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Making Complexity Fun—Machining Procedures in Mechanical Engineering*

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Gamification can be defined as the development of playability of an object or a situation that was not initially playable. When it comes to learning machining procedures in mechanical engineering, the game appears to be an effective way to handle procedures' high level of complexity. Through the study of the serious game Mecagenius, we shall defend the thesis that gamifying the acquisition of cognitive and technical knowledge allows its complexity to be better grasped and matters to be simplified, on one hand by the use of gameplay mechanics, on another hand by leveling several types of complexity in multi-layers game levels. Encouraged to try and involved by the level design, we will show how learners handle more and more complex operations.

Keywords: machining; training; learning game; gamification; complexity; mechanical engineering

1. Introduction

Gamification is defined as an operation aimed at rendering an initially unplayable object or situation playable, by incorporating game-specific codes and mechanisms [1, 2]. By using game mechanisms in this way [3], gamification aims to increase both users' involvement in carrying out an activity, and their ability to problematise and resolve the problems put to them. Gamification thus seems to be an appealing method of involvement for facilitating learning.

When considering the area of manufacturing, gamification has a special resonance. Currently, teaching manufacturing generally depends on an occupation-based approach where knowledge comes with experience. This approach is effective but requires many teaching hours and involves many practical case studies due to the high-level complexity of the tools and machines. In addition, teaching manufacturing is now highly controlled given the risk of mistakes and the associated budgetary implications (for example: tool breakages, repurchasing tools, materials). Thus, gamification seems to be an interesting approach for both helping the student acquire experience by testing a large number of solutions, as well as offering him a gradation in the difficulty of cases tackled [4].

In this article, we aim to study the learning of Numerical Control Machine Tools (NCMT) and machining processes in the learning game Mecagenius (http://mecagenius.univ-jfc.fr/). To our knowledge, Mecagenius is the only serious game existing both in engineering education and relative disciplines such as electrical engineering or electronics engineering [5]. Instead of several simulators already on the market, Mecagenius is not intended to increase performativity in manufacturing process but to increase learning performativity. Played by more than 700 students from high school to Engineering Schools since 2012, the serious game is characterized by a progressive learning scenario framed by explicit game landmarks. In this article, we will focus more specifically on the case of learning manufacturing processes. The aim of this module is to define and then sequence the different machining operations that will allow a student to obtain a part which complies with the specifications, from a blank. In order to develop our argument, we will base ourselves on the game called PF6 "machining procedure", the aim of which is to gradually break down the reasoning and handling stages so

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that one can acquire the complex know-how for manufacturing turned parts. At the end of the game, the student must be able, based on drawing specifications, to define and sequence the different operations needed to obtain the requested part. The choice and sequence of these operations is called the machining procedure. One can use several possible procedures to manufacture the same part, adding to the complexity.

Complexity characterises the scientific and technical knowledge of modern societies [6–8]. In the case of learning manufacturing processes in mechanical engineering, we will focus on the way in which the complexity of knowledge is "brought into play" in Mecagenius. By extension, a serious game will be defined as learning software comprising many elements belonging to several categories of different games, organised and connected through numerous hierarchical interactions. We will argue that learning complexity through games constitutes an added value with regard to traditional teaching [9, 10].

First of all, we will study how to reduce the complexity of different parameters based on the game called PF6 "Sequence of operations", allowing a student to match an operation to an image representing a surface machining process. Then, equipped with these pre-requisites, we will show how learners are encouraged to handle new, more complex operations, choose a tool suitable for the operation to be carried out, and then sequence the different machining processes by using sprites so as to obtain a manufacturing process.

2. "Sequence of operations": an example of activity shell in Mecagenius

2.1 Work environment

Mechanical engineering is characterised by high-level technicality in learning how to handle Numerical Control Machine Tools (NCMT) and machining processes [11, 12].

Traditionally, one learns this knowledge and know-how through frequently going back and forth between traditional theoretical classes and practical work in the workshop with machine tools. These methods aim to promote learning through the direct handling of tools, machines and parts. Nonetheless, this time-consuming and costly operation assumes the learner already has a good grasp of this knowledge and does not allow for it to be completely and freely experimented with. In fact, the risk of making operating errors is considerable during this stage, when technical know-how is being acquired and the financial consequences of breakages are high. Therefore, learners have very little room for making mistakes and one often notices teachers adopting strategies to avoid these risks; for example, by reducing the amount of time spent in the workshop and by limiting training to machines which make simple parts. In addition, it is common practice for a machine to be reserved for the experienced teacher, restricting learners to being spectators of the handling process. In light of the increasing complexity of machines, which multiply the number of possible machine procedures, the trainer thus requires a pedagogical tool which is suitable for encouraging the learner to understand and then handle a set of complex items of knowledge [5, 13]. Training through repetition, without risk of breaking the machine or wasting material can be considered as a mechanism which reduces the complexity for learners.

2.2 Presentation of the serious game Mecagenius

Mecagenius is a Learning game, in other words, a serious game geared towards training [14]. Its purpose is to help a person discover a mechanical engineering workshop by playing, teach him to use Numerical Control Machine Tools (NCMT), then make him understand how to optimise production. It can be accessed online and can thus be used for classroom or distance-learning training. It is suggested for an audience ranging from those in vocational training to students at schools of engineering.

Mecagenius is designed as a video game both to make a field with a poor image more fun and attractive, and to make training in machine procedures and NCMT use easier and more progressive [15]. Mecagenius uses traditional video game codes. It displays an experience bar, advancing levels, a score bar or money won. There is also an inventory allowing one to manage resources and a talent tree, allowing a character's skills to be strengthened according to the player's strategy. The game begins by displaying a unique graphic identity of blues and greys in a futuristic universe, framing a Welcome Screen showing a crushed spaceship on the surface of an unknown planet (Fig. 1).

The game's scenario allows one to understand that this is the Ingenius spaceship, with a young engineer of the future, travelling through space in stasis and suddenly woken by alarm bells warning him of an imminent crash. Alone on the surface of a deserted planet, the character must repair his spaceship in order to leave. The game is made up of three levels (beginner, intermediate and expert). Each level comprises three successive rooms connected by doors which must be unlocked, thanks to prizes won during the different missions. These missions are mini-games (more than 210 mini-games spread out over the three levels of difficulty) featuring specific mechanical engineering skills. The scenario of the game means a player must, by means of pre-requisites (prizes, levels, etc.); make progress in the

Fig. 1. Mecagenius' welcome screen.

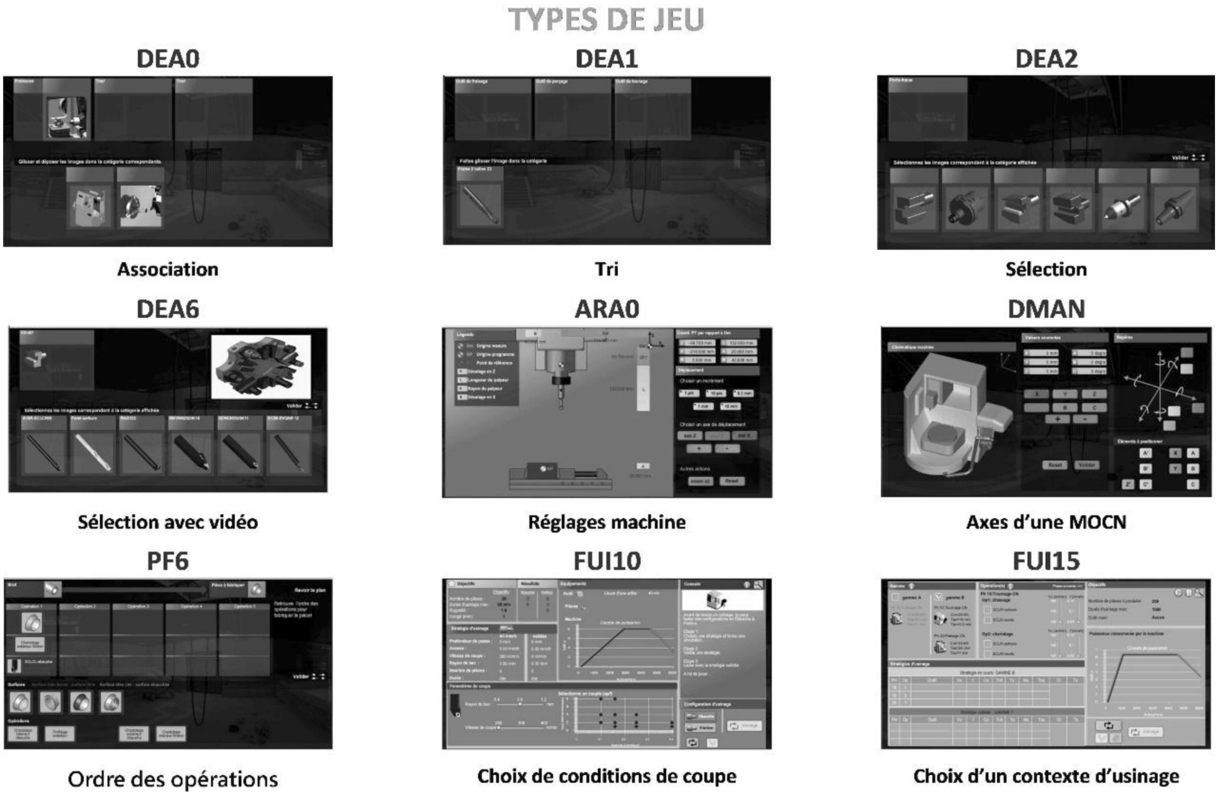

Fig. 2. The 9 mini-game models available in Mecagenius. TYPES OF GAME (from left to right): Matching, sorting, selection, selection using video, machine adjustments, MOCN axes, sequence of operations, choice of cutting conditions, choice of machining context.

level of difficulty and skills he has acquired. These mini-games, or micro-activities, are used throughout the 9 game models (Fig. 2), each one representing the cognitive activities needed for carrying out a specific task. The pictures below do not clearly show the game's 9 models. It would be preferable to make entries based on cognitive action categories.

Some models (DEA0, DEA1, DEA2 and DEA3) are based on interaction methods using drag & drop and corresponding to mini-games for matching, sorting or selecting. Other models (DMAN, FUI0, FUI5, ARAO) are based on interaction methods which make it possible to simulate the cognitive activity specific to learning mechanical engineering. PF6, for example, allows one to define and sequence machining operations by using sprites. This is the mini-game model on which we shall focus in the rest of this study.

The games based on this model are thus aimed at training the player in defining and following the process needed to obtain a finished part. As mentioned above, in the context of learning in the workshop, this process is characterised by a set of cognitive stages, including recognising surfaces to be machined, choosing the operations able to generate these surfaces, sequencing these operations and selecting suitable tools. According to the level of difficulty chosen by the player at the start, the "PF6" activity presents levels of increasing difficulty, corresponding to the different levels of complexity encountered by the learner during his training.

The training needs required prior to carrying out this activity in the game are therefore those of more traditional mechanical engineering learning: list of surfaces to machine, choice and sequence of machining operations able to generate these surfaces, selection of suitable tools. As such, the game aims to be incorporated in a broader pedagogical framework, supporting theoretical learning without for all that doing away with the need to master knowledge. Lastly, completing PF6 activities can take between several seconds and several minutes, according to the student's skill in resolving the problems put to him. Unlike other activities proposed by Mecagenius, PF6 is not timed and does not require a problem to be solved by the learner within a set time. The lack of timing to carry out PF6 is particularly important to the way in which the learner performs the activity. In fact, the game provides him with the opportunity to consult online help, carry out tests and try different combinations for laying out the sprites. Hence, the game activates the learner's ability to reflect on the completion of his own work, rather than on his skill in successfully completing a task quickly. The lack of timing thus provides information about a first skill to be acquired by playing PF6: the game suggests solving a problem using an iterative process, combining successive trial and error and encouraging the learner to consider the operations and their sequence as a whole. The aim of the game is thus not to be able to set up the production of a part *as quickly as possible* but to consider the best way of producing the part and optimising production.

2.3 Gameplay mechanics

In order to understand the mechanisms of the game, one should pay particular attention to the gameplay offered to the player. Gameplay is the game's grammar; an integral part of the more general design of the game called game design [16], and refers to all the actions the player is allowed to perform. In other words, gameplay determines the set of interactions made possible between the player and the game itself. By extension, gameplay is designed as the game's rigid structure, all of its rules, within which the player's experience will unfold [17].

The gameplay of PF6 is classic drag & drop, displaying a screen with a list of items and set of empty boxes. In the "Beginner" mode, there are two types of item, one showing the part's surface, the other proposing operations ("straight turning", "parting off", "profiling", "facing"). The student must therefore, using a mouse, drag the surface illustrations as well as operation names to match them (drop). The aim of the game is first to correctly match the operation which will generate the surface, then to sequence the operations needed to make the required part; facing, straight turning, profiling, and parting off. As from the "Intermediate" level, the player must, in addition, choose the tools suited to each operation, by using their standardised trade name. Throughout the exercise, different visual indicators inform the student-player which of the answers he has provided are right or wrong, so that he can correct them and successfully complete the exercise. Help is permanently available to remind the player of the selection criteria. At the end of the game, a message tells him whether he has won or lost. Lastly, in case of victory, the message displayed specifies whether the solution retained is optimal or if it could be improved.

The first levels focus on the association operation/generated surface. Therefore, no tool must be chosen. The player must then correctly sequence the operations. At each stage, he can open a help tab, focused on his problem, which will give him the selection criteria. In the second stage, the player has to in addition, choose the tool for each operation. The number of operations suggested in order to generate the surfaces is also much larger. For each operation, he must choose a type of tool and then define it precisely. Since the player can fail in different ways (Fig. 3), at each stage, the help tab always provides the selection criteria if needed.

In order to play, the learner begins filling in an answer by laying out the different items available to him in the empty boxes, then by confirming his choice. Following confirmation, the game will highlight in green the correct parts of the layout, and will highlight the incorrect areas in red. The challenge therefore lies in the learner's ability to correct his answers before running out of lives, and by doing this, finding the correct answer. The use of colour codes used in schools and in learning software standardises right or wrong answers.

If the gameplay offered to the learner is the fruit of this consideration, operating upstream of the game's development, what is offered to the teacher is an online "teacher's kit", listing all of the activities

Fig. 3. Different ways of failing PF6 in Mecagenius. First due to operation/ generated surface generated mismatch, then to sequence of operations.

in the game, each of which includes a detailed record of its content: the instructions given to the learner, pedagogical issues to be worked on, different characteristics inherent to each level of difficulty or even the skills the learner will have to master in order to successfully complete the activity. Furthermore, a search can be entered using a mini-game model, according to categories in Mecagenius, or according to the skills of the Ministry of Education benchmark. All of the processes are graphically connected in order to provide the teacher with an overall view of the pedagogical progression in the game. As Mecagenius was being designed, designers had to review in detail which knowledge and skills needed to be offered to the learners in the context of learning in the game and outside it. In this regard, designers had to detect the grey areas that exist when learners carry out machining procedures in the workshop. In other words, the game was designed to identify learners' difficulties, meaning problematic issues in acquiring knowledge as well as different mistakes made when handling this knowledge, so as to reduce the areas where errors occur and where there is uncertainty linked to machining a part.

3. Generating complexity through levels

3.1 Moving from beginner to expert mode

The pedagogical difficulty increases according to the level of the game. As mentioned above, in the gameplay mechanics, only two parameters were proposed to the player at the beginner level (matching surface and operations) and the tool parameter came into play at the intermediate level. The level of the game operates to reduce complexity.

The difficulty also increases within a level, according to the player's experience. Operations become more complex, the notion of machining internal and external surfaces is introduced (not clearly specified). In addition, the number of operations offered for machining the same surface increases, which multiplies the number of choices available to the player. Lastly, the choice of tool also becomes increasingly complex. Whereas choosing the type of tool is enough at the beginning of the intermediate and expert levels, at the last level of difficulty, the player must choose a type of tool, choose its standardised designation (Fig. 4), and then select a type of insert to use with the tool-holder (corner radius; roughing or finishing).

In other respects, Mecagenius remains a game activating conventional game mechanisms and problem-solving methodologies, typical of this genre. The pedagogical difficulty, which is an ordinary stage of learning [18], increases with the difficulty of playing. That is to say, that whilst the knowledge to be acquired to complete the game becomes increasingly refined and substantiated, other difficulties of the game itself are added to make it even harder to complete the activity. Thus, the number of lives available at the beginning of the exercise goes from four in beginner mode, to only two in expert mode. Once these lives have been lost, if the learner has not managed to sequence the operations correctly, choose the correct tool, or has failed to recognise the different designations, the player loses. Lastly, whereas before red and green graphic indicators allowed the learner to correct himself whilst carrying out the activity, these indicators disappear in expert mode. In light of the large number of choices possible and with many more items to handle, the learner's margin for error in completing a more complex activity is therefore considerably reduced in expert mode.

3.2 Multiple complexity

In order to understand and define complexity as it is presented in Mecagenius and in mechanical engi-

Fig. 4. PF6 in beginner, then expert mode in Mecagenius.

Levels of difficulty of mechanical engineering learning
Knowledge of operations and surfaces they can generate
Identification of types of tools, their geometric shape and therefore their function
Technical name of all standardised technical tool references
Methods of interacting with the game, and items offered above empty boxes
Playful methods: reducing the number of lives and increasing game levels

Fig. 5. Division of learning to manage complexity.

neering learning, one must begin by summarising in greater detail the cognitive operations asked of the students. We previously saw that, according to the level of difficulty, the three skills the learner must master are "match", "sequence" then "select". Therefore, the instructions given by the game at the beginning of the activity state; "*You must make one of these parts; you have at your disposal a machine, a blank and a set of tools. In order to do this, you must recognise the operations and then put them in order.*" These instructions play a significant role regarding how Mecagenius uses complexity for pedagogical purposes.

In fact, the learner is asked to *recognise* operations so as to sequence them, whereas the teacher's kit provides information about the three skills mentioned above. There is a difference between these skills, resulting from mastering theoretical knowledge studied, and the skill of *recognising*, based more on a skill unrelated to mechanical engineering and used to complete the entire activity (recognising tools, blueprints or even the tools' technical names). It is in fact precisely the difficulty in *recognition* which increases with the difficulty of the game, whereas the know-how regarding "sequencing, assembly, selection" is fine-tuned according to the level of learning. It therefore seems that the playful use of Mecagenius is understood to be the player's ability to use the skill of recognising different items before running out of lives, a skill that is even specified in the exercises' description.

In this way, we understand how the game dissects complexity into several segmented complexities, according to whether they are pedagogical or playful, but also how the game allows these multiple complexities to be solved by connecting them using a cross-cutting skill that falls outside the context of mechanical. Thus, one can identify five levels of difficulty in the game once the surfaces to be machined have been identified. All of these levels of difficulty effectively require the player to be able to *recognise*, a skill cutting across the entire game, the items in order to handle them and solve all of the problems put to him (Fig. 5).

4. Gamification of multi-layered complexity

4.1 Maintaining guidance parameters through a game

As a system of rules, a game is an area of contingency generating "interpretable outcomes" [19, p. 96]. In fact, when carrying out activity PF6, the game experience is therefore defined by handling knowledge through several cognitive operations, but also by the possibility that the learner might be faced with failure. One of the game's purposes is in effect to allow mistakes to be made, without for all that causing considerable material or financial losses, or wasting time in the workshop. Although this advantage is easily understood from a material point of view, from a pedagogical point of view, the game's advantage is of not stigmatising mistakes and even encourages them to be made in the problem-solving process [20, 21]. The aim of repeating trial and error, not punished by marks given or material breakages, is to play down the operation, encouraging the student to practise until he can thereafter do it easily and quickly. Indeed, the graphic indicators for correct and incorrect answers allow the learner to make attempts then to correct himself before succeeding, with or without using the help online. Although the playful format of learning is not new, the recourse to video game mechanisms makes it possible to handle knowledge in a new iterative way.

It is easier to imagine in this way how the video game provides guidance parameters for the completion of the learning activity. On the one hand, truly playful methods establish the rules of the game and those regarding how the activity must be completed, rules within which, strictly speaking, the learner lets the game unfold. Thus the learner uses his knowledge and cunning to solve the problem put to him: respecting the number of lives given and winning the items provided by the game in case of victory (a cog to move forward in the game, or a small amount of Mecagold, the game's currency). On the other hand, the way the game is built establishes parameters for and directs learning. Therefore, the game's script or even the graphic and sound-based universe in which the learner is invited to project himself—a room on a spaceship with a silent and futuristic background—, contribute to changing the activity from simply machining, to contextualising it in a narrative that is different from classroom reality. In other words, the player is encouraged to ''do things as if'' [22] he were no longer the learner of mechanical engineering, but an engineer of the future, lost in space and alone responsible for the success of the mission. The use of a game metaphor thus encourages the learner to carry out a machining activity which does not explicitly reveal its pedagogical aim, unlike a simple MCNT simulator.

Although the learners are aware of the aim of the game being proposed to them, we notice that using playful guidance parameters a first in the gamification of complexity. In fact, at the same time as the different levels of complexity become increasingly diverse and standardised as the level of the game increases, the playful framework decreases to give room for more realism. For example, in expert mode, the red and green graphic indicators disappear and the number of lives available before completing or failing the activity is reduced. Because the level increases, the part taken up by the complexities inherent to the process of machining takes up an increasing amount of room in the game, to the detriment of the playful metaphor. In other words, the increasing difficulty is expressed by getting markedly closer to the machining activity in the game and in the activity in the workshop, and thus by a reduction in the playful metaphor. The game contributes to building the player's confidence, thus contributing to overcoming difficulties of comprehension.

4.2 Encouraging and involving

We understand in this way how the game enables the gamification of a multiple activity: by setting parameters for complexity via the playful structure, and thanks to the game's ability to encourage the player to solve the problems raised by this complexity. Games are ''half real'' [23 p. 164], built by designers as ''well-structured problem'' [23 p. 8] involving and guiding the player by the use of metaphor. As we have broached the characteristics which establish the guidance parameters of the activity inherent to the video game, we should also report on the guidance characteristics more related to the briefing. In fact, because the development of Mecagenius has been systematically tracked for knowledge and areas of uncertainty as these are handled, the video game provides, during the course of the game, a set of briefings and debriefings informing the learner, a posteriori, about his experience. Firstly, before the activity begins, what we have so far called *instructions* include important information on the activity the learner will have to complete: the instructions themselves of course, but also the elements at his disposal at the beginning of the activity, a standardised technical blueprint explaining the part to be machined, as well as arrows linking the different items to make it visually easier to understand the activity to be completed. We also noted that the screen also provides the learner with information regarding the number of lives he has (Fig. 5).

This first screen, before the activity begins, is thus more of a briefing than instructions, presenting the learner with the set of elements that are useful for carrying out an exercise in a real workshop. Similarly, whereas the ''pass'' type of debriefing screen simply congratulates the leaner on having managed to repeat the operations in the right sequence, the ''fail'' type of debriefing screen (after all the available lives have been lost) is interesting to observe. This screen, featured in all Mecagenius activities, adopts several fun aspects which we have already seen: information on the score, different rewards, and a graphic indicator of failure using the colour red. Even so, this screen also provides the learner with a debriefing including comments or ''help'' thumbnails which go back over different theoretical points studied in class (Fig. 6).

However, no particular debriefing has been developed in case there are several activities like PF6. This decision is related to the third kind of pedagogical support put in place when carrying out the activity, that is to say the immediate feedback on the

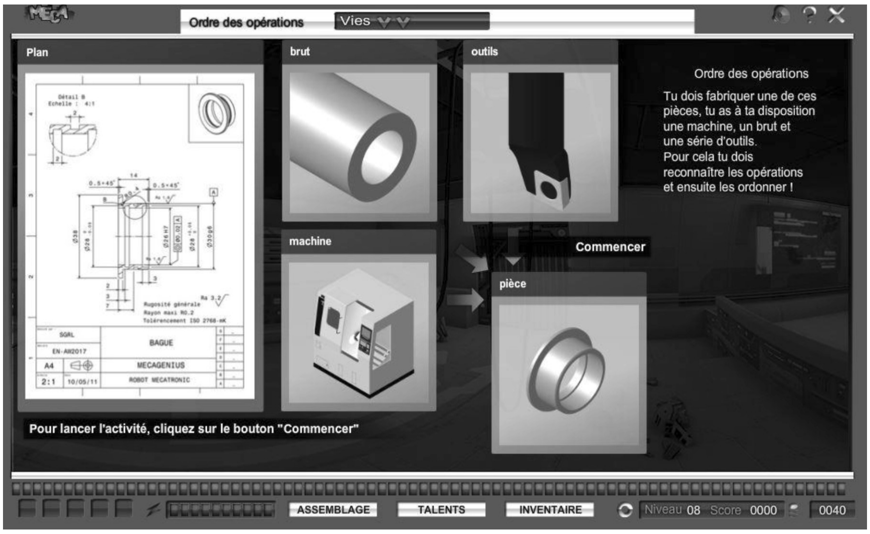

Fig. 6. Briefing before start of activity PF6 in Mecagenius.

Fig. 7. Fail screen at the end of activity PF6 in Mecagenius.

experience. The immediate feedback is characterised by the graphic "pass" or "fail" indicators during the game. Although we referred to them earlier as markers of the activity's playful parameters, we must also understand their role as pedagogical support. On the one hand, these markers allow the learner to make a mistake and make adjustments, on the other, they also provide an opportunity to post messages such as "you lose, the operations are not in the right sequence, did you look at how the part's shapes develop?" or even "Warning, you have mismatched the surfaces and operations." If these indicators were nothing more than simple playful guidance parameters, they would not include advice allowing the individual to make adjustments. Their only meaning would be "this part in red is wrong, this part in green is right, you must change the red part to obtain a set of green parts." However, the way the advice is written makes the colour meaningful, in light of operational knowledge of machine engineering, and therefore places the game directly into a learning context.

All of these playful parameter-setting methods and this pedagogical support mean that the video game structure encourages experimentation with knowledge. In fact, it delineates how the activity is completed according to the codes of the game, but it also directs how it is completed by leaving a certain amount of room for manoeuvre. Just as all the instructions given before, the gameplay during and at the end of activity, encourage the learner to try different combinations, without for all that losing immediately. However, the playful structure specifically gives more and more room for the complexity of machining operations, by increasing the degree of guidance parameters and support as the player progresses through his learning. It is in this way that Mecagenius seems to be both a *game*, as a regulated support structure but is also *play,* given that it allows for free experimentation within the context of this regulated structure. Gamifying learning is thus an attempt to *involve* the learner in his activity by allowing him to problematise a technical situation and resolve it by arranging the means available to him [24]. In the case of the game, this involvement is maintained throughout the learner's progress by gradually removing the metaphor in favour of an increasingly advanced problematisation of complex technical situations.

5. Conclusion

At the beginning of this article we identified three major problems in learning mechanical engineering; the time it takes to train people to use machines, risks of mistakes made by the learner on costly and fragile machines and materials, or even the cognitive and time-based burden involved in highly-technical learning. Having recourse to gamification using the game Mecagenius means learners can spend less time training in the workshop to train in machine handling, they can handle tools virtually. It also eliminates risks of breakages, as well as reducing the cognitive burden by stimulating the learner's involvement. In other words, going back to gamification provides an opportunity for the learner to master complexity before going to the workshop. If the learner no longer has to deal with all of these difficulties when in the workshop, the time spent on real machines is optimised.

Involving and guiding learning using games is thus based precisely on identifying grey areas and levers for carrying out activities, whilst at the same time giving the learner the means to resolve these uncertainties using the game's mechanisms. Ultimately, although we notice an increasing amount of complexity to the detriment of a metaphorical approach to the activity, as a student progresses through the levels of the game, it appears that, in spite of everything, gamifying learning is based on learning and reducing complexity by playing, in other words, understanding and connecting explanations in order to make the right decisions and choices.

By using an illustration of the multiple complexities which define learning in mechanical engineering and by solving the uncertainties they engender by requesting skills and knowledge, Mecagenius is precisely aimed at training the learner in how to understand these complexities. At the same time as the player is exposed to more difficulties, these difficulties are toned down in order to make room for the understanding and skills developed throughout the game. Although recourse to games is nothing new in learning, the scope of possibilities provided by video games, regarding formatting how the learner handles knowledge, encourages us to reconsider the relationship between the complexity of learning and pedagogical processes.

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