers), and first test internally a game mechanic prototype before implementing a high fidelity version.

The next prototype would require a better allocation of resources and a better production order. To achieve that the development was broken down into steps: game concept alternatives; the game concept proof prototype; scenario selection; gameplay selection and final prototype. Between these steps, there would be intentional effort on communicating and exemplifying the next steps which, while decreasing overall development speed, could lead to a better final product and less wasted effort.

On the programming side, we would attempt to get more students with programming capacity on board by tutoring master students in the project.

5.2 Prototype 2 - Intermediate Factory

5.2.1 Overview

The second prototype was developed as a proof of concept and to mediate the game mechanics for the entire project group and to actuallu simulate an industrial factory.

Before starting working on the next prototype, the group decided to take a different approach to inform the next game situation and mechanics. Instead of focusing in articles, we searched used search engines to find examples of industry 4.0. This led to two more issues, first many projects were being marketed as industry 4.0 but had little to do with the overall concept which led to the second issue: how do we determine what is or is not industry 4.0.

To address this questions, we first eliminated any solution that did not use any computational intelligence or used simple PLC automation to create the solution, over half the solutions presented as industry 4.0 failed this criteria. Then we checked if there was any connection with other machines/system or any decision making in the processes. The graduate students in the group then created a synthesis of twenty two industry 4.0 plausible scenarios, and for each of them, attempted to connect it to either the main design principles or the key technologies of industry 4.0. This exercise proved valuable in understanding the misconceptions that exist on this term, with most cases directly relating a technology to industry 4.0 (e.g., 3d printing for manufacturing) and would later inform the development o the Industry 4.0 Boardgame led on the student side by Esdras Paravizo.

Of the aforementioned cases, five were selected to be developed into simplified game/challenge ideas, as presented in Annex 5 – Relation of Industrial Scenes and Industry 4.0, and for each of them a correspondence to design principles and relevant technologies was illustrated based on Figure 11 as the shown example in Figure 12 for the first proposed scene.

Figure 11 - Technologies relation to industry 4.0. Source (GEISSBAUER; VEDSO; SCHRAUF, 2016)

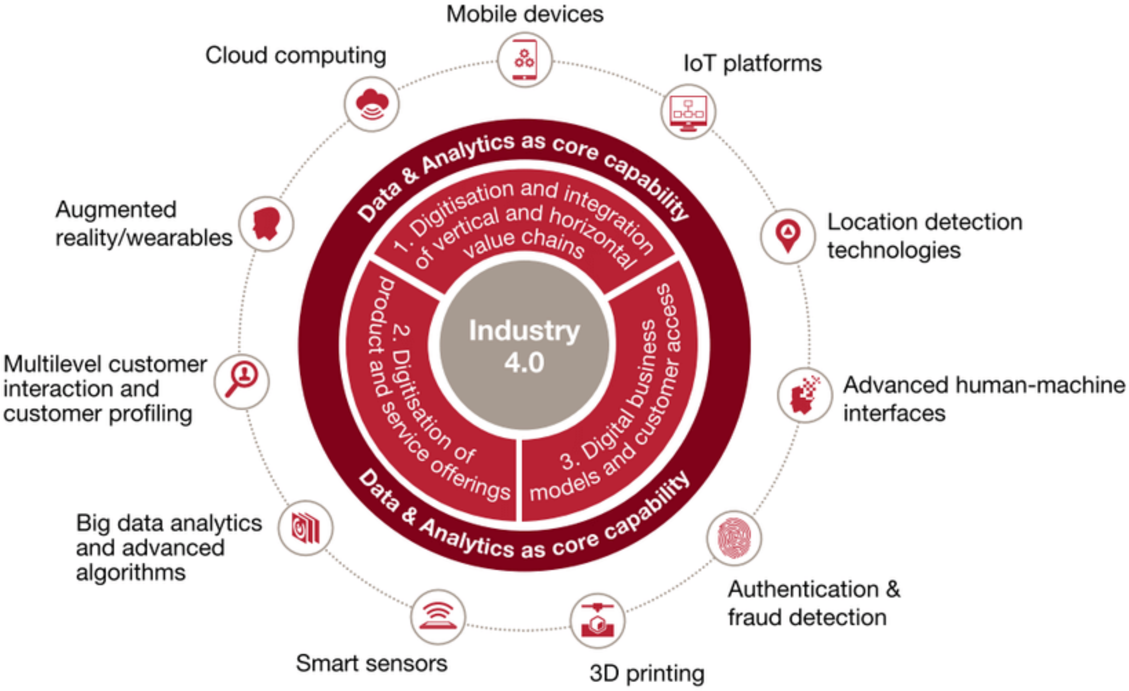
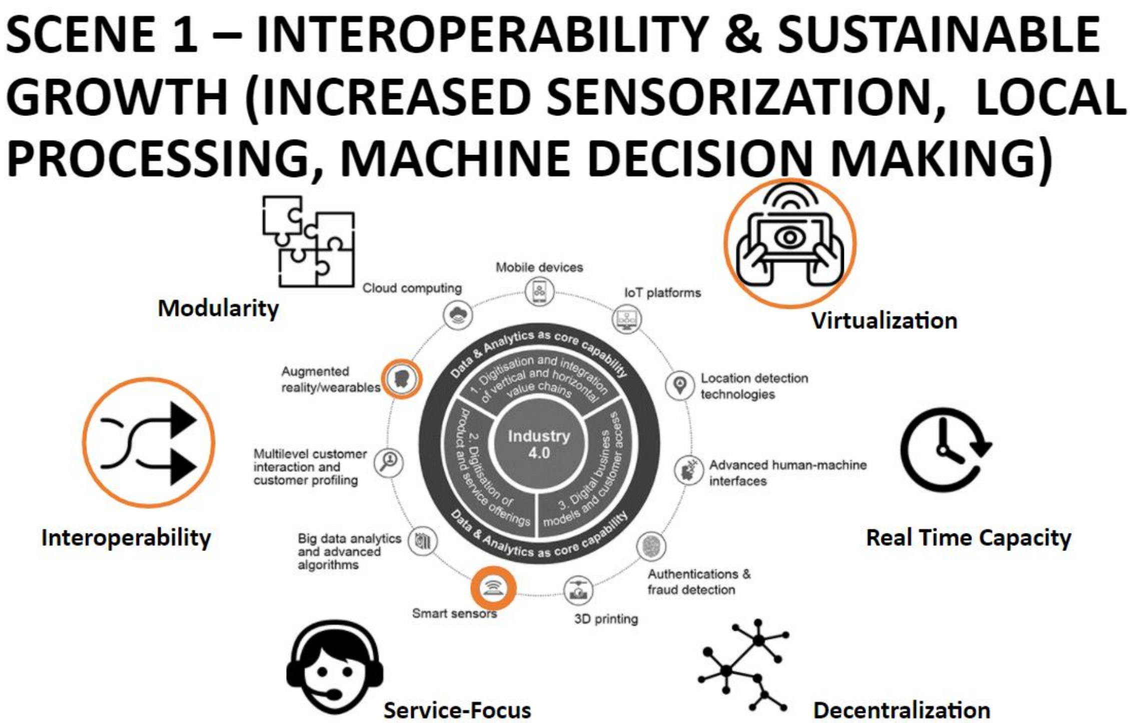


Figure 12 - Scene 1 related technologies and design principles. Source: Edit of the image by Geissbauer et. Al. (GEISSBAUER; VEDSO; SCHRAUF, 2016)



At this point the confidence on the group's ability to produce a game was low enough that more conservative professors of the group proposed changes towards a quiz style game, much easier to implement, and much less innovative and ambitious. A smaller task force more informed on game design brainstormed game ideas and from that a document was created to attempt to communicate the concepts to the entire team as presented in Annex 6 – Second Prototype Initial Game Script. Both difficulties are well documented and attributed the initial difficulty of creating an initial game base from the development standpoint (AHMAD; RAHIM; ARSHAD, 2015; ALDRICH, 2009).

Despite a complete description of the implementation of game mechanics and two meetings of presentations to communicate how the game could work, there were still many doubts and misunderstandings, so we decided to make a blank generic prototype with production planning and factory layout dynamics to present as a proof of concept. This simplified version showing only the game loop became the second prototype.

5.2.2 Development

Many of the functions used in the first prototype (Haifa Workshop) could be used, the communication mode between machines and products had to be overhauled. At first the communication happened with the use of colliders and direct references between objects, meaning that the processes directly altered the product status. For this second example, and to start moving the simulation towards a more modular and decentralized approach, the process initiated a suffer process function in the product which handled the changes. This led to the archictecture described in the Simulating an Industry 4.0 factory, where every factory element was modeled as a combination or instance of Products, Transport, Process and Storage. This system allowed for greater flexibility and modularity of code and was sufient for the implementation of the complete system.

To avoid the excess of text present in the first prototype (Haifa prototype), the dialogue system was discarded and changed for a pop up window methodology, very common in turn based games. Since the dialogue system was the only one containing non-sharable third party code, it also meant that the entire solution and its source code could now be shared.

Among the many game mechanics available and previously discussed, we decided to start by the main objective of the first phase of the BRAGECRIM project, factory layout and production planning, ending with the following mechanics as the bare minimum:

Factory layout:

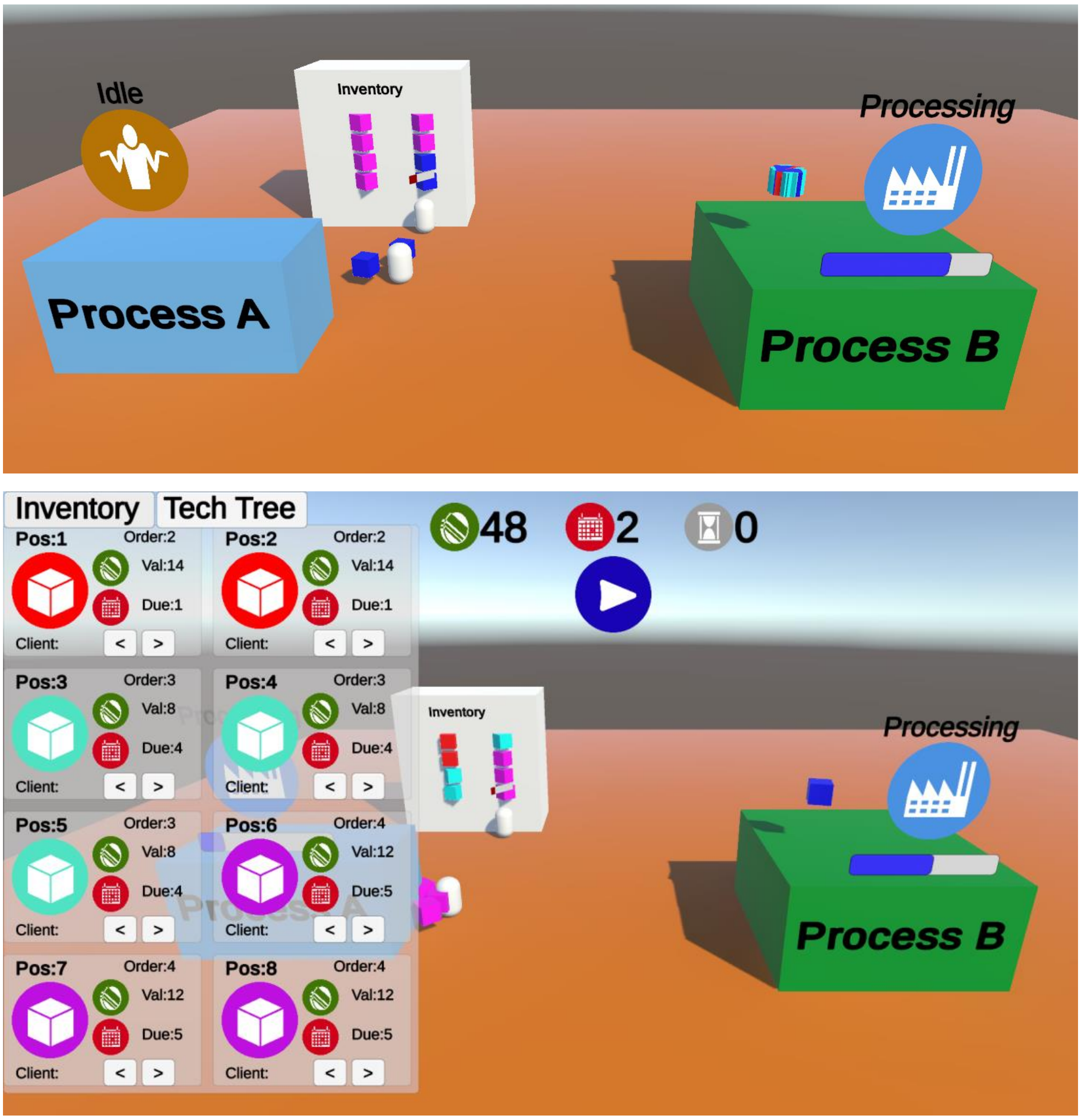
- The ability to place and or move processes and storages.
- The presence and visualization of agents/products being moved from process to process.
- The effects traffic regarding use machines, and by agents´ movements

Production Planning:

- The ability to decide production order
- The ability to manipulate batch sizes.

At first there was little concern for the aesthetic of the components as this functional prototype goal was only communicating a mechanic, still there were multiple UI proposals until we could agree on a functional alternative. While the inventory interface (which actually represent the orders to fulfill) can become clutered, the player can understand what are the next orders and manipulate the sequence. Figure 13 shows the presented version of the second protype.

Figure 13 - Second prototype screenshot



This prototype presentation and feedback was collected over presentations of the biweekly meetings. The final version was made available to all project members and was presented to all at once in a 2 hour discussion meeting where the mechanics were presented and the next implementations were explained as they would happen in game. This helped the visualization of a game loop and the actual learning circle proposition and increased the quality and relevance of the feedback given by the participants.

5.2.2.1 Feedback and changes towards the next prototype

This prototype collected a feedback and allowed the project group to suggest game mechanics and learning situations in the context of the game.

On the game cycle itself, the following suggestions were made:

- Improve the game interface to make what is happening more clear
- Improve the interface to facilitate the movement, reordering, addition and removal of orders
- Add clear graphical differences for the products at each relevant production step
- Make the indicator face the camera
- Other minor text changes and improvements

On the learning and context of the game, the following suggestions were made:

- Add internal events to guide the player at first through the interfaces and options.
- Make events happen to change to affect the production order factory operation
- Allow the positioning of processes
- Add multiple choice events whose selection impact the overall gameplay.

5.2.3 Reflection

This prototype however simple, contained the core mechanics to model an industry 4.0. There was possibility of communication and meta data in the core products, machines could be made to communicate to one another via central processing or directly, the agents had a distinct logic to select what to take were and all this factors were configurable mostly without any programming. This base would serve the next prototype with little modification on the core but many additions to the elements intelligence.

This very simplified representation of the game mechanics was more effective in conveing the game mechanics and how they would relate to the learning goals than the presentations had been. The quality and relevance of the feedback were not the only benefits, the time spent going back and forth the already discussed concepts misunderstandings was significantly reduced.

Despite having taken over two months to develop, the user interface design and implementation proved itself once again a challenge and despite more active responses and more visual indicators, it was yet far from actually functional. After this meeting, Núbia took the role of interface designer, while I provided her the requirement list and consulted on the work in progress.

5.3 Students proof of concept

As part of the partnership with the TU Berlin, I have co-tutored two groups of undergraduate students for their factory management Project. With each of them we created a small proof of concept of a learning game. These proof of concept used the same engine developed for the main serious games.

This was as an opportunity to explore the game development, practice documentation and communication of game elements, and check if the proposed mechanics were implementable in the current engine. From the start, each group knew their allocated time slots, where we would implement their game ideas.

5.3.1 Group 1

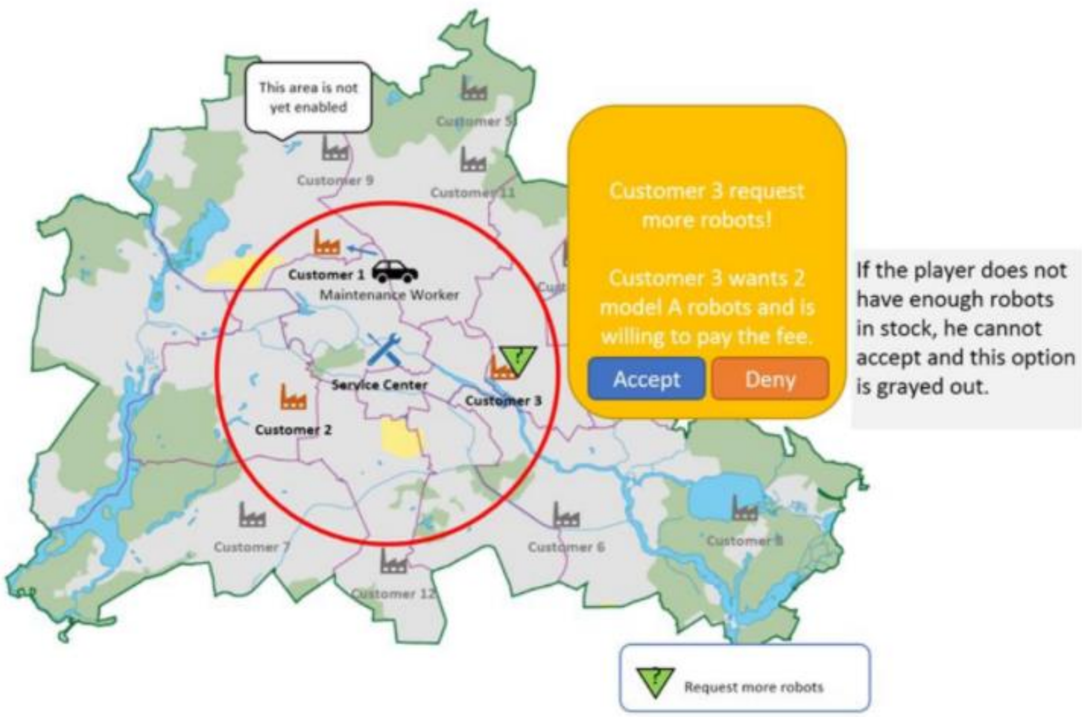
The first group was composed by Chang Xu, Chao Liu, Lingfeng Yu, Moriz Weber, Tiziana Tiberini and focused heavy on mechanics, creating a fixed position factory game Figure 14 where the player controls were the workers are, hiring each one, and which changes are implemented.

The proposed factory would produce industrial robots that could be sold or rent and were connect as service to the player´s factory, meaning the player would be able to either sell the machines or rent them. This would be managed in another level Figure 15 where warnings on failed machines and product requests would be managed. There would be a trade-off between high one time profit and the sustainability of renting the machines over time and some clients might either want only to buy or only to rent their machines.

Figure 14 - Student group learnscene screenshot.

Figure 15 - Learn scene service focus room

8.2.2.Tracking and service focus room



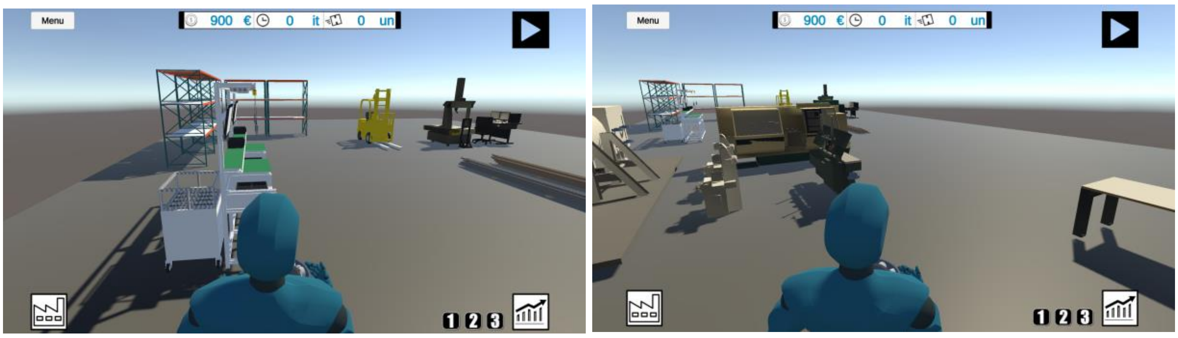
While the Service level map would require a many new behaviors for implementation, they factory scene had many similarities with our original project and was implemented as a proof of concept in a matter of days.

5.3.2 Group 2

The second group was composed by Gabriele Gangemi, Stephan Krauskopf, Luis Reyes Rey, Gabriele Sordi, Lea-Marie Tremmer, Yigit Yener.

The group developed an entire game plan complete with script, learning goals and literature based. In the implementation however they spent significant effort on the appearance of the games and requested first person cameras so that the factory could be seen through the eyes of the workers Figure 16

Figure 16 - Student proof of concept screenshot worker point of view



In the end the following actions were proposed by the students:

- Select production order
- Select machines position
- Respond to factory events in multiple choices

Figure 17 shows the students' main interface idea.

Figure 17 - Proposed interface

5.3.3 Student projects results

Besides their role as a university class final project, both game concepts influenced our serious games specially regarding their care with the interface and the graphic representation of their factories. Some of their research was also incorporated in the project, specially on the later parts relating to their specific scenarios. Also of interest was the simplicity of implementation of their factory in the factory simulating engine being developed for the prototypes in unity, showing some flexibility for the model.

5.4 Prototype 3 – Bicycle Factory 4.0

After developing the generic factory prototype with the mechanics better understood, the development of the actual virtual serious game started. So far we had only decided on the basic mechanics for the factory simulation and nothing else, and yet there was room for change.

5.4.1 Game Concept

While no high-concept had yet been created for this iteration, some conditions were assumed by the development of the second prototype. First, the main scenario would be a multi-step factory. Second, the production steps must be upgradable, so that new technologies and changes could be exemplified and their impact in production observed. Third, the factory should not be able to simply buy these improvements without adapting their data structure or implement factory wide changes, since industry 4.0 works so closely connected with intelligence and connectivity, many of the more profound changes it can enable require this widespread data network.

Since much work had been done to create the previous prototype, we started of with a fair amount of material and agreed on some directives. Table 5 below summarized the legacy from the previous learnstruments.

Table 5 - Legacy from previous prototypes

Item	Description	Changes
I 4.0 Literature Base	The major body of research containing 62 articles.	More articles were added as research progressed
I 4.0 Knowledge Summary		
I 4.0 Industrial Initiatives	22 Selected examples of applications related to industry 4.0	More cases were added as we progress, but they were incorporated directly into the game
Virtual objects librare	Over a hundred commercially usable 3d models, six of which were developed internally	More objects would be added directly to the game
Project Vision	A shared vision of the project	The vision will be reviewed
Animation Database	A collection of human animations from the Haifa workshop ready for use	More animations would be selected and added to the prototype.
Previous Scripts	The scripts created to describe pre vious games	They were used as inspiration and some definitions made their into the final prototype

Since the last main prototype of the serious game had been a generic factory, the industrial context for the serious game had yet to be stablished. The next step on the development was the selection of a learning situation.

There was a lot of discussion of the merits of creating a generic/fictional vs a product-specific factory.

The argument for a generic/fictional factory related mostly to the freedom and lack of constraints from production specifics. With a fictional factory, processes could be designed to better suit the learning goals and technologies and there was less space for scrutiny from experts for the simplification needs of a learning game. On the other hand, the creation of production processes ground-up and the need to communicate a unknown product/production process to a player and convince them to get invested, would require significant effort. Another issue would be the nomenclature of the processes, as using actual process would require the virtual design of an emulated factory while using generic names such as process A or process B and so would further increase the level of abstraction.

When considering selecting an actual product the constraints and possibility of expert scrutiny were considered an issue, however the ease of having a process sequence and machines ready to use and the verossimilude gain were considerable. By studying the main processes of an existing product, the virtual game factory would be able to keep a better connection with reality and use the existing research and implementations of this kind of factory and its equipment as a source for designing the challenges. With the right selection of products, there would also be less need to communicate to the user the factory purpose, as many familiar products could dispense explanations.

Before deciding which model to continue on, a set of desired characteristics were considered. Based on the game mechanics needs, the learning goals of the project and the results of the previous prototypes, the following requirements list was created:

- **Production Steps that allow the dynamic introduction and removal of operators (human or machines) -** This helps represent versatile operators that can select where they are more needed and pick the proper tool to work on that production step. For humans this positioning can benefit from augmented reality;

- **An industry that has products with a diverse set of production steps -** To exemplify the changes promoted by on demand transport between production steps, and the connectivity between transporter and products regarding their next destination, it is important that some products follow a different production path so that the production process is optimized;

- **Products that reasonably allows the production of small lots and customizable products -** For big lots, watching the production happening becomes more tedious and the optimal production system can tend towards specialized lines rather than flexibility. While small lots make the benefits of modularity and decentralization clearer which cooperates in relation to production time and costs, attending to customized demands;

- **Production Steps are physically visible -** To make it easier for the player to follow up processes and the production continuity, it is interesting that the chosen product has relevant visual changes between the steps demonstrating clearly what differentiates it from other products, what characteristics it has that others do not have. So the player has the quick view of a customized product/demand on the production line;

- **Production steps that require resupply, frequent maintenance or break often -** The three would be able to portray key advantages of Machine-to-Machine (M2M) communication and product metadata in industry, making for a more direct observation of production interruption events being optimized and cascading in real to the rest of industry. This may be represented by injectors that wear out, production steps that require frequent parts resupply depending on the products being assembled or a machine that in a harsh that suffers maintenance constantly which can be made by other machines without human intervention;

- **Product graphic 3D models should be easily available -** To place the products in the game, we need a 3D model. Some product choices will have some readily available making the development easier. The alternative would be to create the models ourselves;

- **At least one production step that require set-up when changing the steps' parameters -** To illustrate some of the technologies of I 4.0 impacts on the improvement of set-ups by intelligent algorithms and direct communication with products reinforcing the player's learning about the processes that involve virtualization in the industry.

5.4.2 Factory and Product Definition

With this requirements in mind, three different product possibilities were created. A bicycle factory, a chair factory and an electronics factory (producing tablets and notebooks. All of these factories had another important characteristic, their products are well-known so there is little need to explain what is being produced. With these actionable options at hand, the project team decided to continue the implementation with the representation of an actual product instead. Annex 7 – Selection of product to create the learning virtual factory shows the document describing the overview of the suitability of the three factories but since this Annex was being constantly updated as decisions were made, there is more information on the bicycle scenario than for the other two.

The three alternatives were presented at a meeting and the bicycle factory was selected to be expanded upon. The electronics main challenge would be how to physically represent the changes, as different chips, parts and components are very similar and the assembly are often human intensive repetitive assembly systems. The chairs´ modification was easier to visualize, it had a significant advantage on the other two regarding available 3d models since many manufacturers distribute and allow the usage of their models for non commercial projects, however different types of chair significantly different production steps, with wood, plastic and metal being very distinct, they can be perceived as less technological and ultimately less interesting than the alternative. For the bicycle, its connection to environmentalism, its interest and perception as modern and the role of human, thermal processes and machines contributed to the selection. The selection of the product was not enough to determine the actual factory layout and elements, and since the intent is representing a functional, if simplified, example a more specific context had to be selected.

The production of bicycle is separated by its many parts but for the factory situation select the focus would be at the frame and assembly. On the frame, modern bicycles use two main technologies, aluminum tube (DWYER, 2012) and carbon fiber (CYCLINGTIPS, 2018), each with very distinct production processes. To get an overview of the factory layout, the most useful resource were youtube videos explaining the process, since they showed the factory floor together with all intermediate steps (BIKERUMOR, 2017; FREEHUB MAGAZINE, 2016; GLOBAL CYCLING NETWORK, 2016). From the aforementioned sources, Table 6 was created comparing an example of both production processes:

Table 6 - Bicycle Frame production steps

Production Step	Aluminum Frame	Carbon Fiber Frame
1	Aluminium bar and tubes to parts • Set up and run CNC Machine; • Manually trim excess material	Carbon Fiber Roll (pre-impregnated)
2	Parts Welding • The parts are put in a jig setup where they are tack welded; • The tack welded frame is then taken to the welding process.	Cutting the Fiber
3	Heat Treatment • A batch of frames is put into an oven (in the video 12 frames); • They proceed to a water cooling tank.	Putting the Fiber parts in the mold;
	Straightening	Heat treatment of the molds
	Thermal Hardening	Cleaning the molded parts
	Final Machining	Painting
	Painting	

After the frame production, the production of both types of bicycle frames goes through the same additional steps:

- Components picking
- Multi-step Assembly
  - Fork + Frame
  - Handlers and Levers (“cockpit parts”)
  - Bottom bracket and Crankset
  - Cables
- Packaging

Having these two possible production processes, the group had to decide which to proceed with. Based on the same premisses used for the selection of the product, the final decision was for the aluminum frame, mainly for the visual aspect of the welding process and for the perceived technical difficulties of animating the molding part of the carbon fiber process.

5.4.3 Learning Goals

Before moving on to the actual implementation of the script, the following learning goals were determined from the project subset in a formal meeting:

1. Familiarizing the user with the concepts of I 4.0
2. Understanding the design principles for I 4.0
3. Using I 4.0 related technologies to solve industrial challenges
4. Understanding possible changes that I 4.0 can bring to factory layout
5. Understanding that technological advances (even those related to I 4.0) are means to an end and must be aligned to strategic goals to achieve their potential.

For each each of these goals experiences, mechanics and/or content were developed and introduced in the prototype. In the results chapter the relation between the script, mechanics and learning goals is discussed.

5.4.4 Script

With all that put together, the next component before implementation was the factory script. In this instance we decided for a more gradual performance, introducing the interface of the game as well as the factory challenge with a sequence of smaller tasks or intermediate steps.

To create a more progressive learning curve, the first level of the learning would have one clear final goal with several minor objectives to provide guidance in the in-between steps. To decide what this challenge would be, the researched industry 4.0 cases were combined with the actual production steps of the selected aluminum frame bicycle factory to select the a plausible processes sequence and challenge. The factory would have to increase its flexibility in the production of its frames.

In effort to simplify the production process, only three processes of the complete aluminum frame processing were represented in the final prototype: The assembled tubes on the jig, the welding process and the thermal treatment. These the minimum amount of steps which met the criteria established fot the product selection, and allowed for the implementation of many different solutions related to I 4/0.

With the processes and final objective defined, the creation of the intermediate steps was left. The intermediate steps would by design interrupt gameplay, via a pop up window and require a direct confirmation from the player to proceed. To design them the game interface learning needs and the challenge learning goals were considered and sets of intermediate steps were developed and tested internally and with students from TU Berlin. The implementation/feedback cycles are described below:

- Attempt 1: At first we started with six tutorial text screen on the interface and five intermediate steps only on the factory and learning goals were implemented.
    - Feedback 1: There was too much upfront text and people did not remember what to do when they done. The intermediate steps were not clear enough to follow the game sequence, and players got lost in the middle.
- Attempt 2: The tutorial screens were reduced to four and the 3 more, for a total of eight, intermediate steps were implemented. Intermediate steps only regarded the learning goals and factory issues.
    - Feedback 2: There was still too much upfront text and people did not remember what to do when they done. The intermediate steps were clear enough to follow the game sequence, but some players still got lost in the middle.
- Attempt 3: The tutorial screens were reduce to three focusing more on active things to look at. Intermediate steps were renamed objectives and were increased to 12, with six of them being both related to interface issues as well as gameplay. They were also changed to be more immersive and presented in a in-scenario phrasing.

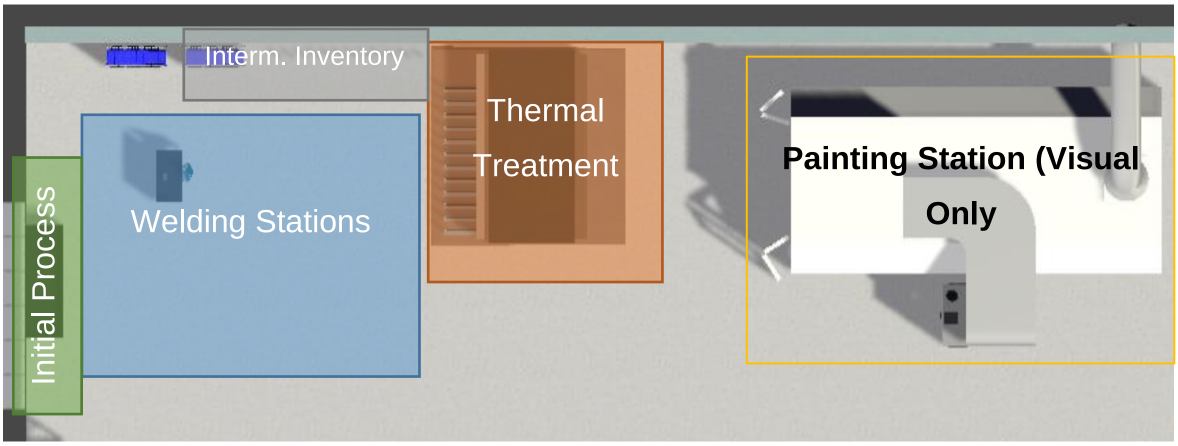
The following table summarizes the 12 intermediate steps in relation to the learning goals.

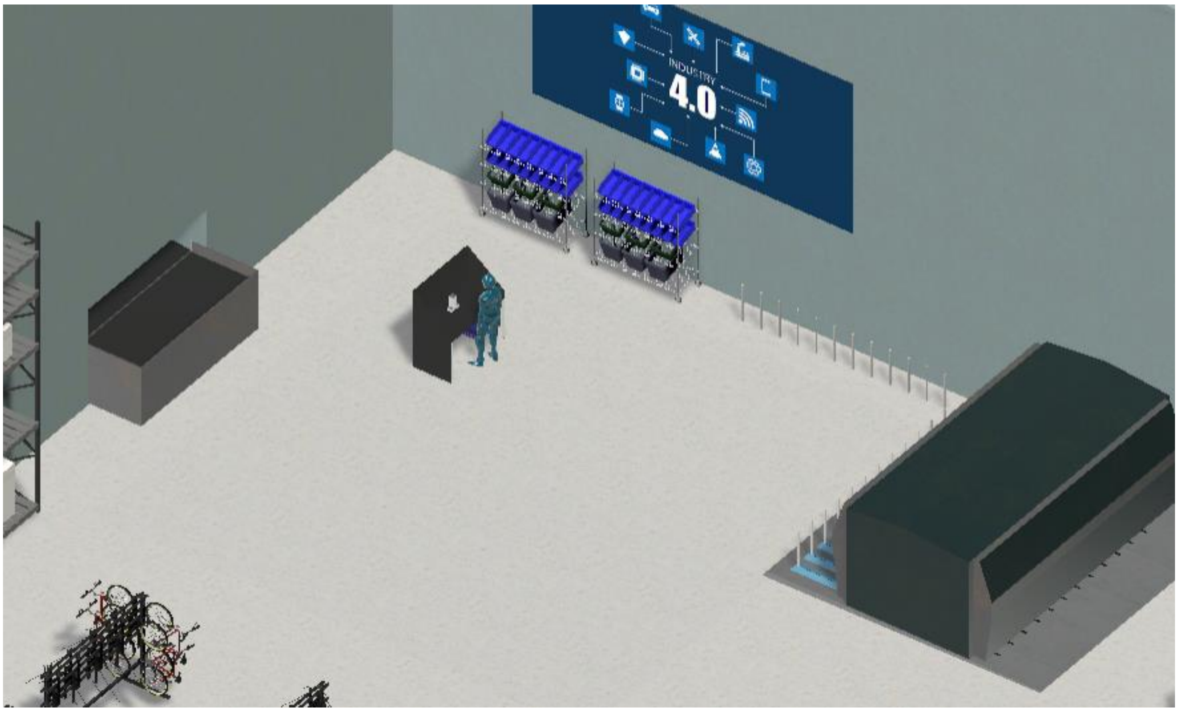
Since this version had no dialogue, this intermediate steps would be the core of the its script.

5.4.5 Factory Layout – 3d Environment

For the factory layout three processes had to be represented the initial steps, the welding process and the thermal treatment. While the thermal treatment and initial processes were imovable, the welding processes had an area were the stations could be added. Since this could affect the workers´ motion and efficiency, proper placement caused slight differences in this process efficiency. Figure 18 below represents the overall factory layout for the final prototype.

Figure 18 - Bicycle Factory layout



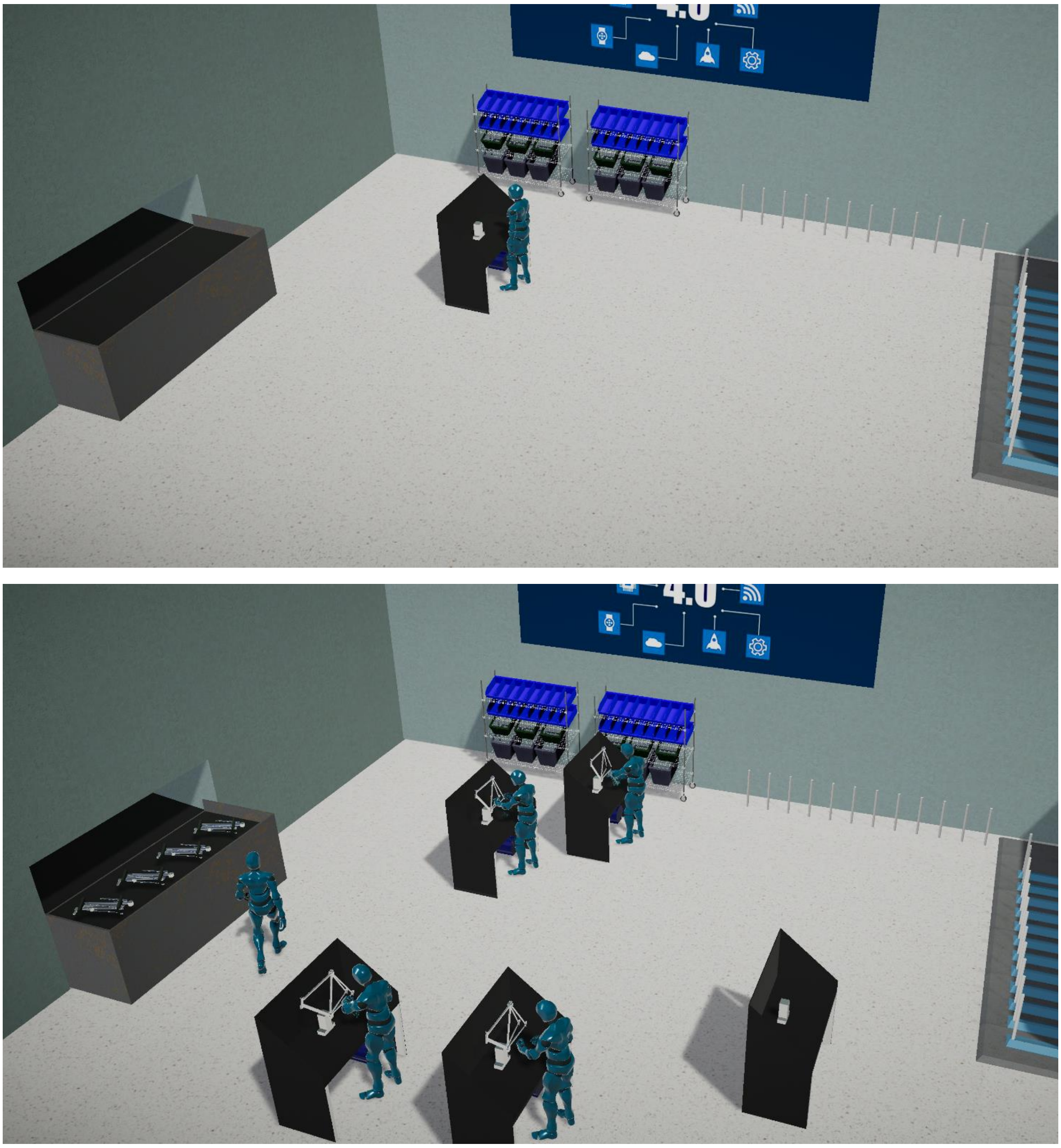


The initial step represents the initial state of the materials when the process is started. In reality for the production of aluminum frame bicycle, it should start with the aluminum tubes to be cut and machined to form-up the frame, however these processes were not within the scope of the first challenge. These steps were remove due to their cost of implementation and complexity. On the costs, an entire set of animations for human-like characters would need to be developed to represent properly these processes and given their specificity no ready-to-use animation could be found, and the insertion of these animations would also add to the computing power cost for the user´s machines, making the final game less accessible for older or weaker computers. On the complexity, it would take additional time for the players to understand and interact with these processes, and while they could replace the selected processes in the implementation of I 4.0 related elements, with distinct consequences, the selected processes were enough for the creation of the game. To simplify it, the initial processes were replaced with a dark window were unassembled frame kits to represent the aluminum parts to be assembled, as shown in Figure 19.

Figure 19 - Initial Process representation

The second represented was the welding stations. Modelled to be life-size in-game, their occupation of space can be relevant to the production, as workers moving from and to workstation can get in each other way and so can the stations. The Figure 20 below shows the starting welding position, a welding station being positioned and a possible, not optimal end-game configuration.

Figure 20 - Initial (top) and possible final (bottom) welding station situation.



The last process is the oven for the thermal treatment. For this process some changes from the real-world equivalent were required. Instead of metal structure holding multiple frames to enter at once in the oven, the frames are loaded in front of the oven in moveable jigs (so the player can easily count them) and when the set minimum batch for the oven is reached, its front door open and the frames enter inside fixed to their rails. This process is simpler to implement, consumes less in terms of computing power and is simpler to understand while still possible.

If the player achieved the flexibility result before the a number of iterations ran out, this first challenge would be done and the player´s score would be shown. Two more concepts were added later. The insertion of short answer questions between some of the intermediate objectives and the addition

5.4.6 User Interface

The user interface was developed as a partnership with Núbia Gabriela, using two main principles, first simplicity, second redundancy. Simplicity not in terms is aesthetic choice, but in terms of click efficiency, our attempt being to require the least amount of clicks to perform any task. Redundancy as in allowing multiple paths to take to the same windows, for example by clicking in a process in the 3d view or in the process panel, getting to the same destination window. Since the main target plataform were personal computers and notebooks, most buttons and commands include a mouse over tooltip.

The Heads-up display is shown in Figure 21

Figure 21 - Bicycle Factory Heads-up Display (HUD)

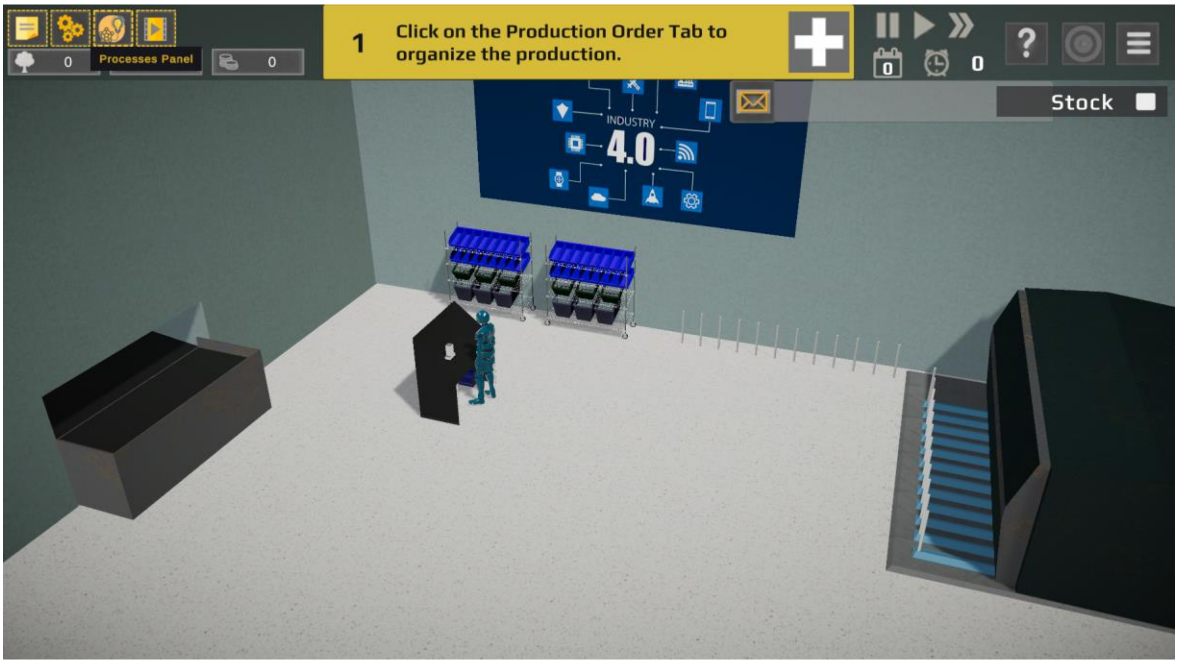


Figure 22 shows a collection of in-game panels control.

Figure 22 - In-game Control Panels

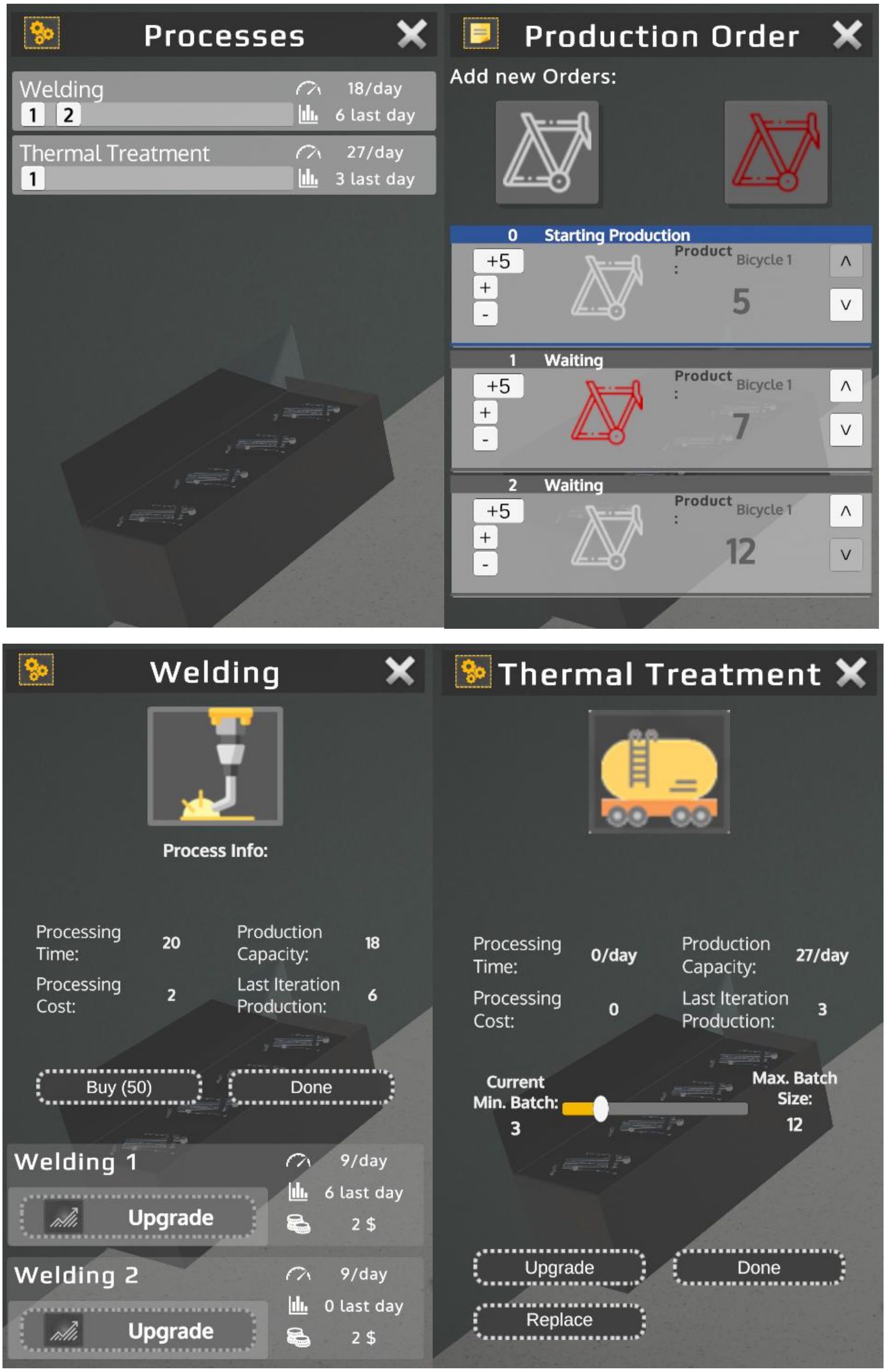


Figure 23 shows the factory improvements screen. On the right side the player can click on each of the Design principles to see their relation to selected improvement and if there is no direct relation, the principle name is grayed out.

Figure 23 - Factory wide improvements screen

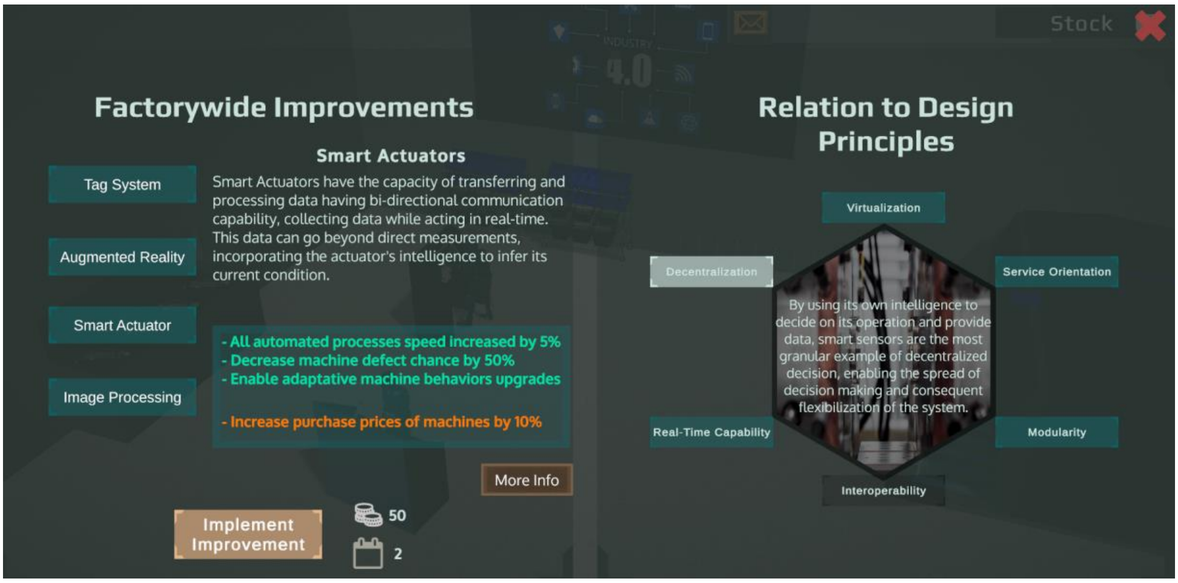
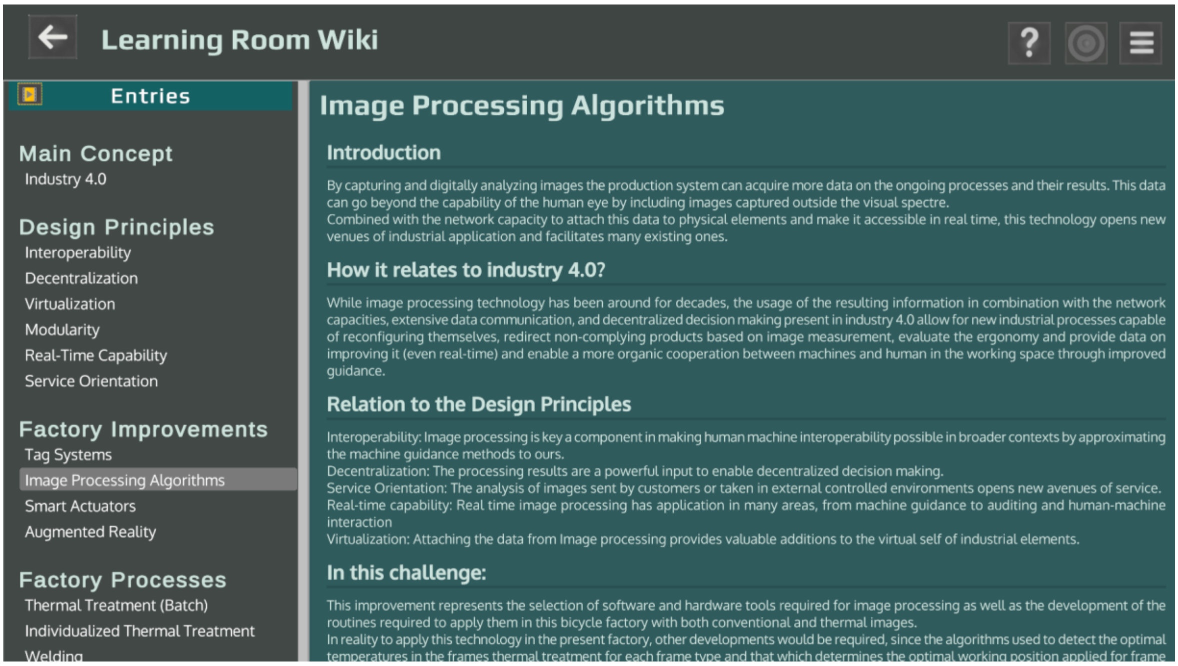


Figure 24 shows the in-game knowledge base in the form of a Learning wiki.

Figure 24 - Learning room Wiki screen



5.4.7 Gameplay Loop

The final serious game is a turn based factory management game with two ending conditions: the player achieved the required flexibility or the allotted time is over. The game has a limited number of iterations (initially set to 15) and includes a in-between iterations decision phase (where most strategic decisions are made) and the factory is stopped, and an iteration phase, where the factory is running and only operation-related decisions are made. Table 7 shows the actions that can be performed in game:

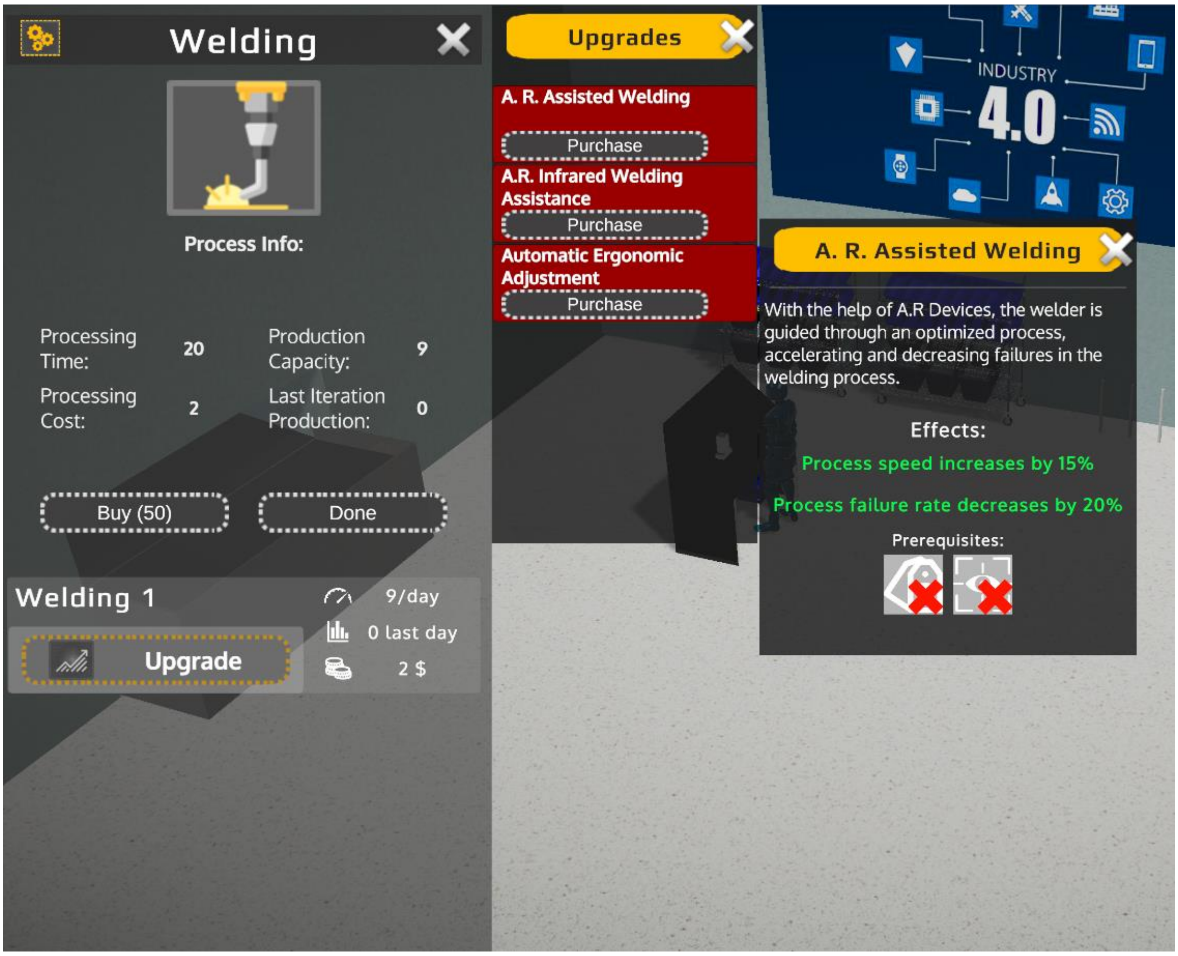
Table 7 - In-game actions and their relation to Industry 4.0

Category	Moment	Action	Requirement	Relation to I. 4.0
• Add Workstations	In-Between	• Add Welding station	Financial resources	-
• Modify Production Order	During Iteration	• Add, move or remove frames from the production order	None	None
• Setup Processes	During Iteration	• Move Welding statitions • Set minimum batch for thermal treatment	none	As the player replaces processes in the industry, some of the operation level decisions are transferred to smart algorithms or made obsolete.
• Implement Factory wide Improvements	In-Between	• Tag System • Augmented Reality • Smart Actuator • Image Processing	Financial resources Time	Each of these key technologies are industry 4.0 related (SALDIVAR et al., 2015; SONY et al., 2021). Their expected impact is expressed in game-mechanics benefits
• Replace Workstations	In-Between	• Replace Thermal treatment system	Tag System Smart Actuator Image Processing	This technology requires factory wide change for its implementation to be functional. It is an example of the need to connect data and use intelligent algorithms to create productive advantages
• Upgrade Workstations	In-Between	• Augmented Reality assisted welding	Tag System Augmented Reality	This is upgrade is an example of use of technology to decrease training times and include more workers in the industrial market.
	In-Between	• Infrared assisted welding	Tag System Augmented Reality Image Processing	This is an example of industrial intelligence depending on the direct interaction between worker and machine and is related both to interoperability and

Category	Moment	Action	Requirement	Relation to I. 4.0
				decentralization design principles.
	In-Between	• Automatic ergonomic adjustment	Image Processing Smart Actuators	This implementation showcases machines adapting to human necessities and is also related to interoperability.

Each of the action possibilities have their consequences listed in the in-game UI as shown in green in Figure 25.

Figure 25 - Upgrade consequence screen



5.4.7.1 Factorywide Improvements

One of the main decisions players can make is the implementation of factory wide improvements. They represent major changes to the factory data system and digital infrastructure. A good example of their conception is the implementation of connected or smart tag systems. Before they can achieve their potential in the factory the overall data belonging to the products must be properly added in a digital system and the participating components of the system must have reading/writing and/or adapting capabilities, meaning this change cannot be accomplished without factory data and intelligence being added to its digital infrastructure.

The following sections detail the final factory components.

Tag System [Improved Communication]

- What it is:

A tag can be placed on an object, such as a product or transporting cart, to identify and locate it. Using the information the tag holds, or directs to, to inform the factory processes and logistics. A tag system consists of the tags placed in the objects of interest, the infrastructure to read and write and the communication system to make it work.

A tag system is a prerequisite to connect a given object to its virtual data. Combined with other tools, it enables transportation optimization, real time inventorying, product tracking, process guidance among others.

- How it relates to industry 4.0?

Tag systems have been used significantly for automated data collection much before the development of industry 4.0. In I 4.0 their role is to enable the construction of a virtual self and the facilitate decentralized decisions based on the tag's information. New technologies of tagging allow for more accurate location detection, increased reading distance as well as data storage capacity, all facilitating the development of a cyber-physical factory.

- Relation to the design principles:

Interoperability: Tag systems contribute by helping in conveying information between machines and humans users, as well as enabling machines to identify one-another.

Modularity: Transfering processing information to the product itself allows for a more modular factory since this information is readily available for the modular processes.

Decentralization: The availability of information enabled by the tags allows processes to gather information for their decision without recurring as much to central databases or centralized commands.

Service Orientation: The tags can serve as a mean of transferring information towards different organizations in the products lifecycle as well as the final customer. They can also be used to track material elements in the services being provided.

Real-time capability: Every time they are read, tags allow the updating on the current status of an object, facilitating its real time location. Tags can also be written on in real time allowing to keep the object status updated.

Virtualization: Tags are the main link between physical objects and their virtual self, as such they are an essential enablers for virtualization.

2 Image Processing Algorithms [Improved data acquisition; industrial intelligence]

- What it is:

By capturing and digitally analyzing images the production system can acquire more data on the ongoing processes and their results. This data can go beyond the capability of the human eye by including images captured outside the visual spectre.

Combined with the network capacity to attach this data to physical elements and make it accessible in real time, this technology opens new venues of industrial application and facilitates many existing ones.

It can be applied among others in process auditing, ergonomics improvements, customer/distributer partnership, self-adjusting processes, machine-human cooperation

- How it relates to industry 4.0?

While image processing technology has been around for decades, the usage of the resulting information in combination with the network capacities, extensive data communication, and decentralized decision making present in industry 4.0 allow for new industrial processes capable of reconfiguring themselves, redirect non-complying products based on image measurement, evaluate the ergonomics and provide data on improving it (even real-time) and enable a more organic cooperation between machines and human in the working space through improved guidance.

- Relation to the design principles:

Interoperability: Image processing is key a component in making human machine interoperability possible in broader contexts by approximating the machine guidance methods to ours.

Decentralization: The processing results are a powerful input to enable decentralized decision making.

Service Orientation: The analysis of images sent by customers or taken in external controlled environments opens new avenues of service.

Real-time capability: Real time image processing has application in many areas, from machine guidance to auditing and human-machine interaction

Virtualization: Attaching the data from Image processing provides valuable additions to the virtual self of industrial elements.

- In this challenge:

This improvement represents the selection of software and hardware tools required for image processing as well as the development of the routines required to apply them in this bicycle factory with both conventional and thermal images.

In reality to apply this technology in the present factory, other developments would be required, since the algorithms used to detect the optimal temperatures in the frames thermal treatment for each frame type and that which determines the optimal working position applied for frame welding are distinct developments.

3 Smart Actuators (Actuator + Sensor + processing + communication) [Improved Processing, Improved data acquisition; industrial intelligence]

- What it is:

Smart Actuators have the capacity of transferring and processing data having bi-directional communication capability, collecting data while acting in real-time. This data can go beyond direct measurements, incorporating the actuator’s intelligence to infer its current condition.

The intelligence present in the actuator can help simplify the rest of the system, which in its turn can increase flexibility. These actuators can also monitor their own health and variations in operating parameters, enabling better maintenance.

- How it relates to industry 4.0?

One of the key aspects of smart actuators is its communication and internal processing capacity, being this the main factor that differentiate it from simpler automation actuators. Smart actuators build on more traditional actuators in similar way Industry 4.0 differs from more traditional industry, by the use of localized and interconnected intelligence and a more strict connection between the physical and virtual realities.

- Design Principles

Decentralization - By using its own intelligence to decide on its operation and provide data, smart sensors are the most granular example of decentralized decision, enabling the spread of decision making and consequent flexibilization of the system.

Virtualization - Smart sensors have a built-in connection between their physical operation and its virtual representation, contributing to the creation of an accurate real-time virtual twin factory.

Service Orientation: Smart actuator data on the use of machines and processes can allow for new business models for providing industrial services based on usage.

Real-time capability: The actuator provides real time data both raw and processed, while its intelligence can accelerate decisions decreasing communication delays with more centralized computers.

Modularity: The actuator intelligence, communications and embedded sensors make it a small example of a modular component.

- In this challenge:

This improvement represents the search for providers of actuators that can be incorporate in the current factory and the computational effort required to connect these actuators to the information system.

4 Augmented Reality

- What it is:

The sensorial superposition of real and virtual realities where computer graphics are combined with the physical world perception in real time. Augmented reality glasses are one of the most well known examples where a virtual image is projected in the lens to complement the user’s view.

The use of augmented reality represents a significant increase in the communication potential between humans and machines, especially for factory workers. This technology also has great potential for training purposes, where production procedures, for example, can be mediated in real time enabling the users produce and learn simultaneously.

- How it relates to industry 4.0?

Augmented reality in its current format is recent and still has not find significant usage in manufacturing, making its development concomitant to industry 4.0. This technology contributes to industry 4.0 in more than one way. First by showing the virtual self superposed to the physical self, presenting information in real time, increasing its potential applications. It is also important for training workers or aiding them to perform more flexible and customized activities. Another significant aspect is enabling maintenance workers to see the machine sensors information and instructions to improve repair consistency, speed and reliability.

- Design Principles

Interoperability - A.R. is one of the key technologies enabling the worker to observe factory information in real time, creating a communication channel between machine and worker.

Real Time Capability - Enables the user to see the virtual information available in the factory in real time.

Virtualization - Allows the visualization of the virtualized elements of the factory while potentially using A.R inputs to enhance the virtual objects and factory data.

Service Orientation - A. R enables powerful communication with customer, be it for post-sale services, such as instructions, maintenance, for customization, marketing and information or for participation in the production process.

- In this challenge:

This improvement represents the search for the most suitable A.R. technology and the computational effort to incorporate it in the current factory. It also includes the digitization of the required documents for the A.R to function properly, such as reference images, digital instructions and projects, as well as the markers and adaptations required for the proper identification of the physical environment.

5.4.7.2 Production Steps Upgrade/Replacement

Upgrades

Individualized Thermal Treatment [1,5]

The communication between process and product coupled with smart actuators allow for the individualization of the frame thermal treatment entry time and duration. This allows frames with different treatment times to be treated simultaneously and according to each's expecification.

Infrared Image Control [1,2,5]

Algorithms run on infrared image to control the thermal process. A faster processing time is the result of a more accurate data acquisition regarding the thermal treatment.

A. R. Welding Assistance [1,2,4,5]

Through augmented reality glasses and a digitized process design for the frames the welder can be visually assisted in each step of the process. This change can accelerate the welding and decrease failure rate.

Infrared Welding Guidance [1,2,4,5]

The addition of a thermal camera surveilling the process allows a better assessment of the actual quality of the welding, providing instant feedback to the welder through the glasses.

Automatic Ergonomics Adjustment [1,2,3,5]

Connecting image processing of the welding stations with actuators to move the frame's jig leads to a more ergonomics working position without the need of frequent manual adjustment. It can lead to improved worker health as well as increased welding speed.

5.4.8 Scoring and Victory Conditions

The scoring system had two main goals in mind, to relate to actual industry 4.0 success indicators or benefits (GHOBAKHLOO et al., 2021), to promote the engagement via the competition games aesthetic (HUNICKE; LEBLANC; ZUBEK, 2004).

For the virtual game we focused on privileging the actual strategic goal before the industry 4.0 achievements. This reasoning was used to reinforce the role of industry 4.0 as an enabler of strategic achievements, and not as a means by itself. General media and the industries themselves have a tendency to oversell the composing technologies as industry 4.0 (BONEKAMP; SURE, 2015), and since the technologies are a component required but not sufficient to achieve the potential of this industrial conception, the score reflected this vision. As a balancing act, and to motivate players to experiment with the offered technologies, factory wide implementations and upgrades related to industry do offer points, but if achieving the overall goal is delayed due to overinvesting in these improvements, the total score will be lower. Table 8 shows the point distribution for the virtual game.

Table 8 - Scoring source for the Bicycle Factory game

Victory Point Source	Total Score	Typical Score Range
Completion time	3000 – 250 per iteration	0 to 1500
Total frames produced	3*(total production)	240-600
Sales lost	-5*(sales lost)	-30 to -300
Energy waste	-Energy consumption	-0 to -300
Factory Improvements	50 per improvement	100-200
Station Upgrades	25 per improvement	50-250

As the table shows, the frame production and sales lost also affect the final score, representing the continued need for industrial economic sustainability. For the environmental sustainability, the only contributing factor is the Energy waste indicator.

The last two factors, factory improvements and station upgrades relate to the implementations described in the sections Factorywide Improvements and Production Steps Upgrade/Replacement and are awarded points to motivate player to implement them. These points however are much less significant to the overall score than the potential benefits this implementations can achieve in-game.

5.4.9 Feedback

This implementation had three distinct moments for the implementation of its feedback, during development by the team, by invited student testers and finally with a more formal application of the tool in the context of the production engineering course in the EESC course. During the first two phases, the main objective of the test was the finding issues in the execution of the game, verifying the clarity of the challenges and verifying how the the players played the game. For the last topic, the game saved a log of the selected actions and recorded the players final score. Many fixes, balance changes and improvements relied on this initial tests.

For the formal test, the survey shown in Annex 9 – Bicycle Factory 4.0 form feedback was created and data was gathered in three different applications of two different versions of the game. From the first to the second version of the serious game, no content was added, however the interface was improved and minor bugs fixed. Despite these being the only significant changes, there was an unexpected change in the perception of learning as the percentage of people who answered positively on their learning increase from 37.5% (n = 32) to 84,8%. Since these results may yet be part of a published article, they cannot be reproduced here in their entirety, however the lessons learned for the revision of the game based on the latest version are listed below:

- The positive perception of the content, learning and motivation were above 75%;
- The changes caused by industry 4.0 were difficult to see;
- The game interface and panels had the lowest positive perception among all players;
- The most common comment was on the length of the game, with some players finding too extensive and easy to beat while others found that the concepts required a longer implementation;
- There were still issues with the player interface, such as how to open and close windows, select projects and so on;
- There was a bug where in some computers workers would sometime freeze and do nothing.
-

5.4.10 Reflection

While the game had a moderate positive reception in its latest implementation, the final result is in terms of project goal underwhelming. The challenges in solving technical issues specially related to user interface led to time constraints that hindered the game potential.

The lack of skilled developers in user interface and animation led to much effort spent through trial and error. Acquiring a more balanced set of skills for the development would have improved the final serious game drastically.

On the factory layout learning goal, the player has no significant option as the placement of welding stations. In this front in my understanding the serious game does not the deliver. Much of the development on this front was based on the development of a second level, where the player would be able to create the layout for his own factory with three distinct steps, however due to time constraints this was never implemented.

5.5 The resulting factory simulation Engine

The prototypes and games described in chapter 5 use a factory simulation to implement their learning strategies, this section describes the challenges of building the factory simulating engine within unity.

5.5.1 The Simulation

To simulate a production system is to create a principled virtualization of technological elements (machines and tools) and organizational behaviour, however even as broad as these two terms can be, they do not represent external elements that affect the system. The simulation of a factory to meet the requirements of the serious games shown above does not focus on the amplitude and numerical accuracy production simulation software need to, but must give a broader response and use simplified models of external systems, such as market demands and technology availability. The goal of this simulated factory for serious games is to promote a learning experience instead of pushing out actual production results.

Given the huge number of elements that participate in the production process of factory and the impractibility of modeling a specific behaviour for each of them, an abstraction had to be created. This abstraction must be able to address new emergent behaviors present in industry 4.0, such as the hive behaviors of transportation devices or the possibility of inter machine communication for decision making.

Before these abstractions were defined and since the project is intrinsically related to industry 4.0, a set of technologies and innovations were selected to evaluate the coverage of the selected criteria. This method served a similar role to user stories used in agile management, defining the requirements for the further development of the programmed behaviors.

One of the main challenges in this consideration was the implementation of human behaviors, as they are also represented in-factory. Many of the advances of industry 4.0 have to do with implementing without assistance optimal decision making which given the response timescaling differences, is also expected in some level from human operators. As such, many decisions made by smart factory elements emulate human decision making, and since it is not in the scopus of this work to study or exemplify these differences and it is of little relevance to the simulated factory experience, they ended up using the same behaviors with different parameters and knowledge of the current state of the production.

In this context, sensor information, one of the main tools for machine thinking, besides processing time, also had to be translated in the behavior. Since it is a simulation, the sensor values are readily available and the implementation only had to account for the weight of the consideration of these elements.

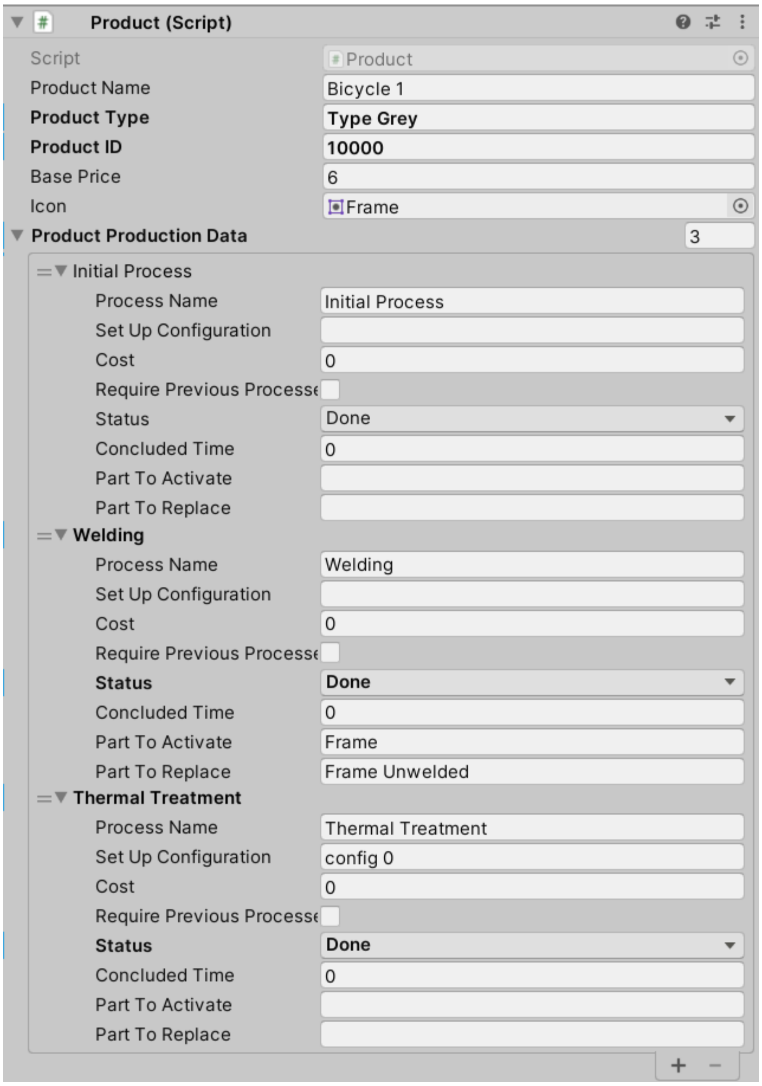
The table below describes other elements that were considered as needed to represent changes more commonly related to industry 4.0.

First, a factory´s main activities had to be broken down into high level modular abstractions that would enable few components to produce the many different behaviors seen in actual factories. The following components were selected to represent all the expected behaviors on a factory:

Product (includes materials) – The object being processed. It includes all informations and graphics required to achieve its finished version. Each product is configured to determine which of its graphic elements gets turned on or off in each process, as well as the process sequence, if they are sequential. Figure 26 shows the product creation screen.

Once a model of a product is created, they can be added to Orders to be generated in game. The Product Production Data configures all the production steps the product need to pass by in order to be considered complete, with the cost in this section representing only the material cost. Products can be easily modified by copying, pasting and editing changes.

Figure 26 - Product configuration interface



Link – Any element capable of moving products and/or itself. Links carry products from one process to another and are by far the most complex of the classes as they compose human workers carrying parts, conveyor belts, carts, autonomous transporters and so on. For this reason, they have multiple implementation (as shown in Table 10) and required the programing of multi variable selection criteria to determine what to get, when and where to take as well as limit how much information they have to make the decision. This limitation of information differentiates a worker relying on visual input to make his decision from an autonomous robotic mover who is connected to the factory network and knows how many products are waiting in each production step.

Storage – Any element capable of storing products or materials. Most processes and links have storage elements.

Process – Any element capable of transforming a product. There are multiple implementations of process, such as batch process, one at a time and single worker process.

Each real thing that participates directly in the transformation process can be modeled using these elements, however the actual implementation is directly related to the production context itself. A worker in the context of a bicycle factory has a transport component, as it can move a product, in the context of car manufacturer, it may be moddeled without it.

With this components in hand we had to check their coverage regarding the actual contexts in which they must be applied. To illustrate this step, some examples are presented in the Table 9 regarding the implementation in the bicycle factory context:

Table 9 - Factory element composition examples

Element	Description	Components	Intelligence
Welder	Worker who takes a bicycle frame to a welding station to process it.	Transport, Storage (space for 1 frame)	The worker must be able to decide which frame to take, which welding station to use and where to put it after the process is done.
Conveyor belt	A simple conveyor belt that connects two processes	Transport, Storage (multiple, depend on size and product)	It may have receive commands on speed direction and status (active/inactive)
Welding Station	A work station where a worker can fix a bicycle frame in a jig and weld it	Process, Storage (1)	It enables the welder to perform the welding process

Element	Description	Components	Intelligence
Thermal treatment oven	An oven which takes a batch of frames	Storage Entry (12) Storage processing (12) Storage Out (12) Batch Process (1-12)	It can be configured to start processing with a player-established parameter of min batch size and calculates the time required to determine when to start the process

As the development continued, this elements where expanded to incorporate new modes of functioning, with the intelligence and operation criteria determining the need to create new variants of the basic components. One clear example of this is the transportation logic. In a simple conveyor belt, as long as it is operating products are taken from one storage or process to the next while a human operator may pick and deliver materials to multiple stations and must use decision criteria to determine the retrieval point and destination. To model this set of criterias a new abstraction was created and named Link.

5.5.2 Program Structure

The general understanding of the routines that compose the code is important to evaluate the different requirements and distribution of effort within the implementation of the serious game. Comparing to the initial allocation of expect development time, some categories of code were vastly missalocated, and while it is only one example and the routine counts do not reflect directly the programming effort, it is can give an idea of the effort distribution.

In total, more than 250 routines were written during the entirety of the project, some have being rewritten multiple times. Considering only the essential routines for the functionality of the developed engine and after using advanced statements to simplify programming loops, 135 remained resulting in over 10.000 lines of code.

Table 10 summarizes only the essential developed code divided by category and classified by type.

Table 10 - List of programming scripts with their categories and types

Script	Category	Type
NtfDat_MessageOneButton	Content Holder	Window Data
NtfDat_TwoButton	Content Holder	Window Data
LearningRoomPageLibrary	Content Holder	Library
LinkLibrary	Content Holder	Library
OrderRepository	Content Holder	Library
StorageLibrary	Content Holder	Library
ProcessLibrary	Content Holder	Library
Obj_CheckForItensInProductionOrder	Content Holder	Objective Type
Obj_MinMoney	Content Holder	Objective Type
Obj_TriggerToComplete	Content Holder	Objective Type
Objective	Content Holder	ScriptController
ObjectiveManager	Content Holder	Game Manager
CurrencyManager	Content Holder	Game Manager
GameManager	Content Holder	Game Manager
IterationManager	Content Holder	Game Manager
ImprovementProject	Content Holder	Library
ImprovementProjectRepository	Content Holder	Library
ReplacementRepository	Content Holder	Library
Upgrade	Content Holder	Library
UpgradeRepository	Content Holder	Library
PurchasableFactoryElement	Content Holder	Library
Client	Content Holder	Library
FactoryElementRepository	Content Holder	Library
ProductionManager	Content Holder	Game Manager
ProductLibrary	Content Holder	Library
EventManager	Engine	Game Manager
ExitTheApplication	Engine	Functionality Extension
ExtensionMethods	Engine	Functionality Extension
Singleton	Engine	Functionality Extension
TriggerOperation	Engine	Functionality Extension
ProcessInteractionController	Engine	Controller
CameraController	Engine	Controller
IGenerateWikiContent	Engine	
StateMachine	Engine	State Machine
GameController	Engine	Controller
Modifiers	Engine	
SaveSystem	Engine	

Script	Category	Type
TriggerList	Engine	
Conveyor	Factory Element	Link
Link	Factory Element	Abstract
MoveableLink	Factory Element	Link
TransportAndProcess	Factory Element	Link
TransportBot	Factory Element	Link
EndProcess	Factory Element	Process
IntermediateInventory	Factory Element	Storage
ProcessIn	Factory Element	Storage
ProcessOut	Factory Element	Storage
Storage	Factory Element	Abstract
TransportationCompartment	Factory Element	Storage
BatchProcess	Factory Element	Process
DispatchProcess	Factory Element	Process
InitialProcess	Factory Element	Process
OneAtATimeProcess	Factory Element	Process
Process	Factory Element	Process
SingleWorkerProcess	Factory Element	Process
FactoryElement	Factory Element	Abstract
GraphicOnElementUpgrade	Graphic	
HighlightObject	Graphic	
WorkerAnimation	Graphic	
OnUIMouseOver	Interface	Player Input
PlayerInput	Interface	Player Input
SelectParentOnClick	Interface	Player Input
Interactable	Interface	Player Input
PlacementSelection	Interface	Player Input
InitiateProduction	Logic	Behavior State
WaitForProduct	Logic	Behavior State
CheckInventoriesForSameSetUpProducts	Logic	Behavior State
DeliverToStorage	Logic	Behavior State
GoToStorage	Logic	Behavior State
GoToWorkingStation	Logic	Behavior State
PickUpFromStorage	Logic	Behavior State
ProcessInStation	Logic	Behavior State
SearchForStorageDestination	Logic	Behavior State
SearchWorkingStation	Logic	Behavior State
WorkTimeOver	Logic	Behavior State
Prerequisite	Logic	Configurable System
Prerequisites	Logic	Configurable System
Prq_ImprovementProject	Logic	Configurable System
Prq_IterationStart	Logic	Configurable System
Prq_None	Logic	Configurable System
Prq_Not	Logic	Configurable System
Prq_Or	Logic	Configurable System

Script	Category	Type
Prq_TriggerTrue	Logic	Configurable System
IState	Logic	Abstract Interface
SortCriteria	Logic	Abstract Class
TransportLogic	Logic	Transport Logic
Trp_FullFactorySearch	Logic	Transport Logic
Trp_InitialAndFinalProcess	Logic	Transport Logic
Trp_ProcessList	Logic	Transport Logic
Trp_ProcessName	Logic	Transport Logic
Order	Main Elements	Order
OrderOffers	Main Elements	Order Offer
Product	Main Elements	Product
OrderProductCount	Subclass	
StoragePosition	Subclass	
CompletedOrderThumbnail	UI	Thumbnail
IndividualOrderUI	UI	Item
OrderThumbnailUI	UI	Thumbnail
OrderUI	UI	Item
IndividualProcessStatusThumbnail	UI	Thumbnail
ProcessStatusUI	UI	Item
ProductionStepThumbnail	UI	Thumbnail
UIProcessesPanel	UI	Panel
UIProcessStationSummary	UI	List
UISpecificBatchProcessPanel	UI	Panel
UISpecificProcessPanel	UI	Panel
NewOrderUI	UI	Item
NotificationWindow	UI	Window
NotificationWindowData	UI	Window
NotificationWindowManager	UI	Window
Ntf_Thumbnail	UI	Thumbnail
NtfWin_MessageOneButton	UI	Window
NtfWin_TwoButtonNotification	UI	Window
TemporaryWindow	UI	Window
ImprovementProjectUI	UI	Window
KPICounterUI	UI	List
PreReqThumbnail	UI	Thumbnail
ReplacementThumbnail	UI	Thumbnail
UI_Screen	UI	Abstract
UIEndScreen	UI	Window
UILearningRoomWiki	UI	Window
UILeftPanel	UI	Panel
UILibrary	UI	Repository
UILineChart	UI	Extension
UIManager	UI	Manager
UIMouseOver	UI	Player Input
UIMouseOverBox	UI	Player Input

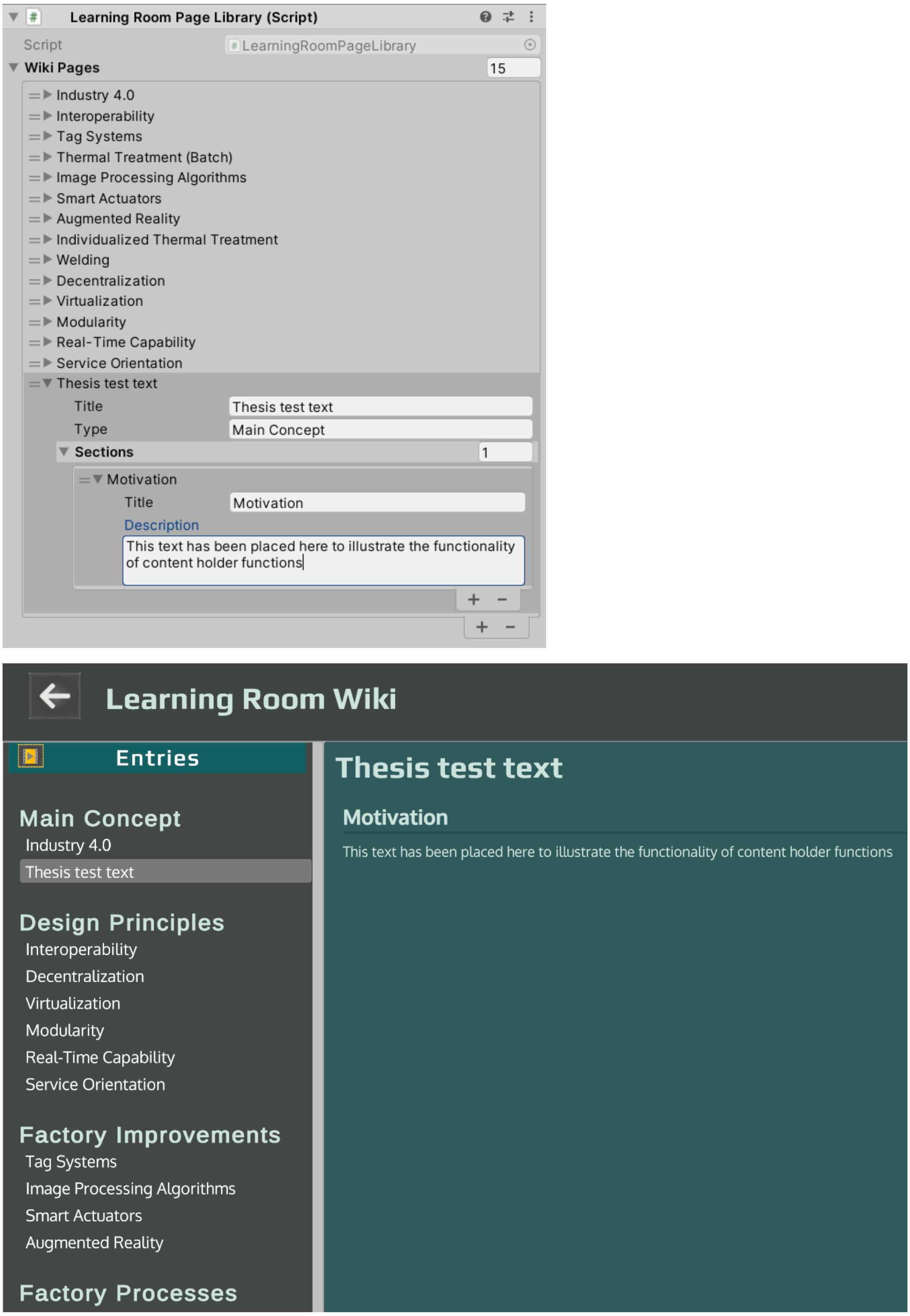
Script	Category	Type
UIMouseOverTooltipObject	UI	Player Input
UIReplacementSelectionWindow	UI	Window
UIThumbnail	UI	Thumbnail
UIUpgradeDescriptionWindow	UI	Window
UIUpgradeSelectionWindow	UI	Window
UIUpgradeThumbnail	UI	Thumbnail
UIWikiSection	UI	Item
UI_ObjectivePanel	UI	Panel

Aiming to improve the understanding of the role of this scripts, the categories are described in the next sections, however only the relevant types for the use of the simulation engine are described with those relevant to engine development being omitted.

5.5.2.1 Content Holder

The content holder category contains all functions that are directly accessed by the game designer when using the engine. These codes are attached to unity objects and are easily editable without any code to facilitate the use by professors, students and any person interested in altering the game. To illustrate its function, Figure 27 shows the insertion of a new window in the learning room within the game via the edition of the LearningRoomPageLibrary text fields, in this example, as many sections as required can be added, and the tool will add divisions and resize interface elements automatically:

Figure 27 - Learning room configuration example and resulting in-game screen.



As by their purpose, modifications in this elements require no programming and can be done in minutes with fully functional shortcuts such as dragging and dropping images, copying and pasting text among others.

This category subtypes are used to set game start variables (Game manager), set in-game objectives and rewards (Objective Type),control resulting events (Script controller), create customized windows (Window Data) and determine available game options (Library).

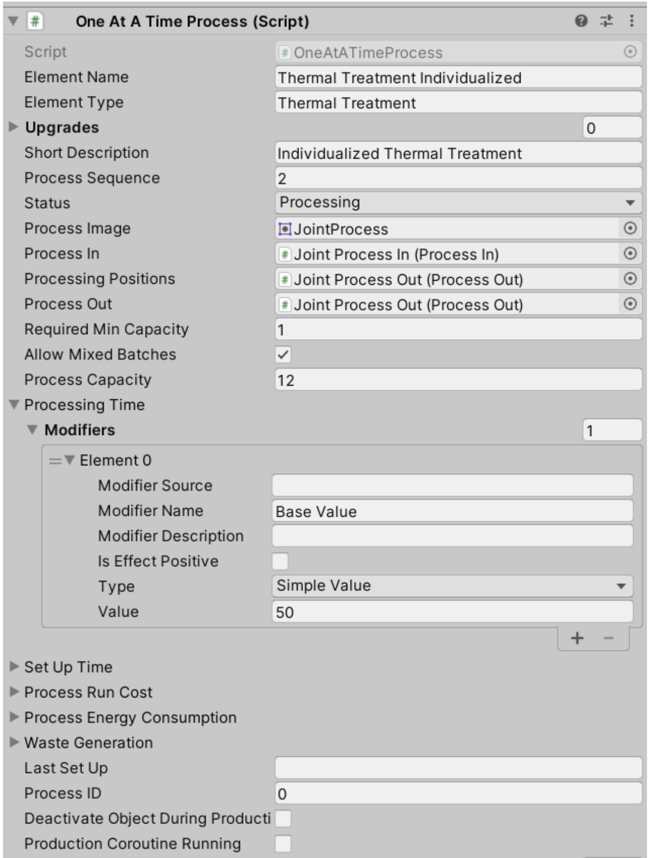
5.5.2.2 Engine

Engine codes are those which expand the unity engine functionalities and are required by other more applied funcions.

5.5.2.3 Factory Element

Factory elements are all behaviors that are part of the production system as the script is attached to 3D factory processes, workers and transportation systems. Their fuction is described in section 5.5.1. Figure 28 shows one example of their implementation on the thermal process with all variables exposed.

Figure 28 - Process configuration screen example



They are divided in four categories: Abstract for the parent scripts that cannot be used directly, Storage for the elements that can hold products, Link for the elements that can move products between processes and Processes for elements that process products.

5.5.2.4 Graphic

These functions deal with graphic controllers.

5.5.2.5 Interface

These functions deal with player input and response to player input.

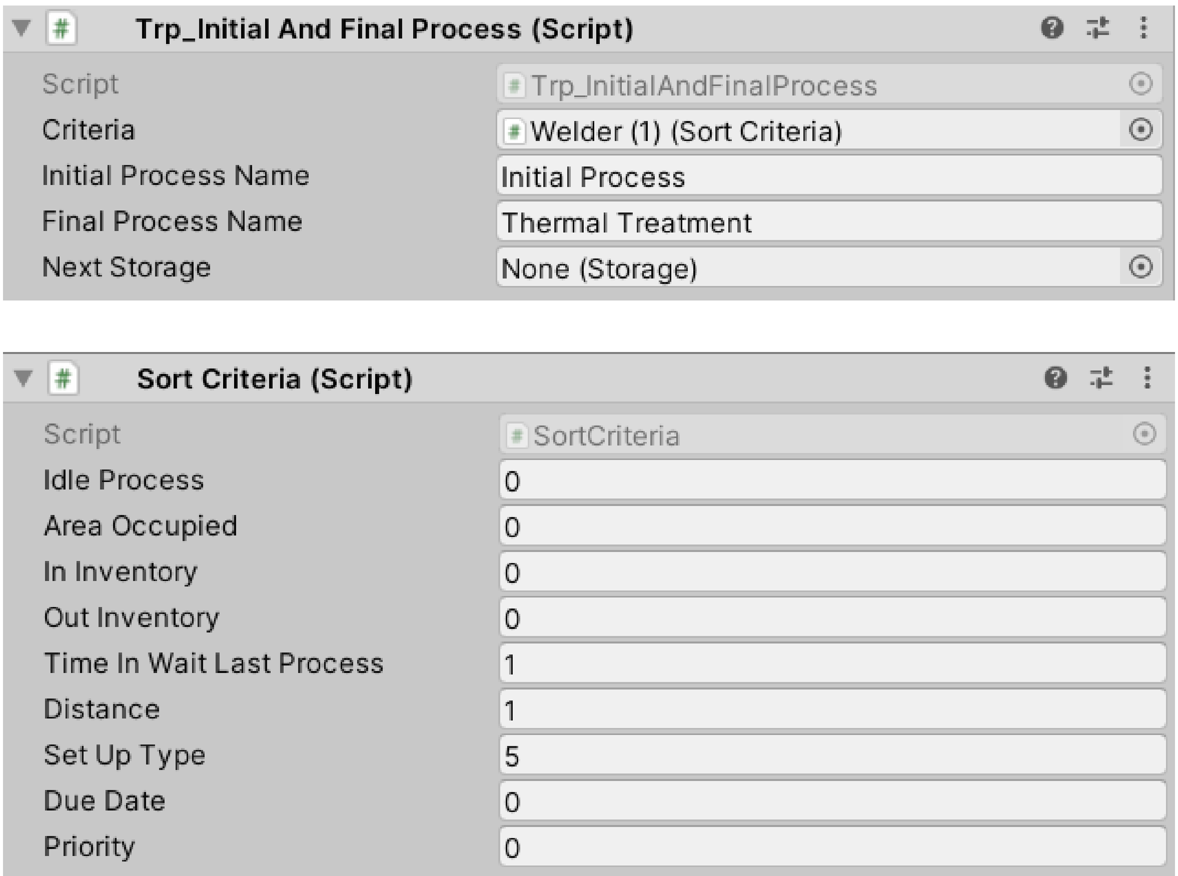
5.5.2.6 Logic

These funcions either determine the artificial intelligence behavior or are part of the configurable logic system used to determine prerequisites. The artificial intelligence behavior was one of the most time consuming implementation due to the sheer number of variables that a link; while a conveyor is easier to model, a worker has to determine which product(s) to take where. Even in very simple situations these questions arise:

- If there is more than one product coming out of a process or in an inventory, which should be taken first?
- The newest? The oldest? Should we try to form batches to the next processes? How much does the transporting link knows about the next procees? And if the next process is completely occupied?

To address these difficulties, some of this behaviors have a multi-criteria decision making functionality embedded. In the bicycle factory implementation, one of the most difficult aspects to communicate was when a worker stopped because there was nowhere to take the frame. Figure 29 shows the AI transport logic selected for the welders and the initial sort criteria:

Figure 29 - Transportation logic and a sort criteria example.



The developed engine is capable to change these logics on runtime, allowing for the exemplification of better routing decision due to industry 4.0 implementation. This functionality is absent from the bicycle 4.0 virtual game due to development limitations.

5.5.2.7 Main Elements

The main elements are products and orders, the first representing actual production and the latter the demand.

5.5.2.8 Subclass

Subclasses are just behavior that belong to other classes but perform different functions. They are subservient and only relevant for the developer.

5.5.2.9 UI

The user interface functions are those that control all that is shown and all that interacts with the player with the exception of the 3d environment. This category was by a significant margin the most underestimated in terms of resource consumption and complexity, it is responsible for almost 30% of the produced behavior and had to be rewritten three times during development as our needs and understanding of the tools changed.

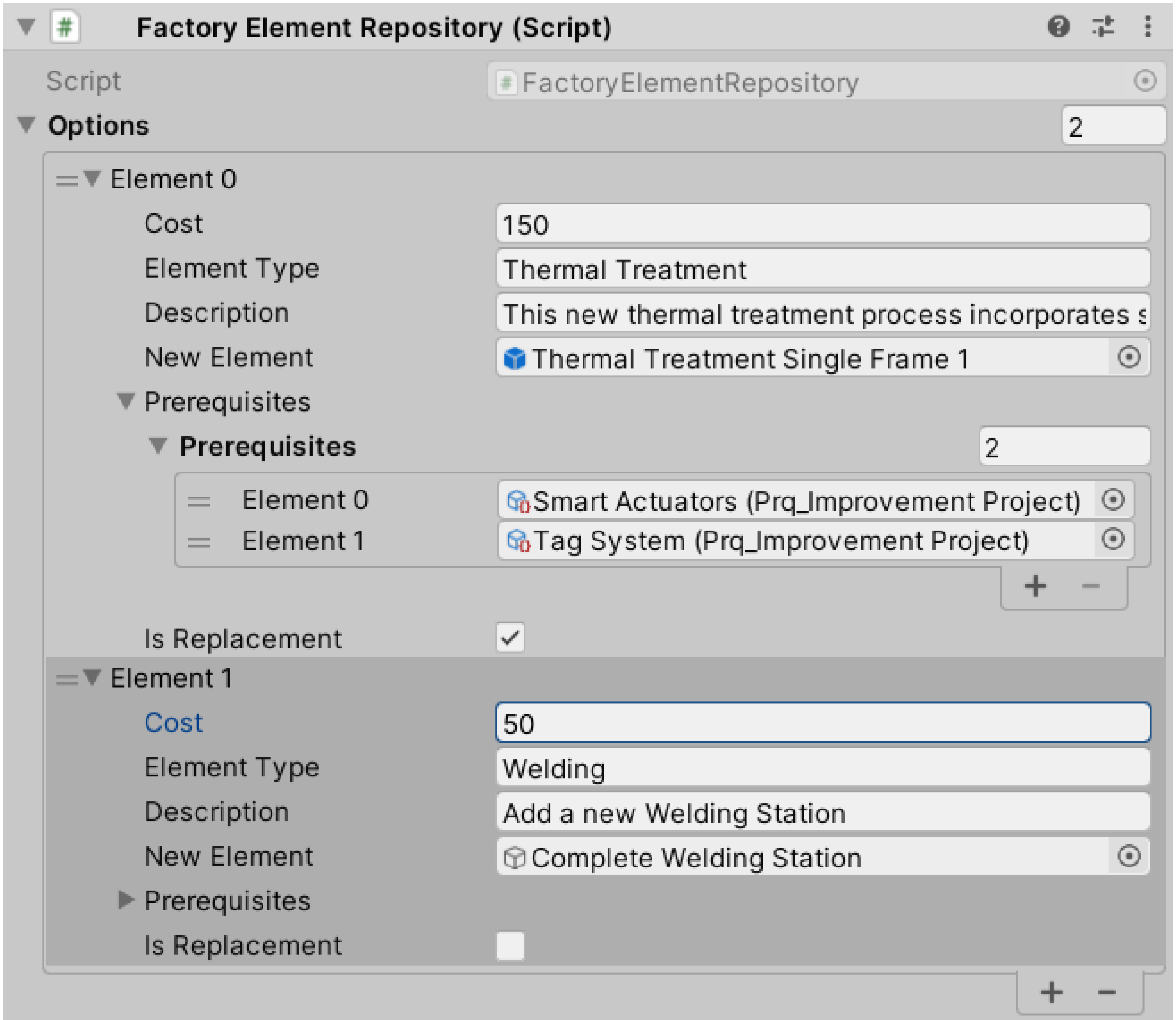
The main issue in the specific case of a factory management game, is that the interface requires many unlimited expansible lists with multiple variables. One example of this is the welding process. Its menu must allow the addition of one extra welding station block for each welding station, and each block must show a set of variables for the corresponding station and buttons to interact and upgrade it.

5.5.3 Usage to develop new serious games

The final tool can be used to create new serious games within the scope of the current game loop. The game would have all the same elements, factory wide improvements, production iterations, a learning room and so on, but the actual factory, available machines, messages, expressed knowledge and almost everything shown on screen can be changed without coding.

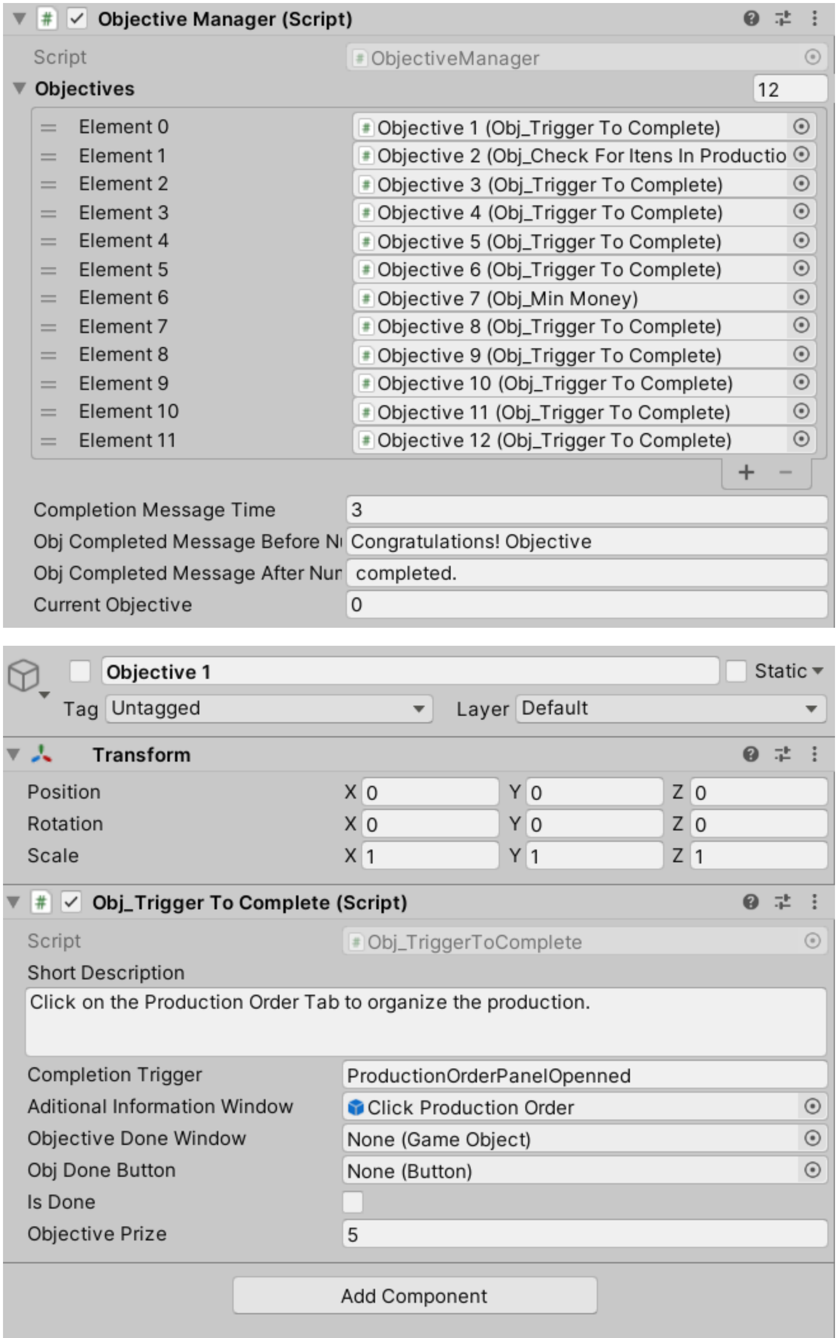
As an example, a new challenge could be made to produce chairs, with different equipments and production steps. After copying a premade starting scene, available in the project file, the first step in its creation would be setting up all the library type scripts described in the previous section, since they determine what will be available for the player to use. In this phase all machines, workers, improvements and so on would have to implemented (simply by adding 3d models to the scene, adding and setting up the appropriate scripts) to be added to their respective libraries. Figure 30 shows an exemplary library which controls the sequence of production steps:

Figure 30 - Factory element configuration example



With the libraries setup, the managers controlling some game aspects and initial variables and the objectives would have to be set. Each objective would be created in an empty object (without a 3D representation) and then added to the Objective Manager. Figure 31 (top) shows the list of objectives present in the Bicycle Factory 4.0. Figure 31 (bottom) shows in detail how a single objective is set up, basically by dragging and dropping predesigned windows and by writing the required information in the fields.

Figure 31 - Object creation example



Despite the programing and interface being already done, these steps alone would likely take days to implement once all decisions were made and all the models and animations were ready. If we consider the time to select and/or make the required models and game design decisions, the timescale changes to weeks or months, depending on the size of the project and how many people are involved.

5.5.4 Reflections

The tool was created to facilitate the design of new levels for the serious games and allow for less experienced programmers and game designers to be able to implement their own versions of management factory games, but could not eliminate entirely the need for programming skills. The implementation does not have a drag-and-drop or configurable function that can manage internal triggers for player actions, such as clicking an object or changing a process and despite its initial objective, it still requires a lot of Unity knowledge to be useful. The interface windows and pop-ups still have to be created from the start and despite the availability of some reusable items, its implementation is as complicated as in a new project.

In the context of developing the bicycle factory serious games and facilitating modification, it is enough. It can also facilitate the creation of new levels for experienced unity users, but as tool to decrease the entry barrier for developing games of similar style, its result is negligible. While some of the developed routines can be reusable and decrease development time, specially the factory elements and AI implementations, they are likely more usable integrated in another game implementation.

In hindsight, this attempt to make everything editable without code was very useful for me during the development, but the goal to facilitate for other developers and even train professors and researcher ot develop their own games was far too ambitious for our resources.

6 RESULTS

6.1 Scientific results

This section describes the articles that have published and submitted as result of this implementation. On the game development front, we have produced two articles with another on the pipeline. In the second funding period of the project, the focus shift towards a board learning game also on the transition towards industry 4.0. This placed the research group at an advantageous position of having two learning games implemented on the same topic, a virtual and a board game.

Following are the produced articles in the scope of this work in which I am one of the authors.

6.1.1 Insertion of sustainability performance indicators in an industry 4.0 virtual learning environment (CHAIM et al., 2018)

Authors: Omar Chaim, Bernd Muschard, Edson Cazarini, Henrique Rozenfeld

Abstract: Despite the profound impact caused by the technological revolution of the 20th and 21th centuries, many training practices, especially in formal education, have experienced little change. More holistic and self-sufficient means of education and training are necessary to meet the needs of manufacturing industry, incorporating success factors besides technical knowledge and economic viability, and one of the tools capable of delivering are serious games. One relevant concern when developing these tools is how to assess the learner's development and which goals to set as the learning challenge. To address this matter, this article contains a review of the sustainability assessment theory, focusing mainly on the social and environmental dimensions, and discusses the possibilities for incorporating theses metrics in a virtual learning environment both regarding their role for learning and motivation, their learning advantages and disadvantages as well as their relation to real practice, all in the context of the fourth industrial revolution. It aims to illustrate the usage of sustainability awareness as a learning outcome and the incorporation of sustainability indicators as tool to promote this development.

6.1.1 Scoring mechanics in a virtual and a board serious game about industry 4.0 and their relation to industrial sustainability goals – Submitted to the Journal of Engineering Education – Not published

Authors: Omar Chaim, Edson Cazarini, Esdras Paravizo, Daniel Braatz, Bernd Muschard

Background: Serious games are a tool for knowledge mediation of increasing importance. One of the main motivational tools within these games is the competition enabled by awarding scores or victory points. In this study two serious games, a board and virtual game, developed with similar learning goals and suitable for application within engineering education are analyzed based on the relation of their scoring systems to actual sustainability related industry 4.0 expected benefits and outcomes. **Purpose:** This analysis aims to answer the questions: What is the influence of the economic, environmental, and social sustainability on the score composition? How does the score relate to the actual learning goals of the developed game? **Method:** With a literary source to base the industrial benefits for comparison, both games scoring mechanics were classified by their source. The mechanics and industrial benefits and outcomes were then compared and the weight of each industrial indicator on the expected final score determined. **Results:** While both games cover aspects of each of the sustainability pillars, they do so with different weights and frequencies, in both cases compatible with their design objectives. **Conclusions:** The analysis provided insights on what was being rewarded and motivated in both games and how the industrial indicators were inserted as scoring mechanics, and the results were aligned with both games design goals, however more research is required to refine and validate the comparison methodology.

6.1.2 Exploring gamification to support manufacturing education on industry 4.0 as an enabler for innovation and sustainability (PARAVIZO et al., 2018)

Authors: Esdras Paravizo, Omar Cheidde Chaim, Daniel Braatz, Bernd Muschard, Henrique Rozenfeld

Abstract: The issue of sustainability in productive processes has become one of the main challenges industries faces in the contemporary era. New industrial paradigms such as the Industry 4.0 point towards the creation of more sustainable processes. The transition process from traditional manufacturing to the Industry 4.0-ready manufacturers, however, presents a range of barriers which organizations must overcome. In this context, we look to the concept of gamification and the opportunities provided by this approach to help tackle such obstacles. In this paper, we expand the discussion on how gamification can be articulated to the Industry 4.0 transition context, aiming to develop a conceptual framework for gamification implementation tackling sustainability awareness issues. We argue that these gamification mechanics can contribute to support manufacturing education on Industry 4.0, enabling innovation and sustainability. Based on a systematic analysis of relevant literature, we verify that the sustainable manufacturing and Industry 4.0 topics were the least reported on having employed gamified applications. The proposed framework articulates gamification elements and sustainability requirements in the Industry 4.0 transition. This contribution may help companies on developing gamified applications to overcome some of the challenges they face regarding the sustainability aspect in the transition towards Industry 4.0.

6.1.3 Manufacturing in the fourth industrial revolution: A positive prospect in Sustainable Manufacturing (CARVALHO et al., 2018)

Authors: Núbia Carvalho, Omar Cheidde Chaim, Mateus Gerolamo

Abstract: Industrialization throughout history has been one of the main contributors to pollution, disregard for environmental issues, resulting in an unsustainable production model. A change from this context, the imminent new industry model called the Fourth Industrial Revolution or Industry 4.0, aims for a manufacturing system that is both viable and sustainable. This paper seeks to describe the main forms of collaboration of Industry 4.0 in relation to sustainability. Scientific works point out the advantages provided by the new industry model such as improved product life cycles, manufacturing works in an integrated way with the use of cyber-physical systems allied to the principles of this industry, such as decentralization, virtualization, interoperability, among others which lead to more adaptability to

natural resources availability and environmental costs. Smaller batches can lead to amore accurate response to the demand curves and consequently lessen the waste for production.

6.2 Research action results

The research action methodology and the action-reflection cycles resulted in a better understanding on the process of developing learning games from the development standpoint. The challenges discussed in the reflection are compiled below and some possible actions to address these challenges proposed.

6.2.1 Estimation of resources

From the creation of the first prototype to the delivery of the functional learning factory, the perception of the development challenges and issues changed drastically. When the project was started my major concern was the creation the tool itself, with all its behaviors, 3D models and learning goals, and the literature on serious game development did not recalibrate these expectations. The skill composition needs and the variety of skills required to produce the serious game were obscured by the apparent availability of free tools and models, while the research activities had a much accurate resource estimantion. A more experienced team would be less impacted by this issue.

To address this issue, the implementation of multiple prototypes and fast internal testing is key to improve the meet this challenge. After the first prototype the entire group had a much better understanding of the challenge at hand, and the scope could be adjusted to be more realistic. This part of the solution addresses the quickening of the perception of the issue but the incorporation of skills in the group remain unadressed.

6.2.2 Serious Game literature limitations

The lack of focus of the serious games design methodologies on the game development itself, specially when considering the small groups that comparatively develop learning games, is a clear limitation of this research field. The reality of even indie studio development is different from that of researchers-developers as the expected role and skills of researcher many times conflict with the development requirements. Despite our group efforts, it was difficult to incorporate inexperienced collaborators in the project, specially when not even the current participants had enough skill to perform the task in the first place. In reality, the participating students had extra obligations with unreasonable expectations as they had to learn a new skill while performing research and delivering a skilled development result. Even if a graduate student from a computing department with the relevant skill came to participate, the opposite would happen, the skill would be less of an issue, but the implementation itself would likely not render material for research in the development area.

6.2.3 User Interface / User Experience skillset

The development of the User Interface was one of the most unexpected challenges. From its functionality, visual style front to programming its behaviors, each part consumed disproportionally large resources in comparison to the initial estimates. From the two different versions of the game where only interface improvements were made, we have evidence of a disproportional improvement (described in section 5.4.10) in the learning self evaluation. Yet, the lack of a skilled designer led to suboptimal implementation even in the final version of the game. Much of the difficulty from the player side to understand the changes that happens when new technologies are implemented can be traced to the final U.I.

6.2.4 Communication Issues

Another difficulty of the development of a virtual game in general is communication (AHMAD; RAHIM; ARSHAD, 2015; SILVA, 2020) and this prototype in particular was the illiteracy of the majority of the project participants with the medium. In the first meeting it became clear that only 3 of the 11 project members involved in the initial meetings were familiar with playing video games and the format itself became a challenge in conveying ideas. This problem would persist for the entire project, with communication and discussion on ideas, mechanics and concepts being much easier to explain to people familiar with this type of games. This difficulty with the format also meant that internal testing often led to discouraging feedback, as it was not clear for the participants whether they were struggling with the prototype or with common video game interactions. Depending on the target audience the final product would greatly benefit from not needing game literacy to be effective however having to aim to provide that during the entirety of the development process certainly slowed development, eventually leading to overdesign and effort spent in making a prototype more comprehensible and clear that it should be in their current state. The feedback quality of the literate and illiterate users were also significantly different, with the former being able to see beyond low-fidelity limitations of prototypes with much more ease than the later, providing more valuable insight.

To address this issue some entertainment games were overviewed, which occasionally led to better understanding of a mechanic or concept, but in hindsight, a game session workshop showcasing entertainment games with similar mechanics could mitigated this limitation.

7 CONCLUSION

While the implementation can be considered successful from the BRAGECRIM project perspective and perhaps from the questionnaire responses, its potential was far from realized. The development challenges within an academic environment were felt from the start, as people trying to develop researcher skillset had to work on game development topics.

Understanding the main challenges on developing serious games in an academic environment was one of the key questions addressed by this work. Based on this experience, the main challenges of developing serious games in an academic environment lie on the intersection of both fields. In the project we experienced difficulties and spent much effort to communicate to academic professors with little gaming experience game design while the communication was of the concepts was much easier to professor who had gaming and research experience. As described in the results section, the difficulty of either developing game development skills in undergraduate students or finding undergraduate students that had this skills and interest in the actual research topic was also significant. The non-linear pacing of results of computer game development was also felt since much time was spent at development at first with little to show leading to skewed effort perception, however much effort is also required to make something functional polished.

As programming is one of the challenges of the development of virtual learning tools, the consideration wether it would possible with currently available tools to develop tools without coding is relevant. While in other contexts it may be possible, developing learning tools, specially serious games, is still a very costly experience in terms of resources. The experiences from the last prototype and the factory simulation engine illustrate the trade-off between complexity and flexibility, as while the final tool came close to allowing non-programmers to modify the existing game to the point of being irrecognizable, the complexity of the tool itself meant that there is a steep learning curve. The edition and modification of a serious game to fit distinct scenarios is more feasible as many changes can be made by simple drag-drop mechanisms and text edition. Even so, the complexity of learning these mechanics, which are specific to each game, are complex enough to know limit significantly the who can modify the tools, as it may takes days to understand the tool well enough to modify it.

- How viable is the creation of serious games within research projects?

The third question addressed the viability of the creation of serious games within research projects, and the conclusion considering the project results is that it gets more viable depending on what skills are available within the working group. A limitation is that the research part of the project had in this implementation several negative impacts in the development process. The research objectives, aiming at research article results, are not directly aligned with the production of an optimized serious game, and the skillsets for game development and researching were not well aligned. The project aspect in this case also had a significant limitation as once the project was over, there was no structure or funding to keep the learned skills within the university structure. The many behaviours created to simulate a factory could be used for many other didactic application, but since they were not in the project scope, they were not implemented.

On the other hand, the access of the developers to a pool of testers through the graduate and undergraduated students in the academic environment is a significant advantage. In a matter of days we were able to assemble engaged testers for less formal applications, and the barriers for larger more formal applications is also lowered. Since the three involved universities had production engineering courses and subjects related to this topic, it was not complicated to include the testing the prototype as a learning activity. To be able to access large groups of your target audience agilized testing.

Further research

The field of serious games development specially regarding to the development of computer games can benefit from more research on the game development side of the equation. As such, other implementations to assess best practices of managing this process in an academic environment would be valuable.

Research on more specific topics of serious game development such as interface evaluation, and score assessment would also have been valuable for the development of this work.

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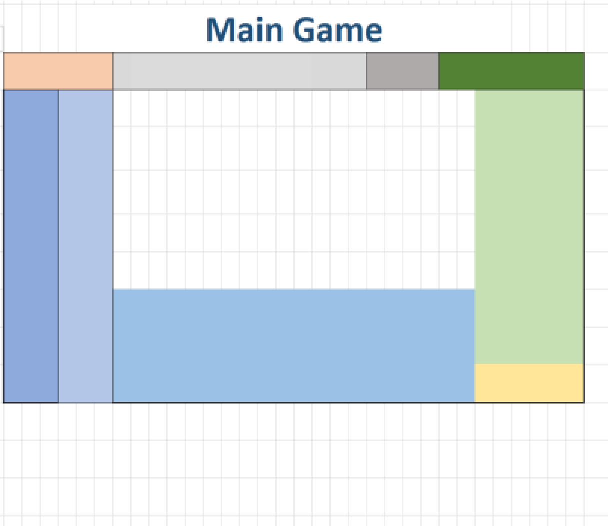
Annexes

ANNEX 1– FIRST GAME CONCEPT PRESENTATION

Starting Scene: The player is in a waiting room when a character comes introduce him/her to the context:

Info given: You have been selected (or perhaps promoted???) to improve our manufacturing company towards I 4.0. You can take your time to talk to other coworkers (maybe a computer???) for introductions. When ready to start your job, talk to me again.
User Interface (UI) addition: Game Screen; Main Menu; Dialog window.

Name	Level
Main Game	1
Game Area	2
Orders	2
Wishlist	2
KPIs	2
Time	2
Timescale	2
Main Menu	2
Object Details	2
Advisor	2
Dialog	2



Level 1 – The training or “As things used to be”

This challenge will be an introductory order filling challenge divided into four steps.
Step one - 1-2 min:
In the first part the production amounts are large and there are only two types of products. It will be introduced by a character saying:
"When we had only two products, things were easier. We got big orders with some advance and kept stocks for the smaller ones."
The player can be successful by simple producing every piece of part A then every piece of part B.
Step two 2-3 min:
In the second part the time to meet the order decreases, requiring more production changes. It will be introduced by a character saying:
UI addition: Orders; Time; Timescale; Stock.

"Since the competition got stronger, we had to decrease delivery times to keep the edge."

At least two production changes will be required not to be late.
Step three 3-5 min:
The product amount will increase to four. It will be introduced by a character saying:
"Well, speed was not enough, the needs from our clients become more diverse"
This is the first maximization challenge. The player will have some orders delayed or some excess of stock.
Step four 4-6 min:
The last part is like the previous, but products will decrease value over time (when stocked). It will be introduced by a character saying:
"Then we had to develop new products and implement improvements faster. This also meant that stocked products became obsolete sooner..."
UI addition: Product Value (under Stock).

Another optimization challenge. The player will have to decide how much stock he or she will keep.

Desired Outcome: Experiencing the difficulties caused in I. 3.0 by fast changing products and decrease of batches sizes. Understand the interface.
Challenge: Meet the orders in time. Every time the product changes, machines have to stop for some time for configuring, so more changes mean less production and more expensive products.
Resources: Time
Decisions: Product Manufacturing Amount; Product Manufacturing Order; Stop production
Info: The next orders to meet with remaining time; The amount of each product in stock.
Events: None

Expected completion time: 15 min.

Level 2 – Changing the manufacturing floor

Given the same difficulties presented in Level 1 step four, the players are given one more tool to work with, upgrading machines in the production line. Also, machines now can break.
"Technology now allows us many more options to deal with this problem…"
Also a maximization problem. The idea is for the player to understand the production impacts of increased flexibility. Choosing the most expensive machine for each production step in the line will not be the best solution.
UI addition: Advisors Pop-up

Desired Outcome: Understanding some of the means by which I. 4.0 can help dealing with changing products and decreased batches sizes.
Challenge: Meet the orders in time, earn money, minimize waste. Alter production line by upgrading machines (faster production change speed, maintenance capabilities, sensors...) to improve production.
Resources: Time, money, machines.

Decisions: Upgrading Machines, Incorporating Sensors; Product Manufacturing Amount; Product Manufacturing Order; Stop production.
Info: Each machine production time and time for changing product. The next orders to meet with remaining time; The amount of each product in stock.
Events: Machines Break

Expected time: 15 min.

Level 3 – Making
Building up from level two, the player now will face more events and have more options to deal with.
"Standardization is playing its role! Now we can have more options of machine to choose from. We've just reached the level of digitalization that allows us to enjoy the benefits of digital twin!"
Also a maximization problem. One machine on the production line will break more often, and one of the options will be to upgrade it to a more robust one (available only from a different manufacturer).

Desired Outcome: Experiencing the impact of Modularity and Interoperability. Understanding the intel from the "twin factory" (virtualization).
Challenge: Meet the orders in time, earn money, minimize waste, seize opportunities. The player now controls 2 production lines (similar) and can upgrade to interoperability ready machines, meaning that more machine options (limited to 5, including from different "manufacturers") are available. Also, the player can choose to add more production modules to change the product and activate them individually.
UI addition: Machine and Object Interaction; Digital Factory Overlay.
Resources: Time, money, machines.
Decisions: Upgrading Machines, Incorporating Sensors; Product Manufacturing Amount; Product Manufacturing Order; Stop production.
Info: Each machine production time and time for changing product. Machine prices; The next orders to meet with remaining time; The amount of each product in stock; Digital Twin.
Events: Engineering will propose the addition of a process in the assembly line to improve products' durability (if the player cost is already high, this will cause decrease in sales). "There is an opportunity we cannot miss! If we just put another step in the production line that will make our product last a lot longer. We can market it!"
Marketing will propose an addition to the production line that will increase sales (trade-off if the player is not being able to meet orders on time, this will lead to losing money). One product will have a demand much higher than anticipated and two will have a lower demand. "You see, our market research points out that having changing the painting and coating to a more polished finish will definitely increase our sales! We have talked to engineers and it is possible, just one more functionality on the line and that is it!"
(Perhaps we should simulate short meetings for these events, so the player can ask the opnion of each of the participants from different areas.)

Expected time: 20 min.

Level 4:
The final challenge. The player now has access to inquiries and orders. Inquiries are desired products with and amount and limit cost (e.g. five gray cell phones and I can pay 10% more). If the factory can meet these requirements, the inquiry becomes an order and generates income, if it does not, the player can see why he lost that costumer. The product characteristics now affect demand through customer internet review, so the player can now see what people say of his or her product (e.g. "It looks awesome!", "It got here three days late", "It works well, but the color is not what I ordered!")
“With our customer relation team and technology we can now see what customers want and even what they think of our product. This can be really helpful if we can seize these opportunities!”

Desired Outcome: Creating an industry 4.0 production line. Experiencing the mass manufacturing and machine decision making (decentralization).
Challenge: Meet the orders in time, earn money, minimize waste, seize opportunities. The player controls 2 production lines (similar) and can set priorities to make machine take orders by themselves. A new type of machine will be add to the mixture, the fully customizible additive manufacturing machine (slow and very flexible machines). The player will now have to balance the amount of mass production and customizable production capacity.
Resources: Time, money, machines.
Decisions: Upgrading Machines, Incorporating Sensors; Product Manufacturing Logic; Stop production.
Info: The "wish list"; Each machine production time and time for changing product. Machine prices; The next orders to meet with reimaining time; The amount of each product in stock; Digital Twin.
Events: Engineering can propose additions of processes in the assembly line to improve products' durability (if the player cost is already high, this will cause decrease in sales). “Hey there! There is this new coating that can help us make our product more durable. Should we implement it?” Marketing can propose additions to the production line that will increase sales (trade-off if the player is not being able to meet orders on time, this will lead to losing money). One product will have a demand much higher than anticipated and two will have a lower demand.
“We found another opportunity to meet our clients needs, think metal shiny!”
“People want more exclusivity to our products, imagine: Fully artwork engraving services directly from the factory!”

ANNEX 2 - HAIFA PROTOTYPE DIALOGUE SCRIPT

Rachel: Hello! You must be our newest collaborator, am I right? We were expecting so much for you!

Player: Oh yes! It's me! I am very happy to be here and hope to learn and contribute a lot in this industry.

Rachel: You sure will! Our factory follows the imminent model of Industry 4.0. Do you already know anything about it?

Player: Reasonably. I've been researching a little and I've heard about a few things. Can you give me an overview, Rachel?

Rachel: Of course! In this industry you will realize that it encompasses a strong context of innovation, breaking paradigms and full use of high technology. With characteristics of open system, it is established by six principles, which you will realize later that are the pillars of this industry. In it the communication takes place vertically and horizontally, there is great use of machines and there are less command hierarchies.

Player: Wow Rachel! How interesting! I really want to know more about the structure of this industry!

Rachel: Really cool, is not it? Oh yeah! Our employees will always be willing to help you, and I will always be here too!

Player: Thank you very much for every info Rachel! (exit)

Information Technology

Joseph: Hello!

Jogador: Hi there! You are with the IT department, right?

Joseph: Yes! We're working on a very exciting project on virtualization right now.

Jogador: Really?! That's also related to Industry 4.0?

Joseph: Exactly. It should help our machines to communicate better, improving the production flow.

Jogador: Cool! Thanks man! (exit)

Jogador: Wow, that should be interesting! What is the best thing about it?

Joseph: Oh, if everything goes well, we'll have a digital twin of our factory, with all data from machines' sensors and everything!

Jogador: Nice! Thanks man! (exit)

Jogador: Hey! Do you know how the production floor works regarding IT? I'm new, and a bit lost...

Joseph: No worries, Perhaps I can help you.

Jogador : Great! I was told they were trying to implement Industry 4.0 here. Do you know why?

Joseph: Yeah, from an IT perspective, it would enable us to better communicate internally (even our machines!) and externally (with customers.

Jogador: Oh I see. Thanks! (exit)

Jogador : Cool! How was the system we used before trying to transition to Industry 4.0?

Joseph: We used a standard ERP software. It took a lot of effort and usually communication took quite some time..

Jogador: Oh I see. Thanks! (exit)

Jogador: See you! (exit)

Marketing and Sales

Cameron: Hello friend!

Player: Hello! Do you work in which department?

Cameron: In Sales and Marketing! Rachel warned us about her arrival! Do you want to know more about our work here?

Player: Please, I really want to know how the activities in this department are made!

Cameron: Come on then! Here, as well as studying the needs of our customers and the best way to satisfy them all the time, we are taking care of providing the customer with a pre-sale vision, monitoring the production of their orders, and also an effective system after-sales service that collects real-time information on consumer demands.

Player: Is that really, Cameron? But how do you keep up with internal and external needs?

Cameron: That's an interesting question! Our industry acts as a fully interconnected network, either physically or virtually.

Player: Very cool! How do you reorganize with the Engineering Department, aiming at a able, agile and efficient production system?

Cameron: Because of the possibilities of customization, repairs, increase or decrease of batches of products, our department has to be always attentive to receive and communicate the external demands to the Engineering, and this one plans and controls the factory machinery so that everything happens of the form right and on time.

Player: So you're always acting together and following every step in the industry and out of it in real time, that's awesome!

Cameron: That's right! One of our great qualities is our fast response time to the environments we are inserted!

Player: Very interesting Cameron! Thank you so much for your attention! Now I need to meet other departments in our industry, okay?

Cameron: We're always here when you need it! Go there! There are many new and relevant things to know around here! (exit)

Engineering:

Hello, you are welcome!

Player Thank you, can you explain me about your department?

Amelie: I'm in charge of the company's Production Engineering department. Come on, I'll show you.

Player Very good, I really would like to understand more about your department

Amelie: We are responsible for meeting the demand by integrating men, materials, equipment and processes, facing them as resources for the realization of productive activity.We are currently deploying new ways to improve processes and internal interaction. Want to know how?

Player :I want to know yes, does it relate to Industry 4.0?

Amelie: Yes it is related to the Industry 4.0. We are implanting sensors in the line of production that communicate in real time and as a consequence we can reorganize the production with agility.

Player :And how can you reprogram production in real time using the sensors?

Amelie: *The sensors help us to verify what is being produced and how the machines communicate with each other, in case of any problems occurred, the machines have the capacity to reorganize so that production does not stop.*

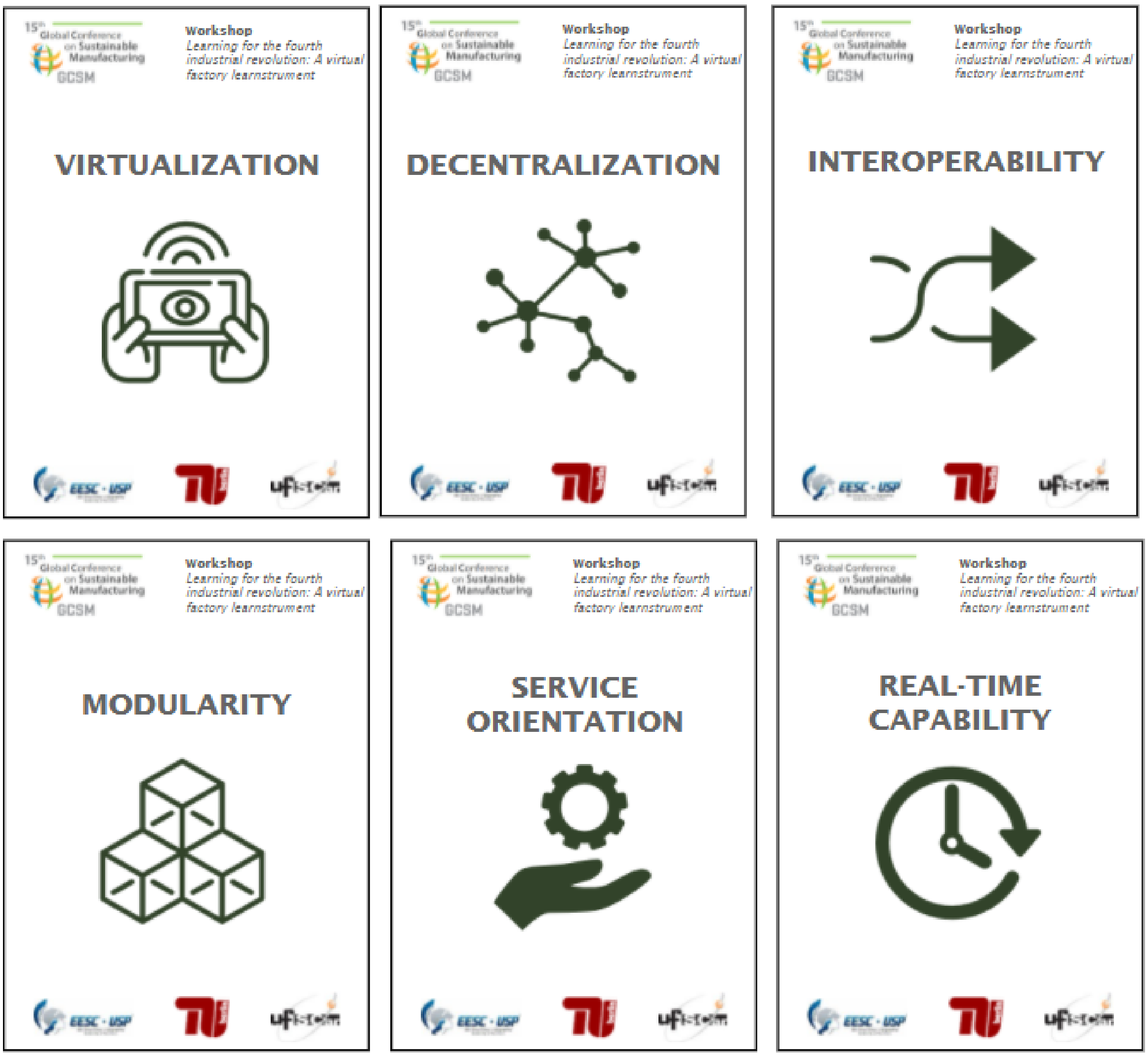
Player :*Wow, so you can optimize your production and still know everything that is happening in real time?That´s fantastic.*

Amelie: *Yes, with the help of new technologies we are changing the way we produce, control and program production.*

Player :I loved learning, now I'm going to know the other sectors! Thank you very much)

Amelie: *It was a pleasure to show you our industry!*

ANNEX 3 - PRINCIPLE CARDS FOR HAIFA



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MODULARITY

The modularity principle assures the flexibility, adaptability and adjustability of the production system, allowing for a smooth implementation of changes in the manufacturing system (e.g. adding, removing, adjusting processes)

SERVICE ORIENTATION

Service orientation is aligned with contemporary PSS strategies, enabling the organization to be agile and flexible in responding to changes in consumer preferences and evolving needs through the use of virtual means

REAL-TIME CAPABILITY

A consequence of the interconnectivity and data sharing among the stakeholders of the value chain. It allows the productive system to rearrange itself in real-time, as soon as the new inputs are received and processed. It also reduces the time needed for changes in product design, customization and corrections

VIRTUALIZATION

The capturing, modelling and representation of real world data and information from the productive process and its products in a virtual environment which can be used for the planning, monitoring and control of the system

DECENTRALIZATION

The ubiquity of cyber-physical systems, embedded in the productive process enable the decentralization of decision making. Machines and systems in the factory floor are able to autonomously adapt to sudden changes and to reorganize the production schedule to improve productivity, as they perceive the need to

INTEROPERABILITY

The ability of a production system to exchange and integrate machines and equipment that perform similar functions. Within the interoperability context, equipment are able to communicate among themselves which is the basis for the development of industry 4.0

ANNEX 4– 3D MODELS LINK LIBRARY

Modelos 3D

Amarelo: Não foi utilizado

Azul: Foi utilizado

Rosa: Pode ser utilizado

- Bicicletas:

- https://archive3d.net/?tag=bike
- https://www.cgtrader.com/free-3d-models/vehicle/bicycle/folding-bike

- Conveyor:

- https://archive3d.net/?a=download&id=2cd4ee36

- Suporte para bicicletas:

- https://3dwarehouse.sketchup.com/model/ub95ce3ad-7aea-4fee-98ef-05474726579/bicycle-stand
- https://3dwarehouse.sketchup.com/model/10a20e2340bb881c3f222a37719e9945/Bicycle-work-stand
- https://3dwarehouse.sketchup.com/model/7b6a9a72-85bc-4cbe-b0aa-3635d3a6d193/DoubleUp-Double-Sided-Free-Standing-Vertical-Bike-Rack-20-Bike
- https://3dwarehouse.sketchup.com/model/646f2459-1013-430c-b652-9c456330bb82/DoubleUp-Double-Sided-Free-Standing-Vertical-Bike-Rack-8-Bike
- https://3dwarehouse.sketchup.com/model/063906ce-d9bc-4627-b865-9abdc4ac086f/Vertical-No-Scratch-Floor-System-Bike-Rack-14-Bike-Double-Sided-16-Spacing
- https://3dwarehouse.sketchup.com/model/56a7e49a-8419-4cf3-916d-5e4531c86d24/Vertical-No-Scratch-Floor-System-Bike-Rack-8-Bike-Double-Sided-13-Spacing

- Cover entre as estações:

- https://3dwarehouse.sketchup.com/model/c3e19fc7dbdb7932f1c348dbeea26fa2/Welding-cover

- Estação de Welding:

- https://3dwarehouse.sketchup.com/model/7fa8c000f59d19eac25cfdac7cd67ea3/Welding-Stations
- https://3dwarehouse.sketchup.com/model/671ee5754bf8ff19fd6b380b04de8c7e/Welding-table
- https://3dwarehouse.sketchup.com/model/u8f779ec0-2c25-4cc9-8fa6-8930cb4870f0/Welding-table

- https://3dwarehouse.sketchup.com/model/6af05d00-2c0b-4cbc-b17c-fbfc9e29c824/welding-tables
- https://3dwarehouse.sketchup.com/model/ed14f86f52625a2a389c801027d55357/Welding-Shop
- https://3dwarehouse.sketchup.com/model/u4eb845eb-c22c-49ef-86c0-7009f638987d/welding-cart

- Estação de Joint:

- https://3dwarehouse.sketchup.com/model/d2bc85fa-6f07-4fcc-9b99-0d7aa1c4b29d/POL-storage-tank
- https://www.cgtrader.com/free-3d-models/industrial/other/storage-tanks-3d-models
- https://3dwarehouse.sketchup.com/model/a6b76066a5efe111fabcc336609ddf83/heat-treatment
- https://3dwarehouse.sketchup.com/model/029aea85-ad1a-4a25-9ce2-69c4c05b338f/Busch-Sulzer-10-cylinder-marine-diesel-engine
- https://3dwarehouse.sketchup.com/model/f59b90a24c1c87d3b229726a165222c0/Industrial-Series-Equipment-Container-Tote-Universal-350-Gal-HDPE
- https://www.cgtrader.com/free-3d-models/industrial/part/condensate-module
- https://www.cgtrader.com/free-3d-models/industrial/other/sump-tank-skid
- https://www.cgtrader.com/free-3d-models/industrial/other/well-access-platform

- Câmera Térmica:

- https://3dwarehouse.sketchup.com/model/f5a7631f4d7eceabc0539f653fbcb1f6/MSA-TIC-Thermal-Imaging-Camera
- https://3dwarehouse.sketchup.com/model/ue7c3076b-5d54-46c5-bf7d-40663665e9f1/Thermal-PTZ-Camera
- https://3dwarehouse.sketchup.com/model/f7c3c89445083a432621b39a3bf79316/Bullard-thermal-imaging-camera
- https://3dwarehouse.sketchup.com/model/2c37ce18f8f87981697e4a2ceb1ad2b7/Gyro-Stabilized-micro-Camera-Gimbal-FLIR

- Frame Jig:

- https://3dwarehouse.sketchup.com/model/a7af041a1322fd4c85b8dfc4615f91d6/Bicycle-frame-jig
- https://3dwarehouse.sketchup.com/model/779b36e8bc82f9f9456cc04e8cfe19f8/Chopper-Frame-jig
- https://3dwarehouse.sketchup.com/model/a91bd9e52e7c18f0cf8ad1c8dd1ad987/Frame-Jig-Base
- https://3dwarehouse.sketchup.com/model/24b0cc80e121f434aab2a04aaf55d6c6/Wizards-bicycle-frame-jig
- https://archive3d.net/?a=download&id=0a09af38
- https://3dwarehouse.sketchup.com/model/a7af041a1322fd4c85b8dfc4615f91d6/Bicycle-frame-jig

- Lift:

- https://3dwarehouse.sketchup.com/model/1279c5fb8b8e18c5d580a37fbfea64e1/Modern-Elevator
- https://archive3d.net/?a=download&id=e8b0dae5

- https://archive3d.net/?a=download&id=83573575
- https://www.cgtrader.com/free-3d-models/industrial/machine/portico-rolante

- Estação de Welding Ergonômica:

- https://3dwarehouse.sketchup.com/model/u2afe8c23-31ea-454b-a06e-790de5c11bf3/Weld-Cell

- Estação de Montagem Ergonômica:

- https://3dwarehouse.sketchup.com/model/a84435ac-22dc-4dbf-ba0e-c14ad36e4ae8/Gantry-Crane-and-Welding-Table

- Máquinas:

- Park Tool PRS-3.2 Suporte de Reparo de Bicicleta de Único Braço: https://3dwarehouse.sketchup.com/model/94804793-b283-4b29-a396-e8641cdb2e66/Park-Tool-PRS-32-Deluxe-Single-Arm-Bicycle-Repair-Stand

- Manutenção:

- https://3dwarehouse.sketchup.com/model/7438d343db442c00e330955d7d7cab3/BIKE-MAINTENANCE
- https://3dwarehouse.sketchup.com/model/25df788a2eec0d57d6bbaa90c7ca9409/Standing-Bike-Rack

- Estação de Painting:

- https://archive3d.net/?a=download&id=7447f15d
- https://www.cgtrader.com/free-3d-models/industrial/part/design-factory
- https://3dwarehouse.sketchup.com/model/645f3496241cd9301e95b03d0314e383/Spray-Booth
- https://3dwarehouse.sketchup.com/model/cc6d5167-dc34-4e2c-b912-fd7d996a2be1/Boya-Tabancas%C4%B1-Spray-Gun-Paint-Gun
- https://3dwarehouse.sketchup.com/model/cc6d5167-dc34-4e2c-b912-fd7d996a2be1/Boya-Tabancas%C4%B1-Spray-Gun-Paint-Gun

- Cabine de Pintura:

- https://3dwarehouse.sketchup.com/model/645f3496241cd9301e95b03d0314e383/Spray-Booth
- https://3dwarehouse.sketchup.com/model/70e65e4aeb12dd3442a938ac4a95a901/Paint-Booth
- https://3dwarehouse.sketchup.com/model/f14a453f-725a-40ed-a3d9-7f690f70d88d/SPRAY-PAINT-BOOTH
- https://3dwarehouse.sketchup.com/model/0ee9470a-5763-4340-be34-ae49d0167bcb/Professional-Paint-booth
- https://www.cgtrader.com/free-3d-models/industrial/part/application-of-paint-booth

- Estação de Assembly:

- https://archive3d.net/?a=download&id=8c854e4a
- https://www.cgtrader.com/free-3d-models/industrial/machine/conveyor-sorting-system

- https://3dwarehouse.sketchup.com/model/82e3cfd7-643f-4d2c-861c-6f3809de8ed8/Assembly-line-module
- https://3dwarehouse.sketchup.com/model/6f01799e5cbcc8f0466b8ecd485c513c/Gear-Bearing-Assembly-line
- https://3dwarehouse.sketchup.com/model/af5d123f0457fc5e466b8ecd485c513c/Press-Conveyor-assembly-area
- https://3dwarehouse.sketchup.com/model/a504868ce563847cbb644041b01c0829/Roller-Conveyor-10-x-3-x-2
- https://www.cgtrader.com/free-3d-models/industrial/part/frame-of-the-bridge-crane
- https://www.cgtrader.com/free-3d-models/industrial/machine/conveyor-assembly
- https://www.cgtrader.com/free-3d-models/industrial/part/application-of-paint-booth
-

- Picking:

- https://3dwarehouse.sketchup.com/model/21e5e06f-2759-4f80-b106-9b188559e0b8/M%C3%A5lningsanl%C3%A4ggning
- https://3dwarehouse.sketchup.com/model/28740f23a6506e3eb8e1b99345a5afd4/Industrial-shelves
- https://3dwarehouse.sketchup.com/model/6eb5e997de4c8a4bb184a11e7c8722b4/Industrial-Shelves
- https://3dwarehouse.sketchup.com/model/e7566200-251b-4126-b66b-ee65be0d753f/Industrial-Shelving-Single-Unit
- https://3dwarehouse.sketchup.com/model/uc4a95c67-14e3-4cb3-b319-edcf618a847c/Shelving
- https://3dwarehouse.sketchup.com/model/u44658099-c84c-4d0a-950b-9264c26b07a6/estante-industrial
- https://3dwarehouse.sketchup.com/model/a8beb1f8-5d44-40cd-be8b-cb327e514d8c/mezanine-racking
- https://3dwarehouse.sketchup.com/model/928faf6d-9af6-413d-9bfb-2125478b8fc3/Rak-Gudang-Heavy-Duty-DC-70-dan-92
- https://3dwarehouse.sketchup.com/model/a6b88092-d322-4414-a013-177860d2072e/picking-cart
- https://3dwarehouse.sketchup.com/model/u62db501f-765c-4199-b703-2c4dff88002a/High-Density-Mobile-Shelving-for-Athletic-Equipment-Storage
- https://3dwarehouse.sketchup.com/model/a386549e10428682486c893ca314ec7f/Shelving-Unit-5-Bays

- Delivery:

-

- Máquinas:

- https://www.cgtrader.com/free-3d-models/industrial/machine/hydraulic-arm

- Forklift:

- https://www.cgtrader.com/free-3d-models/industrial/machine/low-polly-forklift
- https://www.cgtrader.com/free-3d-models/industrial/machine/little-industrial-forklift

- https://www.cgtrader.com/free-3d-models/vehicle/industrial/forklift-ff65087c-7f96-4f21-86b7-2961d526ab19
- https://www.cgtrader.com/free-3d-models/vehicle/industrial/empilhadeira-tipo2
- https://www.cgtrader.com/free-3d-models/vehicle/industrial/empilhadeira-tipo1

- Acessórios:

- https://www.cgtrader.com/free-3d-models/exterior/street/street-stuff
- https://3dwarehouse.sketchup.com/model/1b613e79fbbab43e8f9af5e060686079/Industrial-Stairs
- https://3dwarehouse.sketchup.com/model/4d7a83aa9577fe6d48896752ab35e09a/Industrial-Lamp
- https://3dwarehouse.sketchup.com/model/5977348d-6797-4bb3-925c-4092d6e03c28/Industrial-Stairs
- https://3dwarehouse.sketchup.com/model/abd992a4-7960-494e-9fbb-c0e0820ea88b/Pagar-Mezanine-Rak
- https://3dwarehouse.sketchup.com/model/928faf6d-9af6-413d-9bfb-2125478b8fc3/Rak-Gudang-Heavy-Duty-DC-70-dan-92
- https://3dwarehouse.sketchup.com/model/93676a35f6164bbd6d431f3195ee60/cart
- https://3dwarehouse.sketchup.com/model/bd15233b4cba19470aae756cc53df8d/Laundry-cart
- https://www.cgtrader.com/free-3d-models/vehicle/other/roof-rack-with-bmx-and-mtb-bikes
- https://3dwarehouse.sketchup.com/model/a81f2eb59aa74327bdd16fd7155acdb1/Side-Draft-Booth

- Componentes:

Guidão:

- https://3dwarehouse.sketchup.com/model/318da7bb342d2c9140354de72db8b/Road-Bicycle-Handlebars
- https://3dwarehouse.sketchup.com/model/736a50aa35fe0ec0c6dfda20d2c6e35b/OS-handlebars
- https://3dwarehouse.sketchup.com/model/u33b03f5d-d260-450c-b5c8-5ff453889a68/mtb-Handlebar-Stem-Grips-Kore

Garfo:

- https://3dwarehouse.sketchup.com/model/449b92aed0b34e3c838a897adae56e19/Marzocchi-123-Bicycle-Forks-All-Mountain
- https://3dwarehouse.sketchup.com/model/fc625d7156f9ffb560b68c5ceaae3478/GT-front-fork
- https://3dwarehouse.sketchup.com/model/u95eb518c-df3d-42b6-9458-cb6d19aa2a85/mtb-fork-Fox
- https://3dwarehouse.sketchup.com/model/d1169f4095987951154a7d071a78d1e0/Rock-Shox-Mountain-Bike-Forks

Aro:

- https://3dwarehouse.sketchup.com/model/c13a4b9cbbaaee5a6d76ee5875eb8214/Bicycle-Wheels

- https://3dwarehouse.sketchup.com/model/u21a53709-aea8-43cf-91a8-7781b285d776/27-bicycle-wheel
- https://3dwarehouse.sketchup.com/model/e15adfc4d741442961b45661cf44dea2/Home-made-Bicycle-Fat-tire-Rims
- https://3dwarehouse.sketchup.com/model/d8b83ed729d703e2bcd908f2d1daff4a/BMX-Wheels

Corrente e Pedal:

- https://3dwarehouse.sketchup.com/model/d4f421d44cc88a279140354de72db8b/Bicycle-Drive-Train

Acessórios:

- https://3dwarehouse.sketchup.com/model/u75567254-938f-4c76-8bfa-5cfb2bc72187/BC-BIKE-BOX-BENCH
- https://3dwarehouse.sketchup.com/model/d0eb002ae9c09da92550edc9205ed105/spy-part-1
- https://3dwarehouse.sketchup.com/model/58175659-aa7b-4b35-a6cd-1921a3faaa3c/Point-Supported-Glass-Wall
- https://3dwarehouse.sketchup.com/model/eeaf11d997157b8dca27bba175814d1/tool-wall
- https://3dwarehouse.sketchup.com/model/4c0d57ba-7d78-45ce-b22e-b6f7667653ee/Workshop-Wall-Display
- https://www.cgtrader.com/free-3d-models/industrial/tool/conveyor-belt
- https://www.cgtrader.com/free-3d-models/industrial/tool/vacuum-forming-machine

ANNEX 5 – RELATION OF INDUSTRIAL SCENES AND INDUSTRY 4.0

IS IT INDUSTRY 4.0 RELATED?

SCENE 1 – INTEROPERABILITY & SUSTAINABLE GROWTH (INCREASED SENSORIZATION, LOCAL PROCESSING, MACHINE DECISION MAKING)

Product
Speed reducer (outer shell is cast, holes are drilled with CNC centers).

Process
Drilling the holes on the reducers´ outer shell, so that the ball bearing can be put in place for axis assembly. Operation takes place in a CNC center, on a CNC manufacturing cell.

Problem
Several problems related to part's quality (such as dimensional variation outside the specified tolerances and increased roughness) due to milling tool's deregulation /wear and tear. These quality problems are only verified when the quality control of the operation is performed, through the Statistical Process Control (SPC). However, then it's already too late and only corrective measures are possible. Usually those measures are replacing the milling tool, discarding or reprocessing the defective parts (when possible). This situation also implies that the machine must be set up all over again.

Consequences
Nowadays, it's kind of hard to identify that the tool is wearing, which means that only after the defective parts start popping up at our SPC that we realize the tool needs changing. This also implies that we need to completely stop the production process to change the machining tool on the CNC center, which takes a significative amount of time. We also have a high number of defective parts that cannot be refurbished or reprocessed thus increasing our waste of raw materials and resources.

Industry 4.0?
As discussed in the last meeting not that much for the sensoring part, but the decision on the substitution of the drill made by the machine as well as the cascading system of actions that it starts are more directly related.

Brainstorming on the problem
So the machine detects some extra force while milling, sees if it is within the acceptable change and if not calls for a replacement (that can be made by either humans or machines). It has to decide when to stop if the replacement takes too long, and also keep monitoring (perhaps there was some imperfection in a given part that made it harder or any other external reason). When the replacement is

done, the drill is evaluated by a human worker. These assessment results are added to machine replacement entries so it can use learning algorithms to understand the different problems of the drills wearing off by associating them with sensor signature. This data can then be used (to change the drilling speed, select a different tool, make changes in the process, rearrange the production order so that the drills wear off more evenly....)

Decisions:
Regarding Operation:
- Frequency and sizes of control batches (SPC)
- Frequency of maintenance
- Tool availability

Improve the system:
- Wear-out detection (increased sensorization, learning algorithms)
- Failure Prediction (simulation, increased sensorization, learning algorithms)
- Maintenance time (machine calling maintenance/ augmented reality maintenance)
- Tool durability
- Setup simulation (systemic algorithms, full virtual twin, increased sensorization)

Game idea:
Utilize the gambit sequence to define the machine behavior as to decide the best tactic. the addition of sensors may add new possibilities that further optimize the solution. - *Too complicated. Learning outcome is more related to visual programing than to I 4.0.*
The user decides the frequencies of the control batches versus the frequency of the maintenance and hits play. A report appears (with graphical representation on the side) showing the expenditure in maintenance versus the cost of control and the financial resources available to the user are increased. With these resources he or she chooses an improvement and hits play again.
Learning outcome: Identifying the most critical problem in each situation and deciding what improvements (I 4.0 related) are best for the identified issue. Make use of a simulator (one of the improvements) and make sense out of production data.

Iteration 1: Simulation accuracy 45%, available initial data: 0
Iteration 2: Simulation accuracy 70%, available initial data: 1 Iteration
Iteration 3: Simulation accuracy 78%, available initial data: 2 Iterations
Iteration 4: Simulation accuracy 81%, available initial data: 3 Iterations
Iteration 5: Simulation accuracy 82%, available initial data: 4 Iterations

Figure 1 - Example of speed reducer

Figure 2 - Example of CNC Center

SCENE 2 – VIRTUALIZATION & MAINTENANCE (DIGITAL MAINTENANCE AND ASSEMBLY TOOLS)

Product

Geared Reaction Turbines (complex products, subject to project-specific design).

Process

Maintenance processes after installation and operation of the geared reaction turbines at the clients' facilities. Usually sugar cane processing plants for alcohol production.

Problem

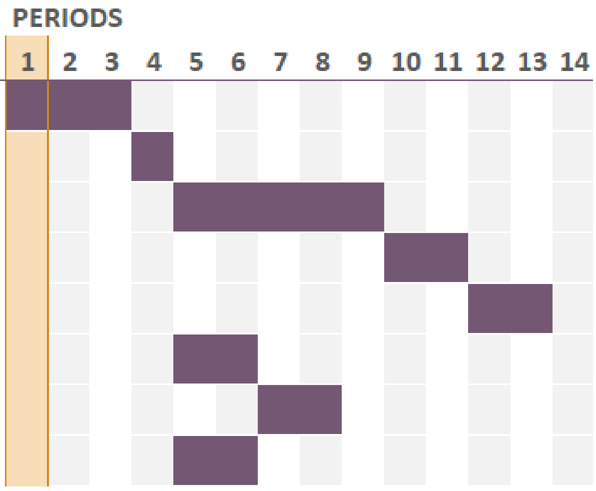
We design and build geared reaction turbines for continuous processes at sugar cane processing plants. Each geared reaction turbine is unique, extremely complex. Recently, we developed a new strategy to offer our product as a service; clients can contract the use of the turbine and only the actual time they spend using it is charged from them (availability based model). This should work for us too, however we are having some troubles in the maintenance and assembly processes of the turbines, Our workers, even the more experienced ones, complain that assembling and maintaining the turbines is very difficult, due to its distinct characteristics from each equipment and client. Furthermore, we assessed that they lose a lot of time searching for the instructions on how to perform the maintenance and sometimes, even when they find those, the instructions contain mistakes. Documentation is hardly always up to date.

Consequences
This situation is extremely critical for us, once that each minute that the geared reaction turbine is not operating is one less minute of earnings due to hour availability-based billing model. We also must pay fines if the downtime of the equipment exceeds the previously agreed on 10% which happened sometimes. Needless to say, that this impacts directly our financial bottom line and thus need to be addressed asap. Therefore, we want to improve our maintenance process efficiency and efficacy. We hope Industry 4.0 can help us in this. Some of the repair pieces, of unique format can be printed.

Industry 4.0?
The solution includes the usage of a distributed maintenance service network as well as local manufacturing companies for the production of maintenance parts. This maintenance network personnel would have seen the specific equipment before, but with the use of augmented reality with the blueprint of the equipment maintenance incorporated can be capacitated on the spot.

Brainstorming on the problem
A machine breaks or is having some issue and a maintenance worker is called, travel to the location then may require no part, a normal part or a custom made one. In the event of a custom made one, there may problems with internalization, delaying the operation potentially for months. The workflow is as follows:

ACTIVITY	PLAN START	PLAN DURATION
Worker Travel	1	3
Inspection	4	1
Produce Part	5	5
Receive Part	10	2
Repair - Ct Part	12	2
Receive Part	5	2
Repair - St Part	7	2
Repair	5	2



So, there can be improvements in the travel time (by creating a network of workers or capacitate on the spot).
On the inspection, through augmented reality and digital assisted repair tools for that machine
On the production time and receive time by creating partnerships with the local manufacturing companies (Challenge 2a).
And repair through augmented reality and digital assisted repair tools for that machine.
-Digital assisted repair tools can include diagnostics based on sensor data or image processing, maintenance processes and checklist for that specific machine, a visual representation of the data highlighting the possible key points for the defect...
Decisions:
Using the Gantt chart the user may make decision on the selection of solutions for each steps, considering the costs and benefits of each to decrease the stopped time. The interface then would be the Gantt chart for the player to make decisions.

Figure 1 - Reaction turbine example

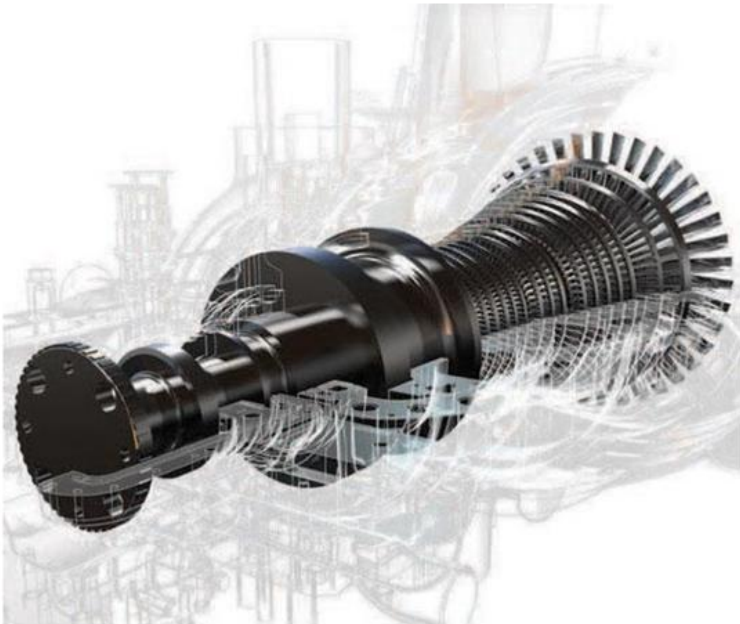


Figure 2 - Geared Reaction Turbine example

Extension: The same factory may hire local companies to produce the replacement parts:

SCENE 2a – VIRTUALIZATION, SERVICE FOCUS & MAINTENANCE

Product

Geared Reaction Turbines (complex products, subject to project-specific design).

Process

Since each product is one of kind, some of the key components are produced specifically to a given machine, as such when a defective part is detected, the piece´s project has to be retrieved produced, shipped and then assembled. The time wasted in such event can be enough to justify paying an external company to produce the part locally to accelerate the maintenance and avoid even longer waiting times due to customs and internalization issues.

SCENE 3 – REAL TIME CAPACITY & MARKET OPPORTUNITY (PROPOSAL DESIGN - DATA INTEGRATION)

Product

Automotive parts (large quantity, subject to project-specific design, just in time).

Process

Most of the orders the company takes are based on tight scheduled designs that when delivered require a production proposal for a preset and challenging deadline. To meet this demand, the engineers have to check with multiple suppliers their prices and delivery deadlines/schedules (from raw materials to production molds), take the values they have and estimate the ones that do not come timely, assess the capacity of the production line to meet the deadline and estimate the cost. While there are estimatives on the production volume, they may change due to the market reception of the final product.

Problem
Normally to respond to a client's' request it takes on a average a week to factor in all the relevant costs, a process which has frequently to be redone as changes in the project, quantities and deadlines occur. The time it takes for our suppliers to send us their proposals is often too long to deliver the proposal fast enough, meaning that estimates have to be used with some frequency.
The longer it takes to get the project approved, the less time there is to accommodate the order in the assembly often resulting in higher costs. Apart from that, a quicker response helps the client to plan and make changes in the design phase and estimate its final cost.

Consequences
Taking around a week to deliver the proposal means that frequently before it is send a part of the project is changed and the the proposal has to be rewritten. It also means that less time is available for producing the parts. Considering the time it takes for our suppliers to deliver us their own proposals, many times estimates results in error, which may lead to reduced competitiveness as well as loss of money. Our intention is to use I 4.0 to decrease the time needed and increase the reliability of our proposals.

Game/Challenge Ideas
The player has access to a type of Gantt chart containing all the steps in order to create a proposal and can act on these steps to automatize them, assign supervisors and negotiate contracts with suppliers as well as data access partnerships. The player may wait for the all the steps to happen and deliver an accurate response, or may use estimates for part of the proposal for the few last steps. After every proposal the player receive resources to further improve the proposal making process and reduce the time.

Industry 4.0?
This idea relates to industry 4.0 learning through two aspects: technological, and horizontal integration. The improvement in the proposal creation steps will be related to industry 4.0 related technologies. For a line it may be the incorporation of the virtual twin in the process (which may be divided), for a client a direct communication between their ERPs and the company´s, for the engineering steps might be negotiating a closer participation (via a virtual environment, for instance) between their engineers and sofort.

Define required conditions
Collaboration.

SCENE 4 – MODULARITY & PRODUCTIVITY (AUTOMATED SELF ORGANIZING TRANSPORT)

Product
Metallic thermal treated parts
Process
The current format of production is a functional layout and the parts are batched and sent for the next step where they are manually allocated to the next process. The main difficulty is the manual transport between different stations, the lack of optimization of the transport lines, the accumulation of parts in some of the steps and the difficulty dealing with more than factor regarding the next step.

Problem
This problem becomes more prominent in the thermal treatment stage where the furnace is constantly underused to meet time constraints. Rushed orders constantly must be placed in the furnace without using its maximum capacity since finding other products in with the same thermal treatment in the queue would be too time consuming. This leads to further delays in the other orders production leading to a vicious cycle.
Despite the all attempts to avoid these emergency rushes; little progress has been made in this regard.

Consequences
The processes are often delayed, the scheduled production almost never works and there is a lot of confusion among employees on what to do when the next step is unexpectedly crowded. The usage of some machines are very low and others work 24/7 despite the consultancy work made to balance production capacity.

Game/Challenge Ideas
This project would allow the intelligent selection of parts and transport for the next steps that is capable to respond immediately to changed requirements, the order being decided on the spot to decrease production time. This can be used integrated with other equipment.
The player would be introduced to the factory with all these problems and will implement the priority of the transport order to get the best results. From time to time an order will be rushed, changing the entire movement dynamic. The player will be able to implement two main changes – the transport system itself and the possibility of hiring externally some of the thermal treating process. The products that were sent to external thermal treatment will have a higher cost and will have to be reincorporated in the line.

SCENE 5 – REAL TIME CAPACITY & MARKET OPPORTUNITY (AUTOMATED PROTOTYPING STATION - DECREASE PROTOTYPING TIME - BATCH SIZE 1)

Product
Notebooks, tablets or cell phones.
Process

Currently the prototyping steps takes a long time to be in production available format. After deciding on a new equipment configuration, the parts are assembled in a prototyping case, the drivers and programs installed, and testing is made in these conditions normally inside the production team and with other employees. With a new product release much feedback is gotten from internet forums and social network and the development team keeps working on improvements.

Problem
From the correction of the issue until a functional prototype that can be sent for external testing similarly to the large-scale version, it takes weeks. This means that the consumer will have access later to the improved version, decreasing the innovation impact of the changes and the perceived quality of the product.

Improvement
One highly customizable line exclusive for prototyping with small batch sizes that allows for prototypes to be created in a matter of hours. Coupled with enhanced supplier connection to enable this accelerated process.

Game Idea
Again the process remodeling based on simple Gantt chart is used to illustrate to the player his decision steps toward the next phases.

Script 4.1 - Self organization transportation systems between production steps

Product: Generic Part

Company: Parts producer (try to find a real case)

Task: The current production layout is functional and the parts are batched and sent for the next step where they are manually allocated to the next process. The main difficulty is the manual transport between different stations which makes it more difficult to changes in sequencing, the lack of optimization of the transport lines, the accumulation of parts in some of the steps and the difficulty dealing with multiple factors regarding the next step.

Current Situation (problem): This problem becomes more prominent in a stage where the equipment is frequently underused due to difficulties in ordering the materials when a specific order has to be rushed. Rushed orders constantly must be placed in this stage without using its maximum capacity since finding other products in with the same process parameters in the queue would be too time consuming. This leads to further delays for the next batches leading to a vicious cycle.

Despite the all attempts to avoid these emergency rushes; little progress has been made in this regard.

The processes are often delayed, the scheduled production almost never works and there is a lot of confusion among employees on what to do when the next step is occupied. The usage of some machines are very low and others work 24/7 despite the consultancy work made to balance production capacity.

Challenges:

1. To create an automated transport system for a single step where materials have to be batched, that can optimize itself around real time constraints and changed orders
2. To create a method to finding, organizing and accounting for the orders in this machine allocated production order (digital twin)

To achieve these two results, the transporting machines will have to coordinate themselves to find and move the orders between steps (like amazon system) and will need to assess the current position of the different parts. This type of transportation system behaves like a live road where instead of cars we have parts. The routes between the processes will also change to accomodate the transport machine movement patterns.

Gameplay:

The game consists of two clearly defined phases, planning and iterating.
In the planning step the time is stopped (the factory machines are not running) and the player makes most of his decisions like accepting and refusing orders, placing these orders in the production schedule (this is how the sequencing and production planning would be implemented in the scene), allocate workers and decide on improvement projects.
The Iterating phase represents an accelerated version of a production period (a day, a week, a month...). In this steps the player sees the consequences of his or her actions while having a limited set of decisions representing quick fixes that may be used in industry, like overloading machines and extending the iteration duration with extra hours. Using any of these will have consequences (namely, a higher chance of machine breaking, added costs, decrease workers satisfaction/ other indicators). Emergency decisions can also generate a decision prompt, such as a machine breaking, clients saying they will cancel their orders, and working accidents among others.
The player also has access to research the implementation of improvements for his factory. Once an improvement is researched it means that the player has now access to new processes, transport system or other functionalities. For example to put an automated conveyor on the production floor, this “research” step represents the industry effort to find supplier, check compatibility with the current installation and plan the implementation. As soon as this is ready the player can look at the results (estimated benefits and cost) and decide whether the project is going to be implemented or not.

ANNEX 6 – SECOND PROTOTYPE INITIAL GAME SCRIPT

Later Recycled for use in the bicycle factory 4.0

Script:

Before first iteration:

For this prototype there are initially two processes with no connection. . After a brief introduction (with the details and specifics on the case, like industry, market and product) the player has to set up the connection between them using workers.

1. Introduction - Shows the factory and briefly explains the scenario
2. Link processes - Ask the player to click on the link between processes and choose how it will work. When the player starts he is prompted by a tutorial message to create the link. By clicking on the link location (between the processes) a list of possibilities appear, all greyed out (or hidden) except the manual transportation. This lack of choice at first serves two purposes, showing how to interact with the link and instigating curiosity about the other options. After setting the link the player will be able to click the worker to set how it will behave, in this case either by getting as many products as available or waiting to fill the transport capacity.
3. //Define the order - the player is responsible for the production sequence
4. Run iteration (Ok)

Iteration 1

1. Message with a new order (good price and feasible due date, for training players how to accept new orders)
2. Message asking the player to choose a new improvement project
    1. Player selects either “automated conveyor” or “sensorized process”
    2. When the player mouses over each more information is given, such as the benefits, which new options would be opened, and the cost forecast.
1. Player has now access to the “Urgent measures option” to use during the iterations (not in the planning phase) such as “extra hours” and/or overloading processes.

Iteration 3

1. The research project is concluded and the player can now either improve the process or implement an automated conveyor in the production floor.
    1. If the player does not “buy” the improvement nothing changes. So far the player has only unlocked this project.
2. The player selects another project (in the prototype the only other available)
3. At the end of this iteration the player compares his result with previous iterations.

Iteration 4-5

1. The second project is concluded and in iteration 6 is the last to be shown in the first prototype.

Where the learning happens?

By experiencing the changes that implementing I 4.0 related projects cause in the assembly line. More specifically the solutions offered to the player will increase the level of decision made by the machines decentralizing the decision making.

With the description of the projects research and implemented steps. Both their description and benefits will be as much as possible connected to the literature on the topic.

By viewing the incorporated help (containing text, audio and videos) on the discussed topics.

By comparing in game the industry before and after the implementation as well as relating them to the design principles.

By seeing visual representations of abstract improvements such as the virtual twin and the machine decision making.

In the next sections texts in **gray** represent ideas that we will not be able to implement for the next prototype but are planned in the game.

Resources:

- Capital
- Client Relationship
- Available projects (techs)
- Available equipment

Game Loop:

- Respond to game messages (see Table 1 and Figure 1) - When an iteration finishes, the player will have to make decisions on all the occurrences of that iteration.
- Select improvement projects - What will be the task of the research personal. This will not imply that the company is developing the technology, but actually searching for solution suppliers and studying how to incorporate it in their production.
- Decide production order logic - The player is the responsible for the production sequencing. She or he has to use whatever methods to optimize this sequence (Kanban, lean…). At first the player must do it manually but as he complete more improvement processes, automatic sequencing based on different parameters will become available.

- Select Links and Processes to improve - The player can buy, change or improve links between processes and processes themselves based on the available choices (can be increased with the development of new improvement projects)
- Take urgent measures - The only action a player can make during a given iteration is to take urgent measures (Table 2). These measures account for real industrial practices and they are useful for the game to allow the player to do more than watch during iterations.
- Decide allocation of workers - workers can be sent to operation floor or to P&D. The more people on P&D, the faster the technological improvements are achieved.

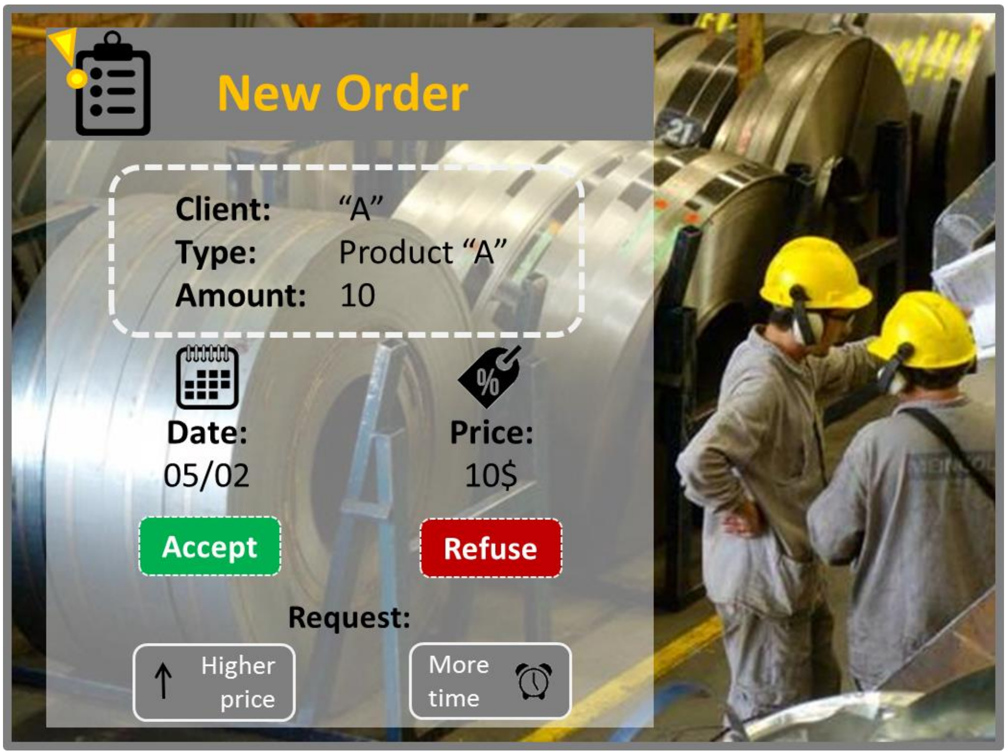
Table 1 - Game Messages.

Message	Description	Goal	Trigger	Choices
Tutorial message	Explains/Shows some game mechanic	Help the player master the tool	Scripted	Varies - “Place the first link between the processes” “Select a worker and assign it to a process.
New order	Presents a new order opportunity with a price, due date and client name.	Allow the player to see new orders coming and deal with them	Conditions are met (e.g. a given date, good env. KPIs, good relationship with client...)	Accept; Refuse; [Request higher price]; [Request more time]; ...
Order delayed	Warns the player that in the last iteration an order has been delivered late. Shows the decrease in the relationship with the client.	Give feedback to the player and update him on his relation with clients	Order delivered late	Ok (close message); [Offer discount]

Project completed	Warns the player that a research project has been completed and the player may have new options	Elucidates the consequences of completing a given project	Research completed	Ok (close message); [See changes]; [Choose new project]

[Optional]

Figure 1 - New order message.



Since the client cannot postpone the date, this option is not available and is grayed out.

Table 2 - Urgent Measures.

Name	Description	Effect
Work Extra hours	Make the shifts longer in order to produce more	Costs money and increase the duration of an iteration. Can also decrease worker satisfaction.

Overload machines	Use a process with a higher capacity than its nominal	Increase machine speed; or capacity. Increase chance of malfunction. Cost money.

Concrete benefits (which KPIs are going to be controlled in the game)

Primary:

- Total income;

Unit/partial/total and variable/fixed costs

- Customer relationship;

A rating system similar to the stars in amazon reviews that represent the customer satisfaction with the industry. If the rating falls below three the client stop placing orders. On the other hand a higher rating may attract new clients and more orders from the same client.

- Waste

- Average Wage

Solution including ind 4.0 (define in items as if it were the solution tree > effect over KPIs and virtual factory mechanics):

Intelligent conveyor

- Allows the player to instal a conveyor that communicates to a process (in the actual game it will be further up in the tree, but to exemplify in the prototype it will be the first)

Sensorized process

- Makes the process more reliable by measuring more variables internally (given that the bottleneck here is in transport, this option will not provide much benefit, and is used as a placeholder) - this lack of benefit is a design decision for this case since we want the player to identify that the critical issue in this case is the transportation line.

Tag System:

- Decrease some processes time (e. g. retrieval processes);

- Establish partnerships with more accessible suppliers;

- Acquire machines and equipment that are intelligent and better suited to the processes;
- Increase efficiency and logistics integration with suppliers and customers;
- Provide training to IT staff to develop new applications;
- Scan more physical processes;

How to score:

Group of parameters that together define the final score and a possible ranking.

Suggestions:

- Resources occupation;
- Deliveries on time;
- Profit;
- Overall client relationship
- Inexistence of interruptions in production;
- Extension of the current client list;
- Current status of sustainable manufacturing;

In game Screens:

Full:

1- Factory floor graphic representation - This is the main screen for the player to interact with the challenge. Contains visual representation of the machines, transportation systems, environment and workers

Decisions:

- Sequence Logic
- Improve Processes and Transportation Systems
- Decide on Process and Transportation System Logic
- Select Urgent Measures
- Start Interaction

2- Digital Twin mode - overlays the factory floor mode to show the information that is present in the digital twin.

Decisions: The same as in the Factory floor screen. This mode is used to show the information available to the player as the digital self of the factory is built. To represent the vision we are using of industry 4.0 it is important that the player uses the screen, meaning that information that contributes to the decision making must be placed here.

3- Improvement Projects - Contains the improvement projects and their descriptions. Each description must be clear about the context, industry 4.0 relation (with sources) and in-game benefits of this project.

Decisions:

- Next improvement project
- Resources allocated to the next projects (not sure. perhaps it would be interesting to allow the player to invest more or less aggressively in the improvement projects. This can lead to a meaningful tradeoff between the idealizing projects and actually implementing them)

4- Business Overview - shows statistics (define which) regarding the production, the customers and the industry finances.

Decisions: Many ideas are possible to be implemented here (change prices, take actions to improve relations with a customer…). Initially it is only a feedback screen to show the player how his company is doing.

5- Learning Room - this is a common room for all the scenarios where we can place information regarding industry 4.0, be it in video, audio, animation, image or text format.

Partial and Pop Up:

These interfaces only occupy a portion of the screen and will be described regarding when they appear, what information they hold and what decisions they contains.

Client

Appear: clicking a client representation in the interface

Information and Indicators: current relationship level with this client; total orders delivered; orders delivered late; purchase total, how long has been a client.

Decisions: Initially none. This can be useful in other scenarios to illustrate different relations business models with given clients, make offers, take actions to improve relations, build data bridges, among others.

Process

Appear: clicking a process (machine, workbench…) representation in the interface

Information and Indicators: Running time; how many products have been processed in this process; total cost of the process: standby cost - cost of keeping the process on; processing cost - cost derived from working on products; maintenance time; time waiting for resupply; breakdown count.

Decisions: Sell back or replace for another process type - opens the Process selection interface.

3-Maintenance

Appear: clicking a client representation in the interface

Information and Indicators:clicking a client representation in the interface

Decisions:clicking a client representation in the interface

4-Storages

Appear: clicking a client representation in the interface

Information and Indicators:clicking a client representation in the interface

Decisions:clicking a client representation in the interface

4-Transport

5-Entry Logic

6-Transport Logic

7-Dialog Box

portrait, name, text.

8-Decision Box

text. Exp.

9-Process Selection

10-Transport Selection

11-Message Pop-Up (Done)

Appear: clicking a client representation in the interface

Information and Indicators:clicking a client representation in the interface

Decisions:clicking a client representation in the interface

ANNEX 7 – SELECTION OF PRODUCT TO CREATE THE LEARNING VIRTUAL FACTORY

Industrial Context for the Learnstrument

Production Context 0 - Bike Manufacturer

The player starts in a small custom made bike manufacturer. This manufacturer uses body measurements and customer profile to design an tailored frame, fork and stem. Then, with the customer, the manufacturer decides the premade components and assembles the final product. Currently, all the workers are capable of participating in any of the production steps.

The player is responsible for increasing the business by getting access to industry 4.0 improvements. The concept would be to keep the number of workers constant while using augmented reality and new machines to increase their efficiency and automation for the task which it can perform better. The factory would also like to offer partial customization services, e. g. starting with a standard frame and just painting and assembling.

From design to production the manufacturer has the following workflow:

1 - Taking the customer's body measurements for ergonomy;

2 - Decide with the help of a bicycle expert what type of frame he or she wants from 3 different options (all the people working in the factory are trained to help the clients);

3 - The frame, fork and stem is resized to match the clients' measurements and the project (paper and cad file) is sent to the production facility;

4 - The client decides on the components he or she wants, these are not custom made, they are bought in the common market, so the custom made bicycle is compatible with of the shelf components of the right size (wheels, saddle, cassette, chainring…);

5- The external components are ordered. The material to build the frame is normally in stock (carbon fiber or aluminium). [Decide only one because the production process is different]

Steps of production involved:

Production Step 1 - Tailoring the tubes (the substeps are described below) followed by Brazing, welding, and/or gluing;
Production Step 1a - Aligning, cleaning and *Add tag;
Production Step 2 - Finishing the custom made parts [Customizable step that uses the tag to define the final painting]. This process has more than one alternative: Painted, Chromed, Chromed + Painted;
Production Step 3 - Assembling the premade components.

*Requires tag system improvement to be used.

Steps development:

Step 1 - Tailoring the tubes, Brazing, welding, and/or gluing

- Manually made with mechanic machines;
- Automated machine with human led control;

- Automated machine connected to the customer orders able to group similarly shaped parts to decrease set-up time.

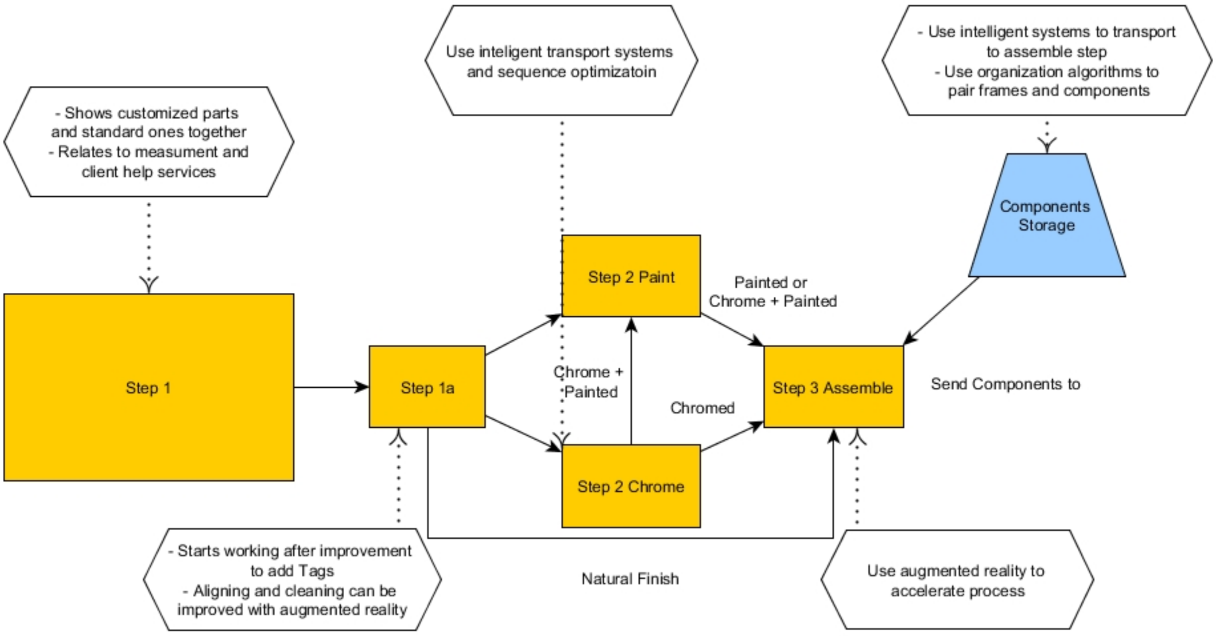
Step 1a - Aligning, cleaning
- Manually made with measurement tools;
- Manually made with augmented reality glasses.

Step 2 - Finishing the custom made parts
- Manually finished;
- Automated finish.

Step 3 - Assembling the premade components
- Human made with mechanical tools. The assembler has to pick up the parts in the stock;
- Human made with digitally improved tools. The components are automatically separated for this frame;
- Human made with augmented reality tools and connection to the system to deliver a fine tuned bicycle for each client (saddle height, air pressure). The components are carried by a robot transporter and taken to the processing spot for faster assemble.

In summary, Figure 1 shows the flow of these stages of the bicycle production process.

Figure 1 - Stages of the production process.



Production Step 1 (breakdown):

- **Tailoring the tubes**
  1 - The metal is annealed, or softened by heating, and hollowed out to form

"hollows," or "blooms." These are heated again, pickled in acid to remove scale, and lubricated.
2 - The hollows are measured, cut, and precision mitered to the appropriate dimensions. Frame sizes for adult bicycles generally run from 19-25 inches (48-63 cm) from the top of the seat post tube to the middle of the crank hanger.
3 - Next, the hollows are fitted over a mandrel, or rod, attached to a draw bench. To achieve the right gauge, the hollows pass through dies which stretch them into thinner and longer tubes, a process called cold drawing.
4 - The tubes may be shaped and tapered into a variety of designs and lengths. The taper-gauge fork blades may have to pass through more than a dozen operations to achieve the correct strength, weight, and resilience.

- **Brazing, welding, and gluing**
  5 - Tubes can be joined into a frame either by hand or machine. Frames may be brazed, welded, or glued, with or without lugs, which are the metal sleeves joining two or more tubes at a joint. Brazing is essentially welding at a temperature of about 1600°F (871°C) or lower. Gas burners are arranged evenly around the lugs which are heated, forming a white flux that melts and cleans the surface, preparing it for brazing. The brazing filler is generally brass (copper-zinc alloy) or silver, which melt at lower temperatures than the tubes being joined. The filler is applied and as it melts, it flows around the joint, sealing it.

Production Step 1a

- **Aligning and cleaning**
  6 - The assembled frames are placed into jigs and checked for proper alignment. Adjustments are made while the frame is still hot and malleable.
  7 - The excess flux and brazing metals are cleaned off by pickling in acid solutions and by washing and grinding the brazing until it is smooth.
  8 - After the metals have cooled, further precision alignments are made.

Production Step 2

- **Finishing the custom made parts**
  9 - The frames are painted, not only to create a more finished appearance, but also to protect the frame. The frame is first primed with an undercoat and then painted with a colored enamel. Paint may be applied by hand-spraying or by passing the frames through automatic electrostatic spraying rooms. The negatively charged frames attract the positively charged paint spray as the frames rotate for full coverage. Finally, transfers and lacquer are applied to

the frame. Chrome plating may also be used instead of paint on components such as the fork blades.

Read more:
http://www.madehow.com/Volume-2/Bicycle.html#ixzz5Bb30cJTe
https://paginas.fe.up.pt/~projfeup/cd_2012_13/files/REL_1M8_01.PDF

Brainstorm - ideas that we may use:
- Show the service of counseling the client and allow the player;
- Divide as to the custom, the production lines between unitary demands and larger lots. Such larger batches refer to the demands of specific customer groups, such as professional racing, which may require a type of sprint bike, for example (would allow the player to interfere with timing, resource, operator, and also regarding the transportation of the products emphasizing the factory layout);
- Measure the level of customer satisfaction in relation to the customization made in the product, as well as the ergonomic service provided to personal needs, such as: convenience, speed, lightness (would link to the level of customer relationship);

Advantages:

It is simple example to implement in an initial version that allows for expansion encompassing many key elements that we wish to discuss.

This example fulfills all the aforementioned characteristics and lends itself beautifully to customization and services due to ergonomy issues. It may connect, even if only as a description of the process, to health professionals with a 3D scanner creating the measurements of a bicycle that would best suit needs of client, configuring a customizable demand for each. Then these special orders would be added to production queue and when ready, delivered directly to the client.

The first step can also include some altered version of additive manufacturing and premade frames sharing the same line.

Later a production step may be integrated incorporating electronic elements for work station chairs, like in built monitors or speakers and so on.

- **Production Steps that allow the dynamic introduction and removal of operators (human or machines) -** In this scene the assembly of the moveable parts and frames could use the same type of operator, having more than one operator in each step;
- **An industry that has products with a diverse set of production steps -** Some chairs would need moveable parts, others not, some might be a single block without cover and so on;
- **Products that reasonably allows the production of small lots and customizable products -** Here they can be done according to a given customer description, like competition teams, bike shops, rental companies for small batches or be custom made based on body measurements;
- **Production Steps are physically visible -** 3D models just have to be separated into the production components for this. e.g. a chair would have to be divided into structure part, arms part, seat and so on;
- **Production steps that require resupply, frequent maintenance or break often -** All the steps have this characteristic;
- **Product graphic 3D models should be easily available -** Many companies provide their chairs freely in the 3D warehouse;

- **At least one production step that require set-up when changing the steps parameters -** This can probably be represented in each of these steps.

Production Context 1 - Chair Manufacturer

In this context we would the example of a Chair due to the ease of perception of the components of a customized request.

Production Step 1 - Frame;
Production Step 2 - Stuffing;
Production Step 3 - Moveable Parts;
Production Step 4 - Digital and Electronics ad-ons (this step would be added at a later stage);
Production Step 5 - Cover.

Advantages:

It is simple example to implement in an initial version that allows for expansion encompassing many key elements that we wish to discuss.

This example fulfills all the aforementioned characteristics and lends itself beautifully to customization and services due to ergonomy issues. It may connect, even if only as a description of the process, to health professionals with a 3D scanner creating the measurements of a chair that would best suit needs of client, configuring a customizable demand for each. Then these special orders would be added to production queue and when ready, delivered directly to the client.

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- **An industry that has products with a diverse set of production steps -** Some chairs would need moveable parts, others not, some might be a single block without cover and so on;
- **Products that reasonably allows the production of small lots and customizable products -** Here they can be done according to a given customer description, like restaurants, offices, for small batches or be custom made based on body measurements;
- **Production Steps are physically visible -** 3D models just have to be separated into the production components for this. e.g. a chair would have to be divided into structure part, arms part, seat and so on;
- **Production steps that require resupply, frequent maintenance or break often -** All the steps have this characteristic;
- **Product graphic 3D models should be easily available -** Many companies provide their chairs freely in the 3D warehouse;
- **At least one production step that require set-up when changing the steps parameters -** This can probably be represented in each of these steps.

Production Context 2 - Electronics Industry

In this context we would the example of a notebook, cell phone or tablet assembly line.

Production Step 1 - External shell and motherboard assembly;
Production Step 2 - Internal components placement (Ram, HD and so on);
Production Step 3 - Keyboard Assembly;
Production Step 4 - Screen Placement;
Production Step 5 - Packing and Delivery.

- **Production Steps that allow the dynamic introduction and removal of operators (human or machines) -** Steps 2 (Internal components placement (Ram, HD and so on)) and 3 (Keyboard Assembly) would allow multiple operators in the same production step;
- **An industry that has products with a diverse set of production steps -** Notebooks and tablets in the same line would represent this, with tablets skipping the keyboard step;
- **Products that reasonably allows the production of small lots and customizable products -** Traditionally, due to high volumes of production, these lines are specialized. Given the amount of parts, the justification of the production system is that it includes only special orders;
- **Production Steps are physically visible -** Difficult to visualize in this step because not all components of the product can appear visibly, which makes it difficult for the player to see the custom production;
- **Production steps that require resupply, frequent maintenance or break often -** All the steps have this characteristic;
- **Product graphic 3D models should be easily available -** Easy to get or to make models, normally basic shapes + images;
- **At least one production step that require set-up when changing the steps parameters -** Step 1 (External shell and motherboard assembly) is the most suitable for this.

ANNEX 8 - DEVELOPED CHALLENGES BASED ON THE INDUSTRIAL EXAMPLES (MEDIA/MARKETING)

Title	**Description** *(macro)*	**Design Principles Involved**	**Envisioned Solution Design Principles**	**Envisioned Solution Technologies**
In process monitoring of tool wear	To monitor tool wear during the machining operation in order to avoid waste from producing defective expensive parts through the application of in process sensors and intelligence to change the tools when needed.	*- Decentralization;* *- Interoperability.*	Using localized intelligence the machine can monitor sensors related to its operation to measure in process the wear/tear of the tool and within given parameters decide on how to act. Through connections between equipments, the machine can coordinate its actions to stop other machine or call for a replacement in an attempt to optimize the reaction.	*- Smart Sensors;* *- Advanced Algorithms;* *- Cloud computing and analytics.*
Maintenance process for one-of-a-kind products	To improve efficiency and efficacy of maintenance process for one-of-a-kind products through digitalization, augmented reality and local producers.	*- Virtualization;* *- Service Orientation;* *- Decentralization.*	The solution includes the usage of a distributed maintenance service network as well as local manufacturing companies for the production of maintenance parts, using augmented reality in resolution.	*- Augmented reality;* *- Advanced Human machine interfaces;* *- Smart sensors;* *- Big data and analytics.*
Proposal time consumption reduction	Decrease the time to produce a reliable proposal based on integration with suppliers and customers.	*- Service Orientation;* *- Real-time Capability.*	The resolution envolves through two aspects: technological, and horizontal integration. For a line it may be the incorporation of the virtual twin in the process (which may be divided), for a client a direct communication between their ERPs and the company´s, for the engineering steps might be negotiating a closer participation (via a virtual environment, for instance) between their engineers and sofort.	*- Multi Level customer integration;* *- Cloud computing.*
Self organization transportation systems between production steps for thermal treated parts	The main difficulty is the manual transport between different stations, the lack of optimization of the transport lines, the accumulation of parts in some of the steps and the difficulty dealing with multiple factors regarding the next step.	*- Decentralization;* *- Virtualization;* *- Real-time Capability;* *- Interoperability.*	To achieve these two results, the transporting machines will have to coordinate themselves to find and move the orders between steps (like amazon system) and will need to assess the current position of the different parts.	*- Sensors;* *- IoT Platforms;* *- Cloud computing.*

Title	Description *(macro)*	Design Principles Involved	Envisioned Solution Design Principles	Envisioned Solution Technologies
Highly flexible prototyping station for consumer electronics	From the correction of the issue until a functional prototype that can be sent for external testing similarly to the large-scale version, it takes weeks. This means that the consumer will have access later to the improved version, decreasing the innovation impact of the changes and the perceived quality of the product.	*- Virtualization;* *- Modularity;* *- Interoperability.*	This line will need a high level of modularity and flexibility to incorporate new technologies and products as fast as possible, using for that new technologies and incorporating external testers while acquiring usage data.	*- Sensors;* *- IoT Platforms;* *- Cloud computing.*
Waste processing machine as an connected Product Service	A company that produces machines to recycle solvents and diluents migrating form a sell or monthly rent with the opportunity to use direct connection to customer machines to improve their service.	*- Decentralization;* *- Virtualization;* *- Interoperability.*	The engineer assigned to improving a product will have data available from test sensors and operators. The product improvement has a relation not only to the available data, but to the algorithms on transforming that data into something useful.	*- Smart Sensors;* *- Advanced Algorithms;* *- IoT Platforms.*
Protecting workers from Hand Arm Vibration Syndrome via Sensorization	To increase worker´s safety by detecting, and acting on, the level of exposure to potentially harmful vibrations.	*- Real-time Capability;* *- Interoperability.*	Incorporate the vibration exposure as limited resource for the works, monitor and respond to it in real-time while reorganizing the processes to finish the required tasks.	*- Smart Sensors;* *- Vibration Sensors.*
Fast detection and solve problems	Orders are collected by the sales industry, are posted to the system and must be delivered on the combined dates. The company works with 3 shifts and 5 machines that manufacture pet bottle caps. Each pet cap mold (water bottle and coolant) has 32 wells. The process of injection and confection is 7 seconds.	*- Decentralization;* *- Real-time Capability.*	The biggest problem faced is cavity clock. When this occurs the machine operator needs to be aware to notice and then check the number of the cavity that is with the problem. (all cavities are listed 1-32). Much time is wasted on this problem. The idea was that the machine warned and did not depend on the operator for this.	*- Smart Sensors;* *- IoT Platforms.*
Using 3D Technology to Accelerate Processes	British manufacturer of Rolls-Royce aero engines is preparing to use 3D printing technology to produce components for its engines. Today, the production of some parts can take up to 18 months due to the tooling process involved.	*- Virtualization;* *- Service Orientation.*	3D printing technology can shorten this process considerably and also makes it possible to manufacture lighter parts.	*- 3D Printing;* *- Augmented reality;* *- IoT Platforms.*
Virtual Training	In Brazil, Embraer began training in virtual 3D what workers would do on the factory floor one year before production began. The project had 12,000 hours of testing before the aircraft took off. Defects that would normally only be detected with the airplane in the air were resolved during the preparation phase.	*- Decentralization;* *- Virtualization;* *- Real-time Capability.*	On the assembly line, workers use computers and tablets with augmented reality technology, and if in doubt, there is always a video to explain how to perform the operation. With all the gains from scanning, the assembly time has already dropped by 25%.	*- Augmented reality;* *- IoT Platforms.*

Title	**Description** *(macro)*	**Design Principles Involved**	**Envisioned Solution Design Principles**	**Envisioned Solution Technologies**
Disposal, storage or reuse of waste	A considerable amount of industrial waste generation, these tires having defects in their structure (bubbles), which do not meet the quality requirements and, consequently, the external demand, resulting in the accumulation of waste. ***- What to do with the waste generated?***	- Decentralization; - Virtualization; - Service Orientation.	Using the concept of circular economy, the defective tire lot will undergo a process of removal of the steel, which can be sold, so that the rubber can be converted into fuel for industrial furnaces through asphaltic composition.	*- IoT Platforms;* *- Machine-to-Machine Integration.*
Interruption of the Internet	Failure to transmit information to machines in a custom packaging industry, due to the interruption of the availability of the internet, making it difficult or impossible to receive input on customer demands. ***- How to deal with the lack of internet?***	- Decentralization; - Virtualization; - Real-time Capability.	Seek to make contact with the internet provider to identify and resolve the failure and verify the possibility of obtaining the internet through another transmission network, or to trigger the simultaneous system of receiving and sharing of information that acts offline.	*- Big data and analytics;* *- IoT Platforms;* *- Cyber security;* *- Cloud computing.*
Absence of energy	Lack of energy in the dairy industry that produces yogurts, so much of their processes are compromised, such as the refrigeration process, since the production, transmission and consumption of energy distributed in different locations do not work together to meet demand of each client with the minimum environmental impact and lower cost. ***- What resources are available when there is no power?***	*- Decentralization;* *- Virtualization;* *- Modularity;* *- Real-time Capacity.*	To achieve energy efficiency, an intelligent secondary power plant can choose the best between import, production, storage or release of energy, using renewable energy resources, selecting energy conversion technologies. It is necessary that the industry 4.0 has a highly effective generator that self recharges while the primary energy is being used in the development of its activities.	*- Human-to-Machine Integration;* *- Machine-to-Machine Integration;* *- End-to-end Integration;* *- IoT Platforms.*
Wrong design of production systems	The textile industry requires that its production processes ranging from the preparation of the fabrics to the final finishing are carried out in such a way that customer orders, manufacturing time, cost of production and, in particular, the movement and execution of each stage of the manufacturing process. These issues involving the transport of fabrics in the factory plant, using machines, require the development of several models of statistical simulation and optimization analysis, which are not well established. - How to optimize production by arranging your lines?	*- Decentralization;* *- Interoperability;* *- Virtualization;* *- Modularity.*	It is necessary to construct a model that reflects the current manufacturing processes and that allows to prove methods of optimization. This automated model uses customer demand data and creates a manufacturing process database for an ad hoc simulation model. One of the results of the model and method in the optimization task is to reduce the distance of the product path through modifications in the factory layout. Although changes in manufacturing processes occur, integration of simulation software, ancillary applications, and databases is required.	*- Smart Sensors;* *- Advanced Algorithms;* *- Big data and analytics;* *- Cloud computing and analytics;* *- IoT Platforms.*

Title	**Description** *(macro)*	**Design Principles Involved**	**Envisioned Solution Design Principles**	**Envisioned Solution Technologies**
Inefficiency of the manufacturing process	Inadequate planning of key issues regarding the manufacture of refrigerators, covering several components of different sizes, with different functions, and varied assembly time for each stage. The productive processes are slow, flawed and involve significant resolution complexity. Due attention is not paid to the large number of products and the manufacturing processes they involve, nor to customer order data. - How to integrate the activities and the time of production?	*- Decentralization;* *- Virtualization;* *- Modularity.*	It is necessary to automate the stages of construction of the products, and to present solutions that allow at the same time a high personalization through the availability of data by the clients, considering the requirements of time, cost and industrial expertise, integrating common points shared by all manufacturing systems, supply chain, storage, transportation and logistics.	*- Smart Sensors;* *- Advanced Algorithms;* *- Cloud computing and analytics;* *- IoT Platforms;* *- Multi Level customer integration.*
Failures to transmit information	The virtual systems of information transfer in relation to the internal and external demands of production in an industry that produces Medium Density Fiberboard (MDF) and do not provide complete and automatic data to the machines, thus compromising the deliberate operational planning. ***- What to do when there is no systemic continuity of communication in production?***	*- Virtualization;* *- Real-time Capability;* *- Service Orientation.*	Operational manufacturing simulation models require a high degree of modeling detail and rely on a significant amount of input data. When these inputs do not occur there is imbalance in the activities of inventory reduction and cost savings and monitoring of operational risks. The industry needs to encompass a system that provides information to model the manufacturing line, such as workstation details, roadmaps, material bills, change plans, manufacturing orders, stock levels, material data, etc.	*- Big data and analytics;* *- Cloud computing and analytics;* *- IoT Platforms.*
Lack of quality control	Due to machine failures, they have begun to produce high-scale ceramic floors batches not suited to external demand, and the quality-checking process is late, which in many cases has already resulted in an extensive waste volume. ***- What alternatives are there to measure quality in the event of failure to verify the vQM system?***	*- Decentralization;* *- Virtualization;* *- Modularity.*	The concept of Virtual Quality Management (vQM) considers, in addition to the information provided from all machines and products, environmental factors that may have a potential influence on the product. Industry 4.0 needs to have a potential vQM system that offers the opportunity to test and optimize virtual process chains before actual processes are set up at the factory, and that it has accurate prognoses, improved quality seal of each product through the process production tolerances, incorporating manufacturing tolerances.	*- Augmented reality;* *- Smart Sensors;* *- IoT Platforms;* *- Simulation.*

Title	**Description** *(macro)*	**Design Principles Involved**	**Envisioned Solution Design Principles**	**Envisioned Solution Technologies**
Inefficient communication with suppliers	Operational failures in virtual planning systems and requisitions of materials for the manufacture of agricultural machinery occur, not informing in a timely manner the updating of demands to suppliers, so that the industry acquires unnecessary components, thus increasing the total cost of the productive processes and raising sales prices to the final consumer. ***- How to simultaneously update requests made based on customers' real-time demands?***	*- Decentralization;* *- Virtualization;* *- Real-time Capability;* *- Service Orientation.*	Through an optimization system the industry needs to be attentive to the demands with high possibilities to cover aspects of individualization and customization of the products. In the same way that the systems of the suppliers and all the stakeholders involved must be continuously interconnected, so that any minor update that is reflected in the systems of all parties involved.	*- Big data and analytics;* *- Cloud computing and analytics;* *- IoT Platforms;* *- Simulation.*
Difficulty of regional adaptation	Many applications in the paper industry are directly linked to local legislation and local businesses that do not provide the necessary conditions for production, since custom products often require specific capabilities and regional manufacturing needs. ***- How to handle the regional requirements for installation and industry activity?***	*- Decentralization;* *- Virtualization;* *- Real-time Capability;* *- Service Orientation.*	In addition to seeking agreement between the needs of the industry and the local aspects of a given region, the industry through scanning should seek to increase the effectiveness in its horizontal value chains by working efficiently within a global manufacturing network to provide components, fundamental products and systems.	*- Big data and analytics;* *- Cloud computing and analytics;* *- IoT Platforms;* *- Cyber security.*
Obstacles to digital culture	The employees who previously performed their activities in their respective areas of activity had the same remodeling based on the design principles of the industry 4.0 and have now to live in an environment with a high index of digitization. ***- How to make employees feel good in a new highly digitized environment that may or may not be common or enjoyable to them?***	*- Decentralization;* *- Interoperability;* *- Virtualization.*	Without the proper establishment of digital culture and its training to deal with it, the talents present in industry 4.0 may not want to stay. In this way, industries need to keep and train their employees to work comfortably in a digital environment. All of these need to work with digital knowledge and skills, willing to work with new technologies and learn new ways of operating.	*- Big data and analytics;* *- Cloud computing and analytics;* *- IoT Platforms;* *- Augmented reality;* *- Simulation.*

ANNEX 9 – BICYCLE FACTORY 4.0 FORM FEEDBACK

Form feedback on the Learnstrument “Bike Factory 4.0”

Objective: This questionnaire aims to determine the level of learning acquired regarding the context of Industry 4.0, your confidentiality is guaranteed, the objective is to consider your contributions to improve our learnstrument.

* Required

We want to know more about you, our participant! Please inform us about:

1. Player's name: *

2. Age: *

3. Nationality: *

4. Occupation: *

5. Institution: *

6. Experience with Industry 4.0: *

Mark only one oval.

- Specialist
- Beginner
- Moderate experience
- I do not know anything about industry 4.0

7. 1) From this game experience, how much did you learn about Industry 4.0 and related concepts? *

Mark only one oval.

- I have learn much;
- I learned something;
- A little;
- Nothing or very little.

8. 2) Your previous knowledge on Industry 4.0 is aligned with the content expressed in the learnstrument? *

Mark only one oval.

- Yes, it's very much aligned;
- Yes, it is aligned. I was already familiar with all concepts presented in the learnstrument;
- It's somewhat aligned. There are some points which are distinct from what I have already knew;
- It is not aligned. The learnstrument presents different contexts from my previous knowledge;
- I had no previous knowledge on Industry 4.0.

I

9. 3) Regarding the manner in which the principles of Decentralization, Virtualization, Interoperability, Modularity, Real-Time Capability and Service Orientation, specific to industry 4.0 have been expressed, answer us: *

Mark only one oval per row.

	Very good	Good	Regular	Unsatisfactory
They were expressed clearly, and I was able to understand their relevance to the new industry	◯	◯	◯	◯
The observed reality is very much in keeping with the real opportunities of industry 4.0	◯	◯	◯	◯
The changes in the processes, making them more dynamic and connected are perceived clearly	◯	◯	◯	◯
The visual resources for the presentation of the design principles are adequate for each step	◯	◯	◯	◯

10. 4) What was your level of motivation troughout the game? *

Mark only one oval.

- ◯ Very motivated;
- ◯ Motivated;
- ◯ Slightly motivated;
- ◯ I was not motivated.

11. 5) What motivated you most during the game? *

Mark only one oval.

- ◯ The layout of the factory and its digital version;
- ◯ Deliberate the production of both types of bicycles;
- ◯ To be able to acquire an integrated technological improvement for a certain process;
- ◯ Track the key performance indicators of the game.

12. 6) Regarding gameflow from start to finish, please tick: *

Mark only one oval per row.

	Very good	Good	Regular	Unsatisfactory
Number of shifts				
Frequency of iterations				
Number of messages on screen				
Time in activity (playing)				
Time without activity (not playing, just watching)				

13. 7) In general, what level of attention did the game demand? *

Mark only one oval.

- High level;
- Significant level;
- Medium level;
- Low level.

14. 8) Please rate the features of the game in relation to your contribution to your complete experience. *

Mark only one oval per row.

	Very good	Good	Regular	Unsatisfactory
Objectives of the game	⬭	⬭	⬭	⬭
Support tools	⬭	⬭	⬭	⬭
Panel	⬭	⬭	⬭	⬭
Interface	⬭	⬭	⬭	⬭
Factory layout	⬭	⬭	⬭	⬭
Improvements screen	⬭	⬭	⬭	⬭
Learning room	⬭	⬭	⬭	⬭

15. 9) With regard to possible confusion during the game, please report: *

Check all that apply.

- [ ] I was confused about process windows;
- [ ] I did not quite understand how to get improvements for the factory;
- [ ] I did not understand how production performance was expressed;
- [ ] When an onscreen alert came up I did not know how to proceed;
- [ ] I did not feel confused at any moment.

16. 10) The content of learnstrument is: *

Mark only one oval.

⬭ Very good, it covers all relevant aspects of industry 4.0 and its full potential, contributing fully to learning about it;

⬭ Good, it includes real aspects of industry 4.0 that contribute to learning about it;

⬭ Regular, some characteristics of the industry 4.0 are presented, but superficially, contributing subtly to learning;

⬭ Unsatisfactory, since it has no aspect related to industry 4.0 and does not contribute to learning.

17. 11) How much did you enjoy playing the game? *

Mark only one oval.

- I enjoyed a lot, it was very fun to play it and the situations that required quick decision did not seem heavy, boring or difficult to solve, were motivating;
- I enjoyed it, while playing it was fun, and the real situations seemed to be simple yet engaging enough;
- I slightly enjoyed it, in some moments the game was monotonous and I did not feel so motivated;
- I did not enjoyed it; the game was not fun, during the stages I got tired and did not want to finish it anymore.

18. 12) In the context of Industry 4.0, do you believe that the game contributed to improve your understanding of and/or to develop one or more skills? *

19. 13) Your perception of our learnstrument is very important for us! Would you like to tell us more about your views/suggestions/complaints about the game?

20. 14) Would you like to know the results of our research or participate in it in the future? Please leave us your e-mail address!

Thank you very much for your participation and collaboration!