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exergyX: A Game on Management of Energy Systems

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Resumo

A redução das emissões de dióxido de carbono é um tema de grande discussão à escala mundial à medida que o mundo enfrenta dificuldades em equilibrar crescimento económico com produção de energia limpa. A educação dos estudantes acerca destes temas é, portanto, da mais alta importância. Sabendo isso, iniciámos a produção de um jogo para melhorar o ensino de disciplinas relacionadas com energia. Jogos são tipicamente associados a diversão e dedicação, e podem igualmente ser uma ferramenta de ensino poderosa. O resultado deste projeto é o exergyX, um jogo pedagógico com o potencial de se tornar numa ferramenta auxiliar para aulas de energia, ajudando os alunos a melhor assimilar a matéria aprendida.

Abstract

The reduction of carbon dioxide emissions is a trending topic worldwide, as the world struggles to balance economic growth with clean energy production. The education of students regarding these subjects is, therefore, of the utmost importance. In this respect, we looked into developing a game to improve the teaching of energy-based courses. Games are typically associated with fun and engagement, and can also be a powerful tool for teaching. The result of this project is exergyX, a learning game that has the potential to become a classroom aid for students, helping them assimilate the subjects taught in energy-related courses.

Keywords

Educational Games

Carbon Dioxide Emissions

Energy Efficiency

Macroeconomics

Jogos Educativos

Emissões de Dióxido de Carbono

Eficiência Energética

Macroeconomia

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Acronyms

IST Instituto Superior Técnico

MIT Massachusetts Institute of Technology

MoES Management of Energy Systems

MOOC Massive Open Online Course

GDP Gross Domestic Product

TFP Total Factor Productivity

1 Introduction

1.1 Games and Education

As far as entertainment products are concerned, games have recently benefited from a growing relevance in today's world. Their virtual subset, video games (also commonly referred to as "computer games") have enjoyed a steady growth in usage, as well as industry and cultural prominence (Harford, 2017).

Games are typically associated with fun and engagement. Therefore, it is natural for games to be taken into consideration as a means of nurturing the interest of people of various backgrounds. Even in non-game contexts, a principle called gamification — the application of elements commonly found in games to other contexts — is occasionally used in order to increase user engagement and motivation (Hamari et al., 2014).

Based on this knowledge, games developed with the purpose of increasing the engagement of students have been introduced in various classes throughout the world, as an attempt to boost the learning process of students (McFarlane et al., 2002).

1.2 A Game on Management of Energy Systems

As part of this dissertation, we developed a video game for computers[1] that serves as a learning tool for students taking courses related to energy management. The game is presented as an opportunity of further improving or complementing the current state of teaching energy-based courses at the University level. It was named "exergyX", sharing the name with a Massive Open Online Course (MOOC) created in 2020[2]. While the game developed for this dissertation was initially designed to be used in classrooms, it is expected to become a part of future iterations of the MOOC, as well.

The idea for the game emerged as Portugal and other countries take measures to ensure they accomplish their environmental goals set in the Paris Agreement (UNFCCC, 2015), while at the same time ensuring the good health of their economical growth, allowing for sustainable development.

In the game, players have to manage both the macroeconomic and energy productivity aspects of Portugal. They are given the role of an advisor to the country's government, and are asked to make decisions in order to lower the emission of carbon dioxide (CO2) to the atmosphere, while keeping the citizens happy.

[1] `https://exergyx.tecnico.ulisboa.pt`, accessed 10th September 2020

[2] `https://courses.mooc.tecnico.ulisboa.pt/courses/course-v1:IST+exergyX+2019/about`, accessed 11th September 2020

exergyX is a simulation game that takes place over various years until the year of 2050, at which point the players' results are assessed. It requires input from the players every year. This input affects the qualitative and quantitative measures of the game, and has a direct impact on the results of the simulation. This impact has an immediate (albeit small) effect on the results for the following year, and a more pronounced effect on the preview of the results for the final year provided to the players. This allows players to make adjustments to their strategy as they play and know how their strategy impacted the results.

The game started development as part of a project called "Massive Open Online Tool for the design of consistent scenarios for energy consumption and CO2 emissions for 2050". A simplified model based on simulations developed with a methodology introduced at the MEET2030 project (Alvarenga, 2017) served as the basis for the scientific data presented in the game.

The goal of this dissertation is to verify that experts of energy-related subjects (*e.g.*, teachers) recognize that exergyX has the potential to be used as a tool for teaching. We also assess if exergyX provides players with a satisfying game experience, if players use practical experimentation in order to learn the model of the game, and if students wish to have exergyX be used in their classes.

1.3 Document Structure

In Chapter 2, we take a look at several games that have a pedagogical component. We analyze these games and take insights for the development of exergyX. In Chapter 3, we look at the scientific background behind the model for our game. In Chapter 4, we detail the development of exergyX, showing how the game evolved over time through iterative design. In Chapter 5, we assess the capability of our game of fulfilling the goals of this dissertation. Lastly, in Chapter 6, we conclude on the results of this dissertation and make suggestions for possible future work.

2 State of the Art

We performed an analysis of studies where games were developed as a tool for learning or as a means to increase awareness on management of energy, as well as some other relevant projects. The critical approach taken while performing this analysis provided information that we used in order to improve the development of exergyX.

2.1 The Effects of Modern Mathematics Computer Games on Mathematics Achievement and Class Motivation

The project in Kebritchi et al. (2010) applied educational games to the teaching of high school-level Algebra I and Pre-Algebra in the United States. 193 students and 10 teachers participated in the study. Students and teachers were split and randomly assigned to treatment and control groups, following Campbell and Stanley (2015) experimental design. 117 students were assigned to treatment groups, while the remaining 76 formed the control group. The site of the study was an urban high school in the southeast of the United States.

For this study, games from the DimensionM suite of educational games[1] were used. The games were used for 18 weeks (an entire school semester), for about 30 minutes each week, during regular class time. Some students played the games in their classrooms, while others played the games in the school labs. Games were used with the purpose of supplementing the material that was taught during class. The treatment group played the games and the control group took regular mathematics lessons.

The DimensionM games used in this study teach Algebra I and Pre-Algebra by placing players in a 3D environment. Players were then expected to complete mathematics-related missions. All games start with an introductory phase where the story of the game is explained. That story is then used as the context for the missions which players are assigned with. This template is common to all of the games used in the study, which then vary in controls and gameplay.

Five different DimensionM games were used: a single-player first-person shooter, a single-player exploration game, a multiplayer problem-solving game where groups compete against each other, a strategy game where players compete individually, and a competitive game where players compete to complete math-related obstacles.

At the beginning of the semester, three instruments were used in order to obtain student-related data: a demographic survey; the results of a benchmark test to identify the students' mathematics proficiency; a motivation survey which was used to gauge the students' motivation towards mathematics.

[1] `https://www.dimensionu.com/dimu/home/home.aspx`, accessed 22nd May 2019

Two of the hypotheses tested are as follows (Kebritchi et al., 2010, p. 429):

> *"There is no significant difference between learners' achievement of the treatment group, versus the control group."*
>
> *"There is no significant difference between learners' motivations of the treatment group, versus the control group."*

At the end of the semester, student results were compared with the initial benchmark results. A motivation survey was also filled in by the students (George and Mallery, 2016, Chapters 12-14).

When testing against the hypotheses raised above, the results indicated that students in the treatment group obtained, on average, higher test results than those in the control group. Students in the treatment group also reported higher levels of motivation, but only when the games were used as part of regular class time in the classroom. For cases when the game is used outside the classroom (in this case, the school labs), there were no significant changes in motivation, leading the authors to believe that students disassociated the games from their math class.

All five teachers and fifteen students were selected for a post-participation interview. These interviews helped the researchers validate the results mentioned above. According to the interview results, the teachers saw the introduction of the game as a positive change and believed that the mission-based structure helped students. They said that the games made students more interested in learning mathematics, and helped them understand the real-life applications of mathematics. Finally, teachers believe that the games made the concepts stay longer with the students, as they needed them to complete the games.

The students mentioned in their interviews that they saw the games as entertaining and as something that "took them out of class". They enjoyed the adventure and exploration, thought the challenges presented were interesting, found the combination of game mechanics (such as shooting) with solving problems and learning mathematics to be very attractive, and also found themselves having fun while learning.

2.2 A Learning Cycle Approach to Developing Educational Computer Game for Improving Students' Learning and Awareness in Electric Energy Consumption and Conservation

The project in Dorji et al. (2015) developed a computer game based on a learning cycle model, the 5E Learning Model (Duran and Duran, 2004). This game aimed to educate high-school students on electrical energy conservation. The development of the game was motivated by the authors' research that concluded that most people have no awareness of their energy consumption, and do not know how to save electricity appropriately. In addition, very few young students are aware of the workings of daily life electrical appliances and, as such, most have no awareness on energy consumption.

The 5E Learning Model defines a specific sequence of steps to apply to a learning process. 5E stands for *engage*, *explore*, *explain*, *elaborate*, and *evaluate*, which are the five steps of the model. The authors advocate that this model improves students' achievements and their ability to relate conceptual learning with real life applications.

In order to assess the effectiveness of the game, a study was conducted in a high school in eastern Bhutan, during the teaching of an energy consumption and conservation topic taught in a Physics course.

The game consists of three subgames, all of which use simple point and click mechanics, with interfaces that are easy to understand. Each subgame is introduced at the relevant part of the 5E Learning Model. The subgames are as follows:

1. **Energy Detective Game** - Used at the exploration step. A game where the player must find out how much energy certain appliances use, allowing the students to identify the two essential variables in energy consumption: wattage and duration of use.
2. **Energy Efficiency Game** - Used at the elaboration step. A game that allows players to monitor their power bill in real time, by being efficient with appliance use. The objective of the game is to save as much money on their power bill as possible before time runs out (the game is in real time).
3. **Shopping Game** - Used at the evaluation step. A shopping game where players should pick and choose the most energy efficient appliances. Students are expected to make purchases by dragging and dropping items into a shopping cart, while taking into account the energy efficiency of said items. This is meant as a way to gauge the understanding students gained in previous steps.

The students who played this game reported an improvement of their grades from an average of 7.52 to an average of 10.08 (in a 20-point scale). They also scored higher in tests related to energy consumption awareness. When answering a game satisfaction questionnaire, students reported high satisfaction in all fields.

2.3 EnerCities, a Serious Game to Stimulate Sustainability and Energy Conservation

Knol and De Vries (2011) believe that, despite sustainability and energy conservation being hot topics in many EU countries, they are still rather abstract and complex concepts to explain, particularly to youngsters. The authors argue that educating and inspiring younger citizens, influencing their (future) energy-related behaviours, is a need in line with current European policies.

The authors introduce the concept of “serious gaming” as one of the solutions to reach and involve youngsters in sustainability and energy efficiency. They argue that serious games are great motivational tools that, through challenge and inspiring curiosity, help inform and inspire students.

The study was conducted as a means to find out if playing a game could encourage student learning about sustainability, renewable energies, and energy conservation, as well as ascertaining if a game could influence their energy saving habits during their daily lives.

The game EnerCities was presented as the subject game for this study. It is an educational game co-funded by the European Commission as part of the Intelligent Energy Europe programme (IEE, 2010). The original project started in September 2009 and ended in August 2011[2].

EnerCities was made with the goal of making students aware of the importance of energy on societies, as well as the significance of energy saving. The game is specifically designed to be played even on computers with low specifications, allowing the game to be played in most schools.

As a simulation game, the game starts with an empty sandbox village with some land to build structures on. These structures include residential areas, industries, environmental objects, people-oriented objects, and several types of energy sources (both renewable and non-renewable). If the player successfully achieves a balance between the states of the economy, the environment, and the well-being of the citizens, then they receive more space in order to expand their city and unlock more features. This makes it so that the player’s strategy plays a vital role in the success of the game. There are four levels that the players should try to beat, with each level having different requirements for fulfillment. The game begins in the year 2010 and ends in the year 2100, with the player’s score being registered at that time.

For this study, the game was played by over 600 European students in their classrooms.

Students were receptive to the game’s theme, the gameplay, and the game’s presentation. They also also liked the sense of challenge felt throughout the game. However, some students felt that the goal of the game was unclear.

Students were also tested on possible gains on awareness about energy conservation issues and energy saving attitudes. The results of the study clearly showed that playing EnerCities increases the awareness of students on issues related to energy and the environment. Respondents in the study indicated that they were more interested in learning about renewable energy sources and energy saving. The respondents also mentioned that they were concerned about the environment and are now more aware of the link between economy, energy usage, and the environment. They also mentioned a wish to improve their energy-saving habits at home.

[2] `https://web.archive.org/web/20190909064259/http://www.enercities.eu/project/`, accessed 9th September 2019

2.4 Power Grid

Power Grid[3] is an award-winning board game designed by Friedemann Friese and originally published in 2004. There are several versions of the game, representing various countries of the world. Portugal and Spain have a version as well, with a playable Iberian map.

Power Grid is a strategy game with an economic component, with players having to manage their resources in order to supply as many cities as possible with power from their network. Players have the option to bid on power plants, which are needed to power cities. However, power plants need resources to function, with most of these resources coming from non-renewable sources. There are some types of plants that produce renewable power, therefore not requiring any expendable resources. This highlights the importance of producing power through renewable means.

The game has a heavy economical component, with players having to manage their wealth in order to stay competitive. Money is also a tie-breaker at the end of the game, making it even more important. This helps reinforce the close relationship between energy and the economy.

While saving money may sound desirable while playing, investing in power plants allows access to more efficient equipment. While this opens up the risk/reward element of the game, it also indicates the importance of investing in the production (and therefore consumption) of energy, which is closely linked to an economy's growth (Fouquet, 2009).

2.5 Beer Distribution Game

The Beer Game[4] was invented in the 1960s by Jay Forrester at the Massachusetts Institute of Technology (MIT). The game is usually used in order to teach students about the coordination problems of participating in a supply chain process without appropriate systemic thinking.

Many versions of the game allow players to access analytics and debriefing information, with data visualization resources such as graphs and charts being available.

The game simulates the entire supply chain of the distribution of beer. Players are divided into the various stages of the chain, starting with the beer factory and ending with the costumers.

The various stages of the supply chain are not allowed to communicate among themselves, which creates frustration and leads to the creation of what is called the bullwhip effect (Lee et al., 1997), in which distorted information between different stages of the supply chain and poor understanding of how the system works results in gigantic inefficiencies.

2.6 Summary

Looking at the games previously mentioned, we can take several useful insights.

[3] `https://boardgamegeek.com/boardgame/2651/power-grid`, accessed 7th September 2020
[4] `https://beergame.org/`, accessed 29th May 2019

In Kebritchi et al. (2010), we identified that a game that includes a story that eases players into the game is more appealing. It also helps players disassociate the “learning” part of the game from school work. A strong context for the game is therefore a plus. Also, it is easier to deduce a relationship between the subject matter and real life when presented via a well-contextualized game.

In addition, a mission or objective-based approach may help students focus and feel a sense of accomplishment when they are successful. Since students who played the games outside of the classroom reported no increase to their levels of motivation, it was important to think about where exergyX would be played while developing it.

Students in Dorji et al. (2015) appeared to have no problem interacting with the games. The user interfaces were easy to understand. This allowed for a low barrier of entry and demonstrates the importance of following rigorous game usability methodologies. We concluded that the way users interact with our game should, therefore, be simple and use protocols that are familiar to the players.

It should be noted, however, that the games developed for this study are quite simple, have very little gameplay elements, and are almost completely devoid of any challenge. Challenge begets critical thinking, which stimulates learning (Boyle et al., 2011).

Players of EnerCities liked its strategic component. This highlights that strategy and challenge is important in a simulation game. Players like to feel like they are effectively planning something with meaning, something that makes them feel challenged.

On the other hand, some players felt lost while playing the game. This highlights the need to have well-defined objectives in the game. Players should know exactly what they are working towards. Providing clues as well as feedback on the effects of the players’ actions on the scenarios is very important.

Power Grid places a lot of emphasis on the production of power through renewable means, as well as the management of resources. It displays a link between energy and the economy. For exergyX, it was important to state the importance of investing in renewable power while keeping the distribution of resources under control.

The bullwhip effect that the Beer Game generates showed us the importance of properly communicating how to use systems and other information. In our opinion, players of exergyX should feel that all relevant information for playing the game is communicated clearly to them.

3 Architecture

3.1 Theoretical Background

Before introducing the architecture of the model that serves as the back end for exergyX (in Section 3.2), it is necessary to provide an overlook of the concepts behind it, in order to provide context.

For the purposes of explaining the theoretical domain of the game, there are two key concepts that need to be introduced: **Energy** and **Exergy**.

Energy is, in physics, a quantitative property that represents the capacity for doing work. The survival and growth of all human and animal life, as well as the development of society, is dependent on the consumption of energy (Felício, 2017).

Exergy is a measure of the quality of energy in a system. It is the maximum amount of work obtainable from the system as it comes into equilibrium with the environment. For example, in an environment at 25ºC, the exergy of 105 MJ of steam at 160ºC and 3 bar is 22 MJ while the exergy of 105 MJ of water at 50ºC is 2 MJ. As such, in a system that has reached thermodynamic equilibrium, the available exergy is zero. Unlike energy, exergy can be irreversibly destroyed as a consequence of the Second Law of thermodynamics (Serrenho, 2013).

In addition, there is a close link between Energy and Economy. An economy's growth appears to be strongly related with energy (Fouquet, 2009). Specifically, with the amount of useful exergy that is used by the economy (since this is the energy that is effectively used to produce economic value), and with the overall efficiency in converting final exergy to useful exergy (because this affects the cost of useful exergy).

exergyX uses the scenarios for Portugal developed in the MEET2030 project (Alvarenga, 2017) as the basis for its scientific model. These scenarios follow the rules demonstrated in the conceptual map in Fig. 3.1.

Following the map, we see that Energy and Exergy are key components of the different **stages of energy flow**.

The first stage of energy, primary energy, is the kind of energy that has not undergone any sort of transformation (*e.g.*, coal). This energy may be stored in either renewable or non-renewable resources, with the use of the latter having an impact on the environment.

Final energy is the energy after it has been converted and delivered to consumers, ready to be used.

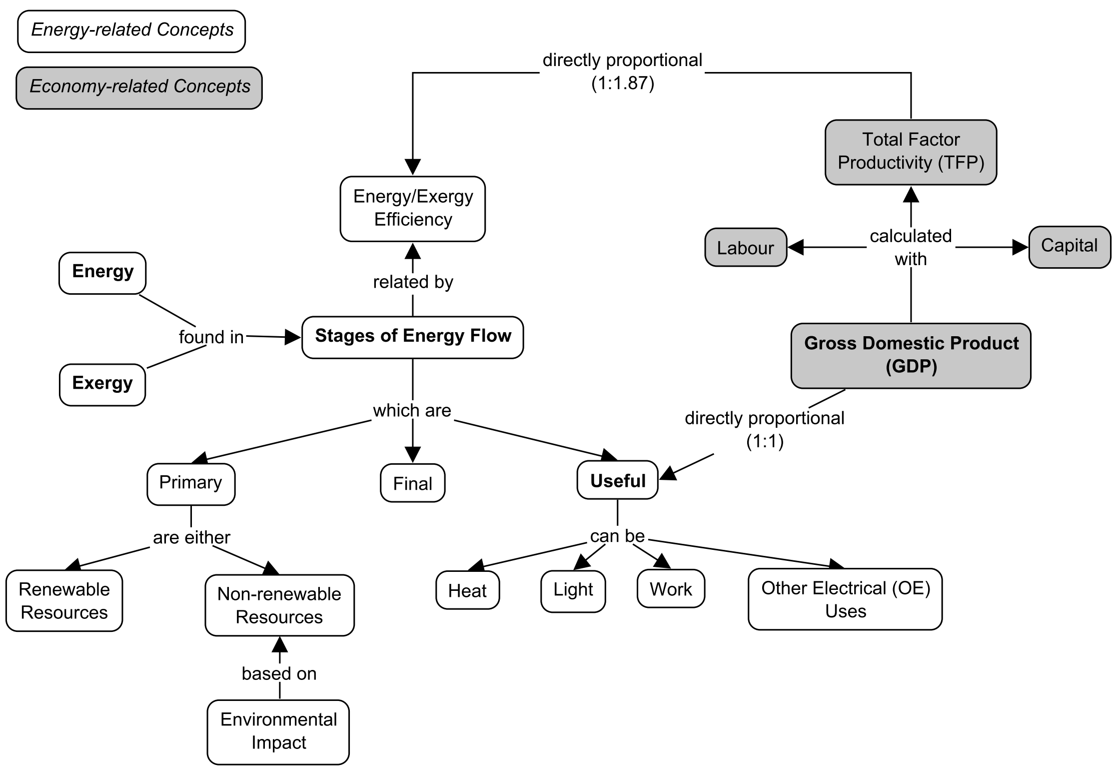

Figure 3.1: A conceptual map demonstrating the relationship between energy- and economy-based concepts

The final stage, **useful energy**, is energy as it is used by consumers. It can have various uses, such as heat, light, and work. Uses that don't fall into any of these groups are classified as *Other Electrical Uses*.

All of the three stages also apply for the flow of exergy (Felício, 2017).

It was found in Serrenho (2013) that useful exergy has a proportional relation to Portugal's **Gross Domestic Product (GDP)** (1 megajoule per euro of GDP), facilitating the creation of simulations and further validating the link between energy consumption and economic growth.

Affecting the calculation of the GDP are the following measures: Labour, which is a measure of hours worked (SNA, 2008, p. 468); Capital, which is the sum of the values of all fixed assets still in use (SNA, 2008, p. 456); and the Total Factor Productivity (TFP) (also known as Multi-factor Productivity), which is a measure that takes account of the productivity that cannot be explained by labour or capital (SNA, 2008, p. 470). GDP can be calculated with Equation 3.1.

$$GDP = TFP \times K^{\alpha} \times L^{\beta} \tag{3.1}$$

In Equation 3.1, α and β represent, respectively, the share of payments (in total income) for capital (*K*) and labour (*L*) (Felício, 2017).

An empirical relationship explained in Alvarenga (2017) demonstrates a proportionality between final-to-useful exergy efficiency and the TFP, one that indicates that if that efficiency experiences a 1% annual growth rate (for example), then the TFP will grow up by approximately 1.87% in that same period.

3.2 Model for the Game

exergyX relies on a scientific model in order to process all the calculations the game performs. This allows the game to provide results that are consistent with the subjects taught in energy-based courses. This model was developed in conjunction with Professor Tânia Sousa, and PhD students Laura Felício and João Santos, from Instituto Superior Técnico (IST). It is an adapted version of the model developed for the MEET2030 project (Alvarenga, 2017).

In exergyX, there are two goals that players must meet in order to win the game. They must:

- Lower Portugal's CO2 emissions below a certain threshold (in the current version this threshold is set at 14 Mt CO2).
- Maintain or improve the happiness levels of the average citizen of the country.

The aforementioned "happiness levels" shall henceforth be referred to as "utility". Utility is a measure of happiness and general well-being used by economists.

Since the model was developed for the game, the end result of its application will be an annual value of emissions and utility. The model was designed to be iterative, with a number of equations using values from the previous year. This also means that a number of starting values ("year zero values") need to be fed to the model in order for it to work.

What follows is the detailed description of the model, from start to finish, broken down in subsections. In every equation, y refers to the current year in the model.

3.2.1 Power per Source

Every year, the player chooses how much power (in gigawatts) to add to the existing annual production. The chosen power is then shared between infrastructures using one of three different renewable sources: solar, wind, and biomass.

The power to be installed is usually divided by 3, in order to be fairly distributed for each source. However, there is a maximum amount of power that can be produced per source. The algorithm in Listing 3.1 indicates how distribution is managed in all cases.

```
if(!max_reached_solar && !max_reached_wind && !max_reached_biomass):
        new_solar_power = new_power / 3
        new_wind_power = new_power / 3
        new_biomass_power = new_power / 3
elif(!max_reached_solar && !max_reached_wind && max_reached_biomass):
        new_solar_power = new_power / 2
        new_wind_power = new_power / 2
elif(!max_reached_solar && max_reached_wind && max_reached_biomass):
        new_solar_power = new_power
elif(max_reached_solar && !max_reached_wind && !max_reached_biomass):
        new_wind_power = new_power / 2
        new_biomass_power = new_power / 2
elif(max_reached_solar && !max_reached_wind && max_reached_biomass):
        new_wind_power = new_power
elif(!max_reached_solar && max_reached_wind && !max_reached_biomass):
        new_solar_power = new_power / 2
        new_biomass_power = new_power / 2
elif(max_reached_solar && max_reached_wind && !max_reached_biomass):
        new_biomass_power = new_power
```

Listing 3.1: Algorithm for the distribution of power to be installed

A check is then performed to see if any source will exceed maximum power production after the new power is added. If so, the power to be added is adjusted so that the total stays at maximum.

Finally, each source's power for the year is calculated following Equation 3.2, with P_{so} being the installed power per source and NP_{so} being the new power to install per source.

$$P_{so}(y) = P_{so}(y-1) + NP_{so}(y) \tag{3.2}$$

3.2.2 Cost of Power

Each renewable source has an independent cost for power production (in euros). This cost C_so is calculated using the installed power obtained in Equation 3.2 and G_so, which represents the costs per gigawatt for each source, which are constant.

$$C_{so}(y) = P_{so}(y) + G_{so} \tag{3.3}$$

The cost of each source is then combined to obtain the total cost of renewable power generation for the year.

$$C(y) = \sum^{s} C_{so}(y) \tag{3.4}$$

3.2.3 Capital Investment

Capital investment (I) refers to a percentage of the country's GDP to be used for capital that year. This percentage is represented by constant P. The total cost of renewable power generation is taken from this value. Since capital investment is presented in billions (10^9) of euros, the cost of power needs to be converted into the same unit for the purpose of our calculations.

$$I(y) = P \times GDP(y-1) - C(y) \times 10^{-9} \tag{3.5}$$

3.2.4 Total Capital

The total capital (K), introduced in Section 3.1, is obtained by adding capital investment to the previous capital of the country. Capital, Labour, and the TFP

$$K(y) = K(y-1) + I(y) \tag{3.6}$$

3.2.5 Labor

Labor (L), introduced in Section 3.1, is the number of hours worked by all of the economy's working individuals. While usually the equation for labor is obtained by using data such as work rate, unemployment rate, and others, in order to simplify the game we use Equation 3.7 instead.

(3.7) $$L(y) = \alpha \times Pop$$

In this equation, α is a constant that represents the substituted data with an approximation of the usual results. Pop represents the country's population of working age. For the purposes of this model, Pop is a constant as well.

3.2.6 Total Factor Productivity

The TFP, introduced in Section 3.1, is calculated in this model as a function of aggregate efficiency EFF (seen in Section 3.2.16). It uses the value of the aggregate efficiency in 1960 as a reference.

(3.8) $$TFP(y) = \left(\frac{EFF(y-1)}{EFF(1960)}\right)^{1.93} \times 0.00000102 + 0.00000039$$

3.2.7 Gross Domestic Product

The GDP uses, as previously stated, Equation 3.1. α and β are given a distribution of 0.3 and 0.7, respectively.

(3.9) $$GDP(y) = TFP(y) \times K(y)^{0.3} \times L(y)^{0.7}$$

The GDP obtained comes in billions of euros.

3.2.8 Useful Exergy

The amount of useful exergy of the year $UEx(y)$ comes from the GDP, using the relation from Serrenho (2013).

(3.10) $$UEx(y) = GDP(y) \times 10^3$$

The megajoule value from the relation is converted to terajoules (multiplied by 10^3) in order to facilitate future calculations.

3.2.9 Final Exergy

We go backwards in the stages of exergy flow in order to find the final exergy value ($FEx(y)$) in terajoules, which is obtained by applying the previous year's aggregate efficiency to the useful exergy found before.

$$FEx(y) = \frac{UEx(y)}{EFF(y-1)} \tag{3.11}$$

3.2.10 Final Exergy Shares per Sector

The user decides on the distribution of final exergy per each sector on the game ($DEx_s(y)$). By applying this distribution to the previous year's shares, we get the current year's final exergy shares per sector ($SFEx_s(y)$), as a percentage. If the distribution does not equal 100%, a correction is applied.

$$SFEx_s(y) = \begin{cases} \frac{SFEx_s(y-1) + DEx_s(y)}{\sum^s (SFEx_s(y-1) + DEx_s(y))}, & \text{if } \sum^s (SFEx_s(y-1) + DEx_s(y)) \neq 1 \\ SFEx_s(y-1) + DEx_s(y), & \text{otherwise} \end{cases} \tag{3.12}$$

3.2.11 Final Exergy per Sector

A simple multiplication of the final exergy shares per sector by the total amount of final exergy finds us the amount of final exergy per sector ($FEx_s(y)$) in terajoules.

$$FEx_s(y) = FEx(y) \times SFEx_s(y) \tag{3.13}$$

3.2.12 Sector Electrification

The users can decide ($DEl_s(y)$) to increase the amount of power that each sector gets from electricity ($El_s(y)$).

$$El_s(y) = El_s(y-1) + DEl_s(y) \tag{3.14}$$

3.2.13 Final Exergy Shares per Sector per Carrier

There are six energy carriers that are part of this model: coal, petroleum, natural gas, renewable fuels, and heat. By applying Equation 3.15 to every permutation of carrier and sector, we can find out the individual shares of final exergy ($SFEx_{s_c}(y)$), which are percentages.

(3.15) $$SFEx_{s_c}(y) = SFEx_{s_c}(y-1) \times \frac{1 - El_s(y)}{1 - El_s(y-1)}$$

3.2.14 Final Exergy per Sector per Carrier

We use the same logic here as in Section 3.2.11.

(3.16) $$FEx_{s_c}(y) = FEx_s(y) \times SFEx_{s_c}(y)$$

3.2.15 Efficiency per Sector

By calculating each sector's useful exergy through the efficiency of every carrier per sector, we obtain the total percentage of each sector's efficiency ($EFF_s(y)$).

(3.17) $$UEx_s(y) = \sum^{c}(FEx_{s_c}(y) \times EFF_{s_c})$$

(3.18) $$EFF_s(y) = \frac{UEx_s(y)}{FEx_s(y)}$$

3.2.16 Aggregate Efficiency

The country's aggregate efficiency ($EFF(y)$), obtained from all sectors. We also use this step to update the values of useful and final exergy with more accurate values.

(3.19) $$UEx(y) = \sum^{s} UEx_s(y)$$

(3.20) $$FEx(y) = \sum^{s} FEx_s(y)$$

$$EFF(y) = \frac{UEx(y)}{FEx(y)} \tag{3.21}$$

3.2.17 Final Exergy per Carrier

We check every sector in order to obtain the total final exergy per carrier ($FEx_c(y)$).

$$FEx_c(y) = \sum^{s} FEx_{s_c}(y) \tag{3.22}$$

3.2.18 CO2 Emissions (Except Electricity)

In this step we find the CO2 emitted (in kg CO2) through all means except the production of electricity ($CO2_{ne}(y)$).

$$CO2_{ne}(y) = \sum^{c} Fex_c(y) * EmF_c \tag{3.23}$$

3.2.19 Electricity from Renewable Sources

In this equation, PrF_{so} refers to a source's factor of production, while H is the number of hours in a year. The electricity calculated here ($Elec(y)$) is measured in GWh (gigawatts hour).

$$Elec(y) = \sum^{so} P_{so}(y) * PrF_{so} * H \tag{3.24}$$

3.2.20 Non-renewable Electricity

We convert final exergy from electricity ($FEx_{Elec}(y)$) from terajoules to gigawatts hour (1 GWh = 3.6 TJ), and we apply a factor of inefficiency in the transition from primary to final exergy ($INEFF$). From the obtained value we subtract $Elec(y)$ in order to obtain the non-renewable electricity of the year in GWh.

$$NElec(y) = \frac{FEx_{Elec}(y)}{3.6} \times INEFF - Elec(y) \tag{3.25}$$

3.2.21 Non-renewable CO2 Emissions

In this equation, $EFF_{Elec_{NG}}$ refers to the efficiency of electricity production by using natural gas. EmF_{NG} is the factor of emission of natural gas. EmF_C is the factor of emission of coal. $EFF_{Elec_{NG}}$ and EFF_{Elec_C} are the efficiencies of electricity production with natural gas and coal, respectively. MAX_{NG}

is the maximum electricity produceable via the use of natural gas.

(3.26)

$$NCO2(y) = \begin{cases} 0, & \text{if } NElec(y) \leq 0 \\ \frac{NElec(y) \times 3.6}{EFF_{Elec_{NG}}} \times EmF_{NG}, & \text{if } NElec(y) \leq MAX_{NG} \\ \frac{MAX_{NG} \times 3.6}{EFF_{Elec_{NG}}} \times EmF_{NG} + \frac{NElec(y) - MAX_{NG}}{EFF_{Elec_{C}}} \times EmF_{C}, & \text{otherwise} \end{cases}$$

3.2.22 Total CO2 Emissions

One of the goals of the game. Obtained by the sum of all emissions, in kg CO2.

(3.27)
$$CO2(y) = CO2_{ne}(y) + NCO2(y)$$

3.2.23 Expenditure

Money spent (in billions of euros) by the economy.

(3.28)
$$E(y) = GDP(y) - I(y)$$

3.2.24 Utility

The other goal of the game. A measure of happiness.

(3.29)
$$U(y) = (E(y) \times 10^9)^2 \times \frac{e^{\frac{-1 \times CO2(y)}{10000000000}}}{Pop}$$

4 Implementation

4.1 Game Overview

When starting exergyX, players are introduced to their role in the game, where they are assigned the title of advisor to the Portuguese government. They are given two well-defined objectives (reduction of CO2 emissions and management of utility) and work toward them during the full extent of their play time.

exergyX was implemented with an interface that is simple to use and understand. The main screen of the game contains three panels that include, respectively, the previsions and the utility and emissions goals for the final year of the game (the expected results of the game), the data for the current year in the game, and the decisions to be made for the next year. These decisions are the new renewable power to be installed (new_power in Listing 3.1), the distribution of final exergy per each sector ($DEx_s(y)$ in Equation 3.12), and the electrification of each sector ($DEl_s(y)$ in Equation 3.14).

Players who prefer a more visual representation of data have the option to access a sub-screen with graphs showing their past data and forecasts. It is also possible to check the results of previous decisions, allowing a player to plan ahead effectively depending on their results. This sub-screen displays more data than that which is available in the main screen for players who wish to understand even further how their actions influence the country.

4.2 Chosen Technology

exergyX was developed using the free, open-source game engine Godot[1]. It was chosen for this project due to its ability to export HTML5 games, which are playable on any modern web browser. This increases the accessibility of the game, as students are able to play the game using their existing devices. In addition, the logic for the game, as well as the model, were implemented using the complementary GDScript programming language.

4.3 Programming

There are two crucial parts to the game: the front end (the game interface and its logic), and the back end (the game model). They have been implemented independently and (excluding deliberate points of access) they can also operate independently of each other. When a player makes a set of yearly decisions, the game communicates these decisions to the model. The model then performs all of its

[1] `https://godotengine.org`, accessed 13th September 2020

calculations, and stores a copy of the results in variables that are accessible by the game. The game then updates its interface with the new data.

The front end was developed using a combination of the Godot visual editor and code. The visual editor allowed us to place elements such as buttons and text on the screen at will, with the behavior and theming of the elements being delegated to GDScript code.

The back end can run without the need for the game's interface, as long as its calculations are performed in the order described in Section 3.2. Due to this versatility, we considered that some experts might be interested in accessing all the data the model provides without having to play the game, in order to more efficiently harness its usefulness. As a result, we have also developed a version of the game that includes a simulator that exclusively uses the model[2]. This version was also used to debug the model during its implementation.

4.4 Iterative Design

exergyX was developed using iterative design, with the project being regularly tweaked and improved based on feedback and testing. There were some end goals that guided the development process. We knew that exergyX would have a short play time in order to more easily be introduced in the final minutes of a class. We also knew that the goals the players must obtain would be quite ambitious, with the adjustment of strategies mid-game being necessary in most cases. We also wanted all information to be communicated clearly to the players.

In the beginning of the process, we created paper prototypes that depicted the game's interface and the data that would be displayed. This prototype was later turned into the first version of the game, using mock data (see Figure 4.1).

This interface underwent internal testing, and we decided that the elements of the game should be easier to read, with larger text and better spacing. We revamped the look of the interface (while maintaining the data that was displayed), and obtained the look that can be seen in Figure 4.2.

We considered that this look was an acceptable starting point to develop the rest of the game, and development focus shifted towards functionality, with the implementation of the player decisions and generation of data. The aspect of the game at the end of this step can be seen in Figure 4.3. The "History and Predictions" button was non-functional at this time.

The next version was the biggest breakthrough of the project, as this was the first version to communicate with the game model. This meant that the game could now stop using mock data (see Figure 4.4). Using data from the model revealed a few bugs with its implementation, so we took this opportunity to fix the model as well.

At this point, we implemented the "History and Predictions" button, which includes a graph (see Figure 4.5). After a few final tweaks, the game was ready for user testing.

[2] `https://exergyx.tecnico.ulisboa.pt/model`, accessed 15th September 2020

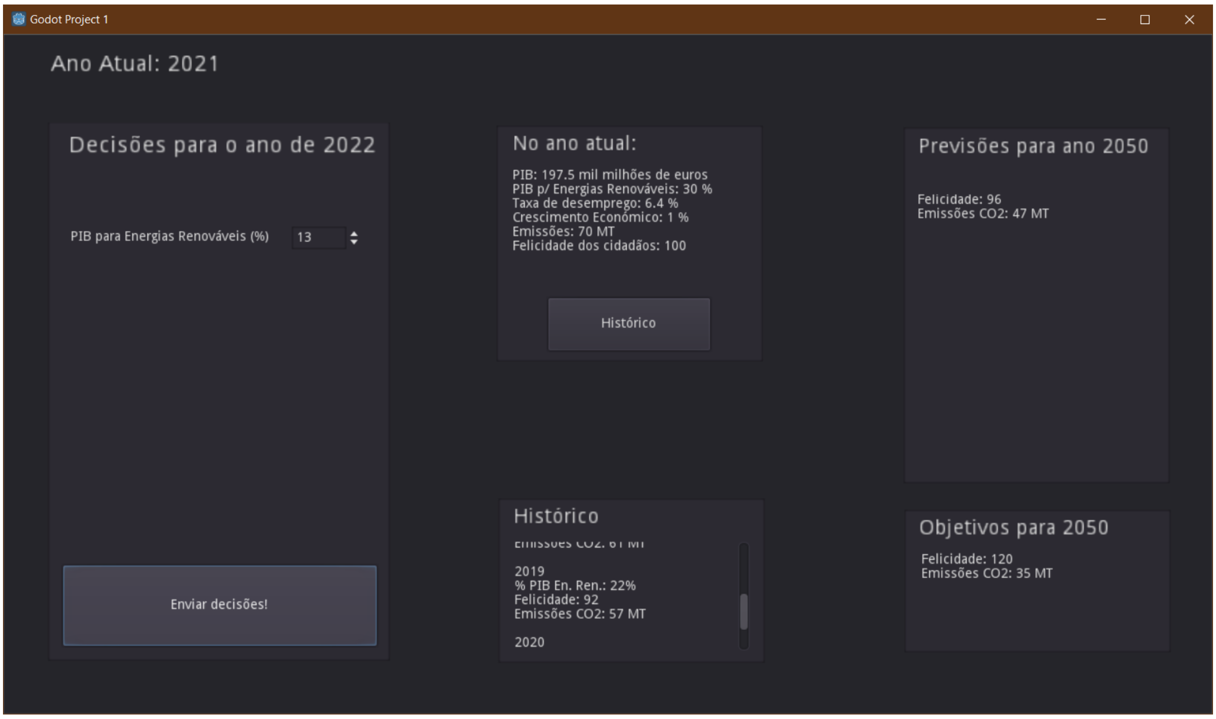

Figure 4.1: The first version of exergyX

Three students participated in user testing. The tests were performed via online video call with screen sharing. The users were asked to play the game from start to finish and to make any comments they wished, while we took notes. The full set of notes we took is available in Appendix C. Using the feedback from this test we built the final version of exergyX (see Figure 4.6). One of the users had trouble identifying which elements of the Decisions panel were clickable, so we added a round button background to them to make them more obvious. We also noticed some confusion in identifying the goals of the game, so we gave them their own section. We also made it so that the player can hover their mouse cursor over any element of the game in order to obtain help, in an effort to prevent any confusion. We also expanded on the initial screen of the game (where the players are given the role of advisor) in order to further explain how the game works and what the player can do.

Figure 4.2: The second version of exergyX, with an improved look

Figure 4.3: The third version of exergyX, already including most of the main screen data

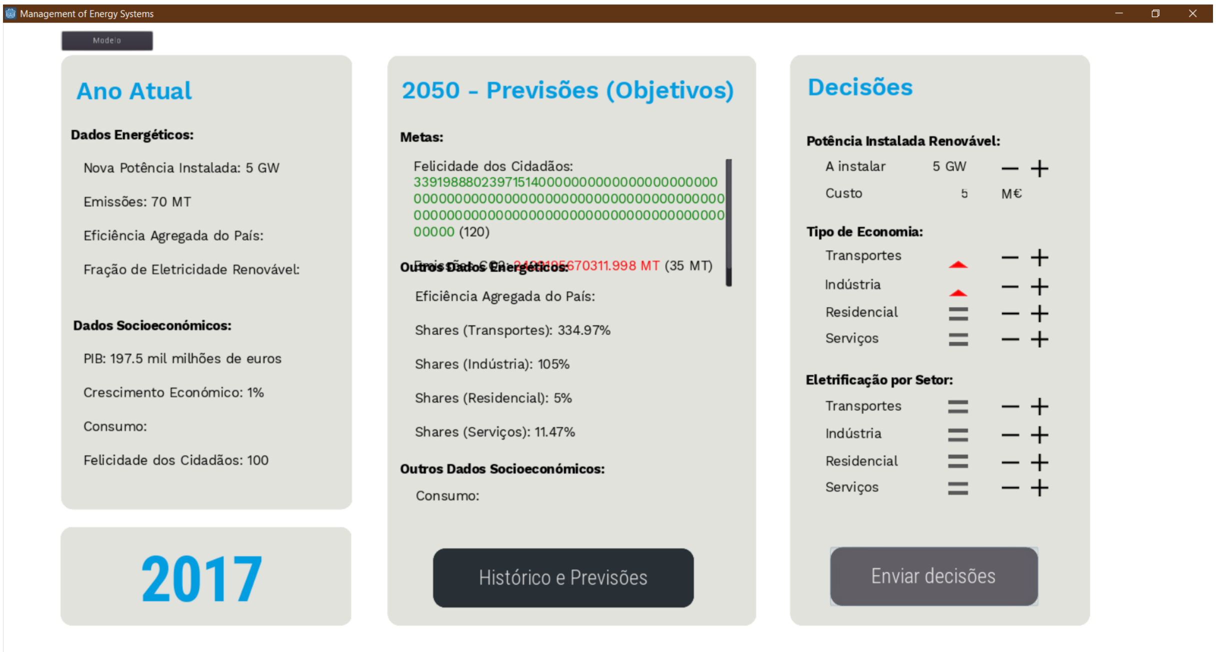

Figure 4.4: The fourth version of exergyX. Some bugs with the data from the model can be seen. After fixing the model, we used this version for user testing

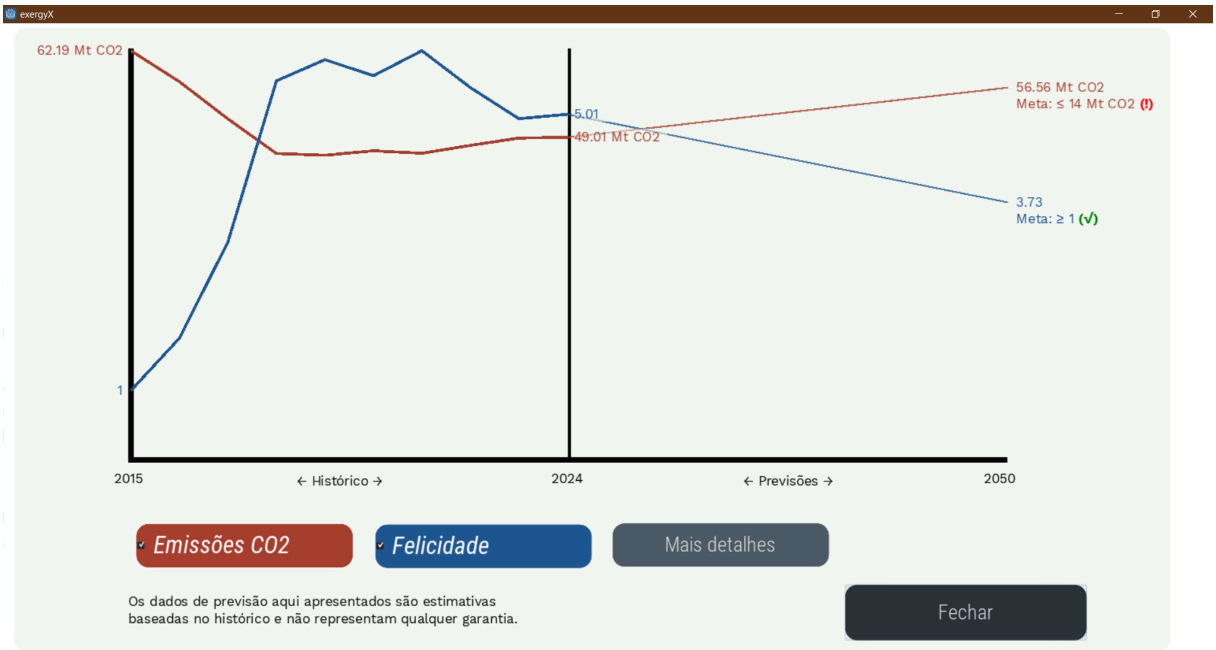

Figure 4.5: The “History and Predictions” area of the game

Figure 4.6: The final version of exergyX, implemented after user testing

5 Evaluation

The implementation of the model in Section 3.2 was reviewed by Laura Felício and João Santos, co-authors of the original model in Alvarenga (2017), who confirmed its correctness.

Two groups of users tested the game. One group was composed of experts in teaching energy-based courses, while the other was composed of students of Management of Energy Systems (MoES), a course taught in IST. Each of the groups received a different questionnaire with its own set of questions.

5.1 Experts

A questionnaire was sent to experts in the field with 4 questions about the game's potential as a teaching tool. Of these, 1 was a yes or no question and the remaining 3 were open-ended questions.

All experts recognized potential in using exergyX as a teaching aid (Figure 5.1), mentioning as contributing factors how the game exposes the connection between CO2 emissions, the GDP, and utility, as well as how energy consumption impacts on economic growth. The full set of responses can be seen in Appendix A.

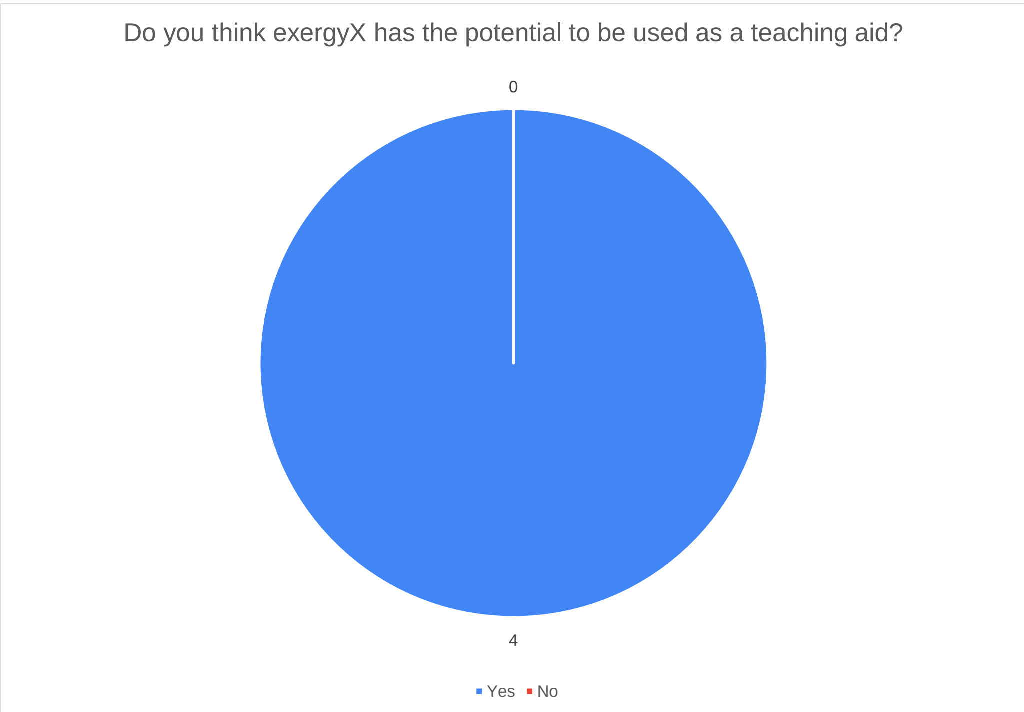

Figure 5.1: Answer to the question "Do you think exergyX has the potential to be used as a teaching aid?"

5.2 Students

A questionnaire was sent to the students of MoES with 22 questions about their game experience — based on the questions in Abeele et al. (2020) — and the game's ability to reinforce the subjects taught in the course. The questionnaire was composed of yes or no questions, questions using a Likert scale from 1 to 5 (Likert, 1932), and open-ended questions. A total of 6 students replied to the questionnaire.

The students reported satisfaction with the overall game experience. The game had an average curiosity score of 4.17 out of 5 (σ: 0.75), average ease of control of 4.17 out of 5 (σ: 0.75), average challenge score of 3.83 out of 5 (σ: 0.75), and average clarity of goals and rules of 4.83 out of 5 (σ: 0.41) (Figure 5.2). The full questionnaire answers are in Appendix B.

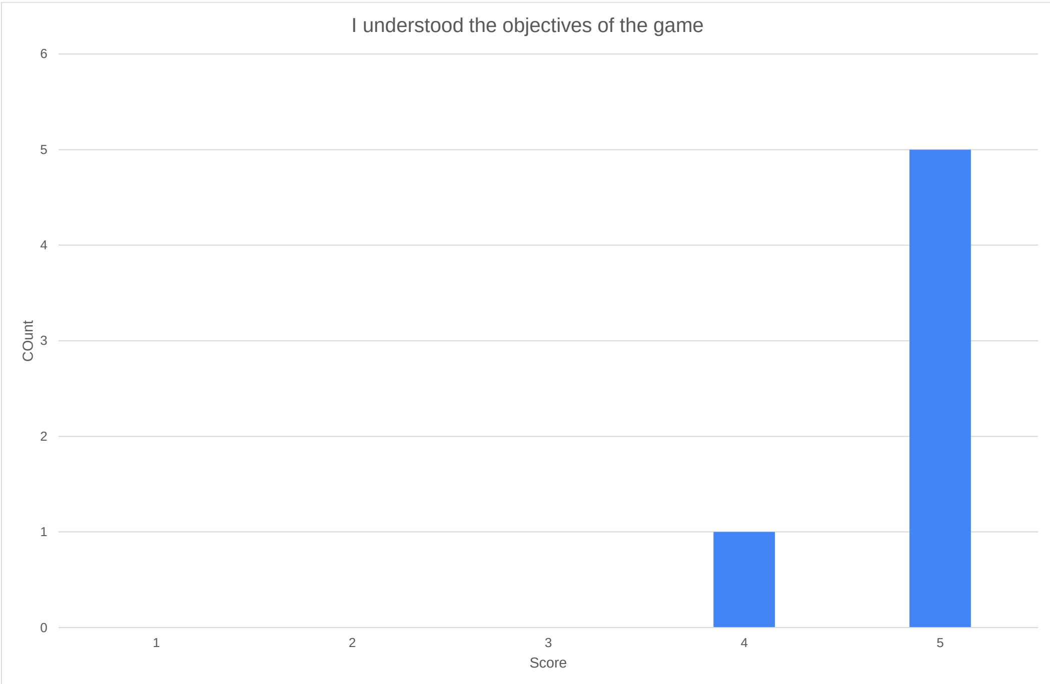

Figure 5.2: Answer to the question "I understood the objectives of the game"

The game was also able to reinforce the subjects taught in the class with all the students reporting that they were able to identify in the game the subjects reported in the course (Figure 5.3) and that the game portrayed the subjects properly (Figure 5.4).

Two of the students who answered the questionnaire added in the open-ended questions that they were able to recall parts of the subjects from the course through playing the game.

All students showed interest in playing the game as part of their class — with an average score of 4.5 out of 5 (σ: 0.84). The students showed less interest in playing the game in their homes as an

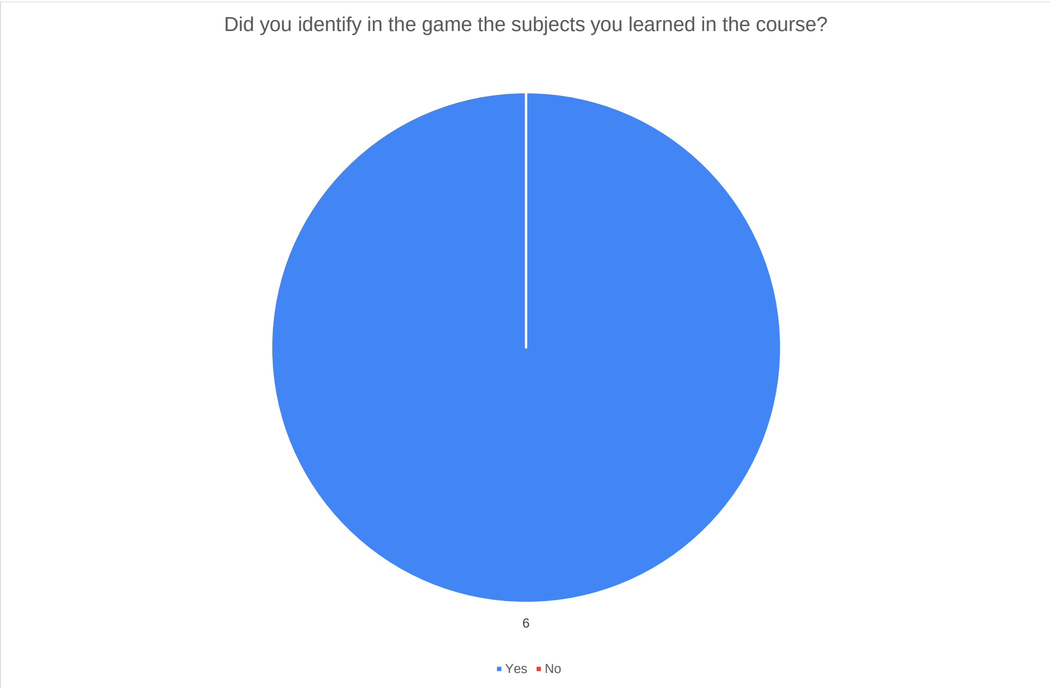

Figure 5.3: Answer to the question “Did you identify in the game the subjects you learned in the course?”

out-of-class exercise — average: 2.67 out of 5, σ: 1.21. These results can be seen in Figure 5.5 and Figure 5.6.

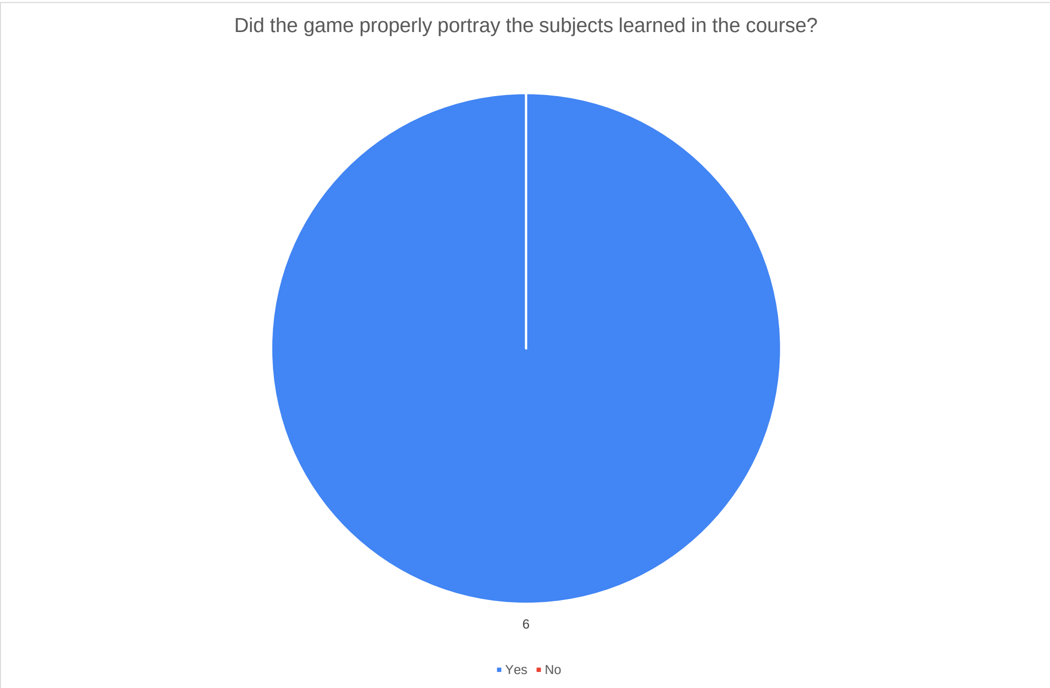

Figure 5.4: Answer to the question “Did the game properly portray the subjects learned in the course?”

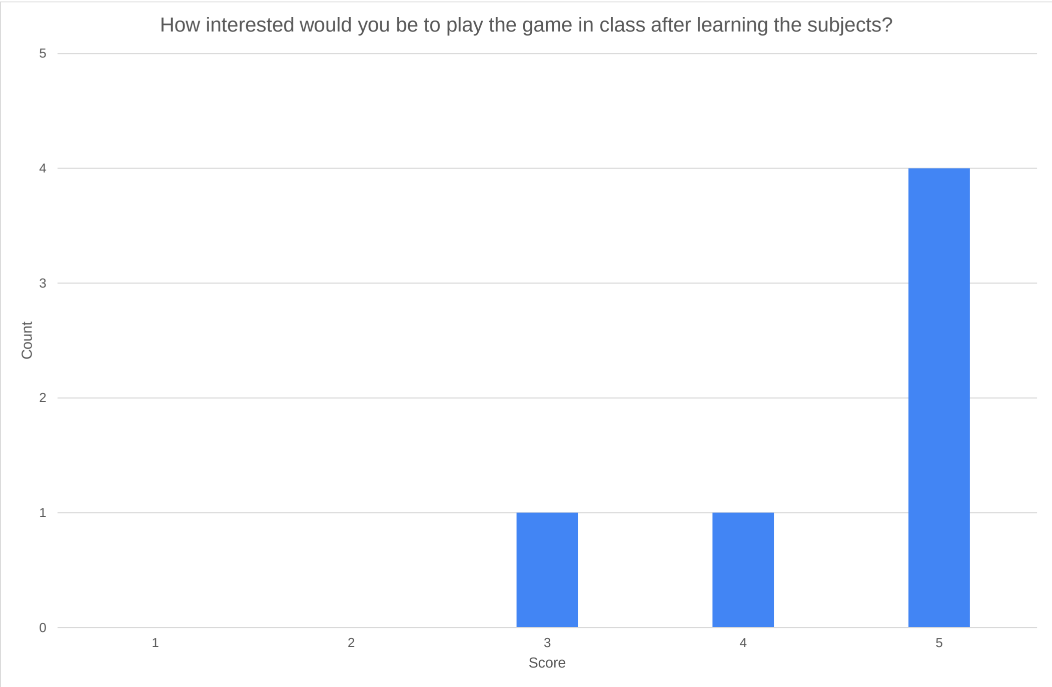

Figure 5.5: Answer to the question “How interested would you be to play the game in class after learning the subjects?”

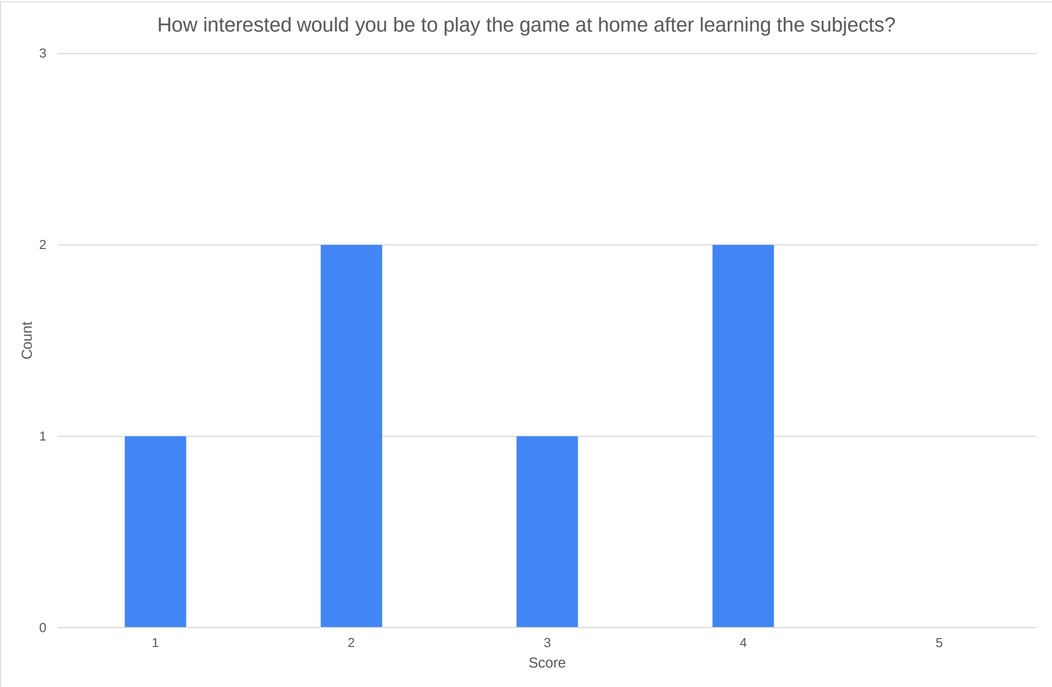

Figure 5.6: Answer to the question “How interested would you be to play the game at home after learning the subjects?”

6 Conclusions and Future Work

Following the evaluation of the game, we can see that exergyX has the potential to become a classroom aid for students to play with and assimilate the subjects in energy-related courses. Students appear to have enjoyed experimenting and seeing how their actions would affect the results. We can also assess that students felt engaged and were able to reinforce their memory of the subjects taught in their course. There appears to be a particular interest in playing the game as part of a class, as well.

Something that can be done to further improve engagement scores is the addition of more challenges. For example, adding events to the game such as natural disasters could add an interesting twist to the game and make players adapt their strategies. Another suggestion is adding a scoreboard to the game, allowing players to try and beat their highest score.

There are also some improvements that can be done in order to improve the game experience, such as increasing the pace of the game and being more explicit as to the effect of the distribution arrows in the Decisions panel.

We consider that exergyX can also be used as a basis for the creation of learning games for other areas. Since the model is mostly separated from the game, a tweak of the interface with a new model would be a good starting point for a new game.

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Appendices

A Expert Questionnaire Answers

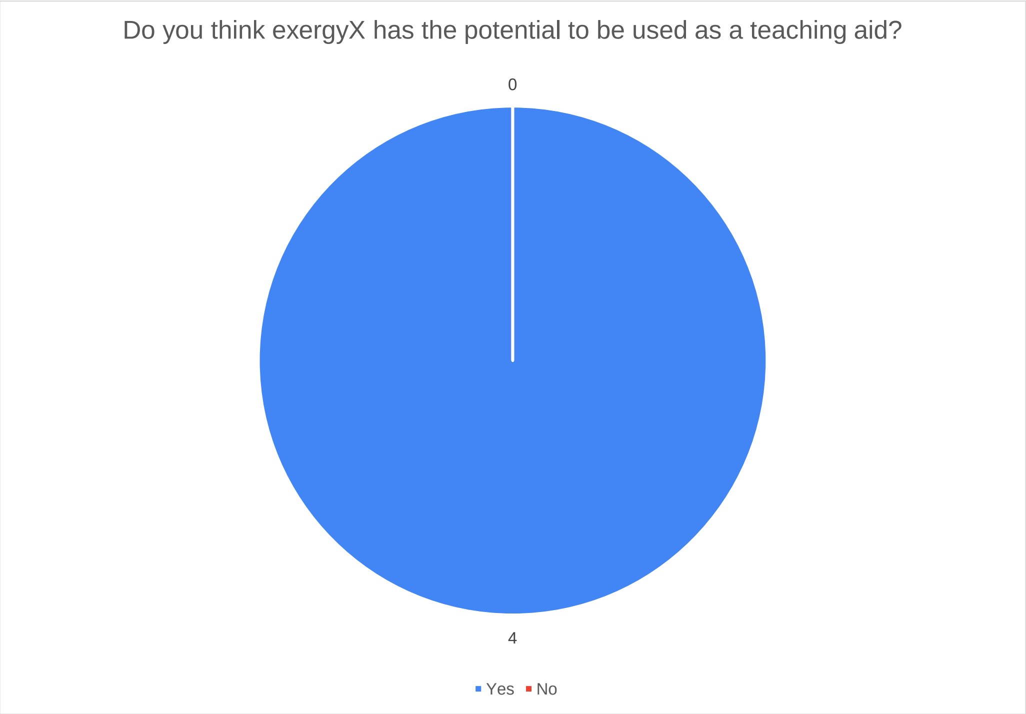

Figure A.1: Answer to the question “Do you think exergyX has the potential to be used as a teaching aid?”

Por favor, justifique a resposta anterior. Que elementos do jogo mais influenciaram a resposta?

O interface é fácil e intuitivo, e estimula o raciocínio lógico relativamente ao crescimento económico e as suas consequências, nomeadamente ao nível do consumo de energia necessário para manter (e promover) esse crescimento económico, bem como os aspectos negativos do mesmo, na forma das emissões poluentes. Transmite, de forma clara, a noção de que "não há almoços grátis"no que toca ao desenvolvimento de uma sociedade que quer a felicidade para os seus cidadãos, mas que precisa de perceber que essa felicidade depende também do cumprimento de metas ambientais.

Mostrar que a conexão entre emissões, PIB e felicidade são complexas e que não há soluções óbvias. Dar ênfase ao efeito de rebound da eficiêcia.

Dá para ver o impacto de diferentes acções, quer na procura de energia quer na geração (aqui é mais fraco)

---

os objetivos serem claros

Existe alguma funcionalidade (ou alteração) que gostaria que o jogo tivesse? Houve algo de que sentiu falta enquanto jogava?

EUmudava muita coisa no jogo. 1 - começar em 2020; 2 - por saltos de 5 em 5 anos (o jogo assim é chato e pouco realista, qualquer decisão politica de instalar X GW ou electrificar um sector demora alguns anos até estar em prática); 3 tem de se explicar o indice de felicidade; 4 - so ter custo de renováveis é pouco realista 5 deveria ter taxas de electrificação... as setas sao indicativas, mas não é facil ter a percepção do impacto..

Pelo que percebi a potência instalada de renováveis tem um máximo penso que é necessário, por isso, ter em conta/acrescentar a possibilidade do aparecimento do armazenamento de energia. Podendo o jogo ter ainda uma outra função em que seria possível promover políticas de aumento de eficiência com os custos e vantagens/desvantages associados

---

Algo a considerar talvez fosse um botão de "salto"para o ano meta, nos casos em que o aluno já atingiu ambos os objectivos do jogo mas ainda faltam vários anos para terminar.

+ feedback técnico-pedagógico sobre os impactos decisões

Imagine que usaria este jogo no contexto de uma aula, de forma a que os alunos consolidassem conhecimentos recém-adquiridos. Como integraria o uso do jogo na aula? (Exemplos de resposta: nos últimos 20 minutos de uma aula / como competição entre alunos / com atribuição de bónus na avaliação, etc.)

Após introduzir os alunos aos conceitos económicos de crescimento, investimento, consumo, e felicidade (ou utilidade), bem como aos conceitos de energia versus exergia, e geração de energia renovável/não renovável, utilizaria o jogo como forma de ligar estes conceitos de forma a que os alunos pudessem compreender que o sistema económico em que vivem e no qual participamos não pode existir "num vácuo", mas sim inserido num sistema maior, o ambiental, do qual retira energia (ou exergia) e para o qual envia emissões poluentes. É necessário que estes dois sistemas estejam em equilíbrio.

Competição entre alunos sendo atríbuida uma bonificação por classificação. Os alunos poderiam ter datas para submeter x anos em que tinham de dar os detalhes do jogo para esses anos, sendo depois enviado para os alunos uma classificação provisória e os resultados que agora saem normalmente.

---

logo no inicio apros breve explicação e depois o resto da aula para debate dos vários resultados!!

---

competição

Use esta caixa de texto opcional se quiser adicionar mais algum comentário sobre o jogo.

Possivelmente criar uma outra forma de investimento em pesquisa e desnvolvimento que podia resultar na produção de novas tecnologias. Ou ainda acrescentar eventos políticos ou desastres naturais que afetassem as decisões a tomar.

Excelente ideia e apesar dos meus comentários adorei o jogo e fiquei com vontade de usar já este semestre!!!

B Student Questionnaire Answers

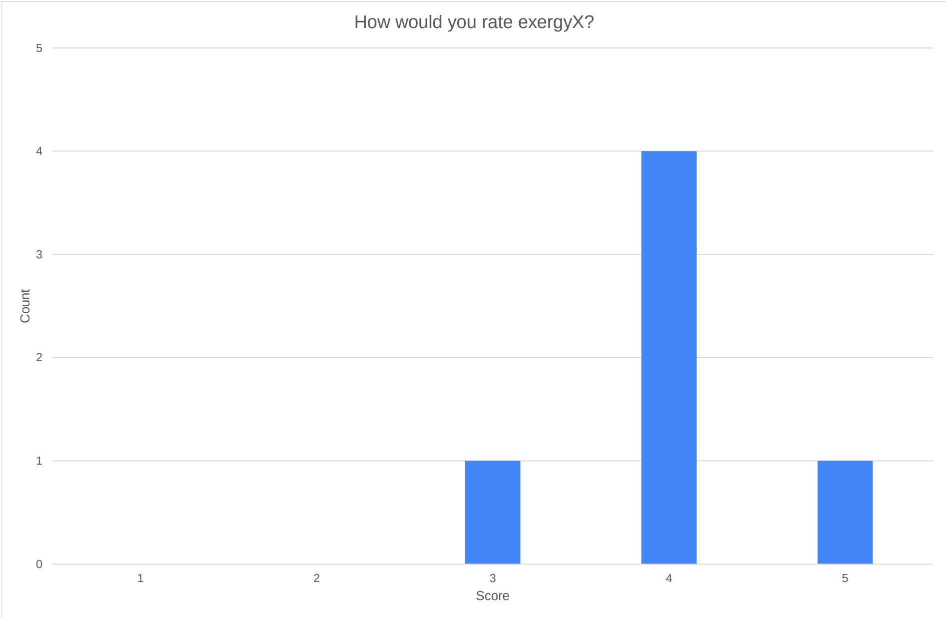

Figure B.1: Answer to the question “How would you rate exergyX?”

Identifica o que mais gostaste no jogo.

Perceber a influencia que tinha variar cada variável e conseguir jogar com isso a meu favor.

Ver os valores das previsões a mudar até conseguir bons resultados

---

os gráficos que indicavam o progresso eram uma boa maneira de ver como estava a progredir

---

As ajudas, senti-me acompanhada durante o jogo.

Gostei da curta duração do jogo,acabou antes de se tornar aborrecido.

Ver os valores a vermelho ficarem a verde deu-me satisgfação

Identifica o que menos gostaste no jogo.

Ao atingir os objetivos, basta manter as variáveis com crescimentos iguais nos anos seguintes que nada se altera. Isso faz com que o jogo fique ganho a partir do momento que se atinge os dois objetivos.

Achei o jogo um pouco repetitivo

---

o jogo tem um aspeto um pouco amador, mas pode ser suposto, não sei

---

- Às vezes tinha a impressão de não ter bem a certeza que estava a fazer.

O jogo é demasiado fácil, é só ir experimentando até ver o que funciona.

Tive de meter o monitor em full screen para conseguir ver melhor alguns dados, porque apareciam um pouco desfocados

Houve alguma parte do jogo onde tenhas sentido dificuldades a jogar? Se sim, identifica os problemas que sentiste.

Não

---

seria bom poder deixar o rato clicado num botão para aumentar o valor, em vez de estar sempre a clicar repetidamente

---

Era difícil perceber o peso que as setas tinha.

Ver acima

Indica o quão concordas com as afirmações seguintes, relacionadas com o que sentiste ao jogar o exergyX.

Sobre as tuas aulas de Gestão de Sistemas Energéticos:

Se respondeste à pergunta imediatamente acima, por favor justifica aqui a tua opinião.

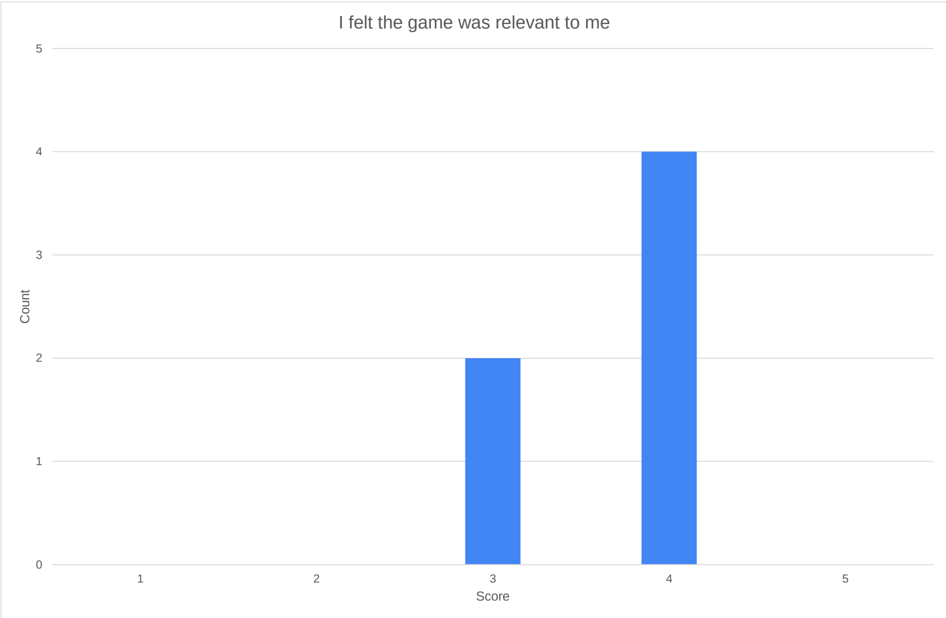

Figure B.2: Answer to the question “I felt the game was relevant to me”

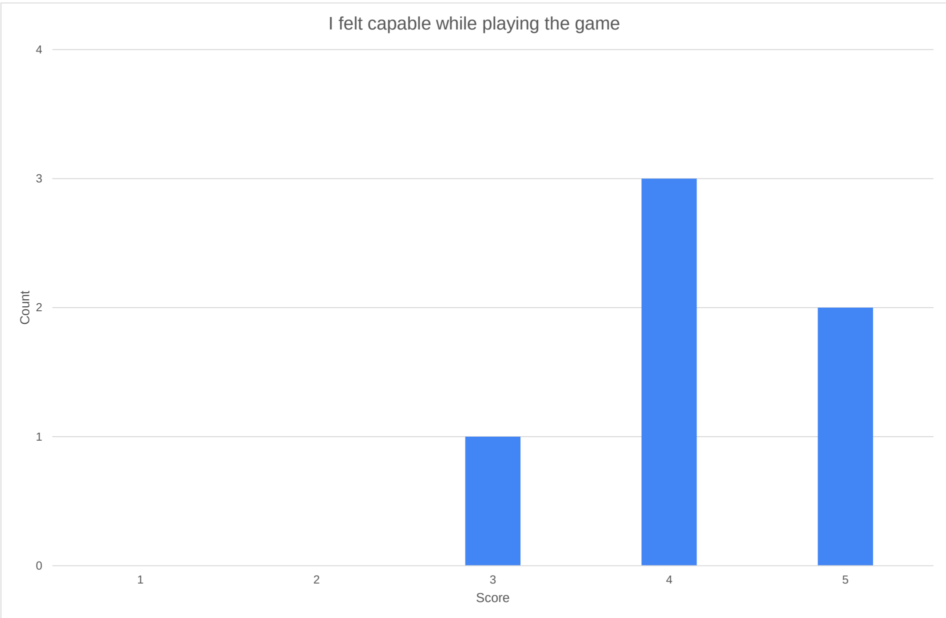

Figure B.3: Answer to the question “I felt capable while playing the game”

Os termos usados foram os mesmos que nas aulas

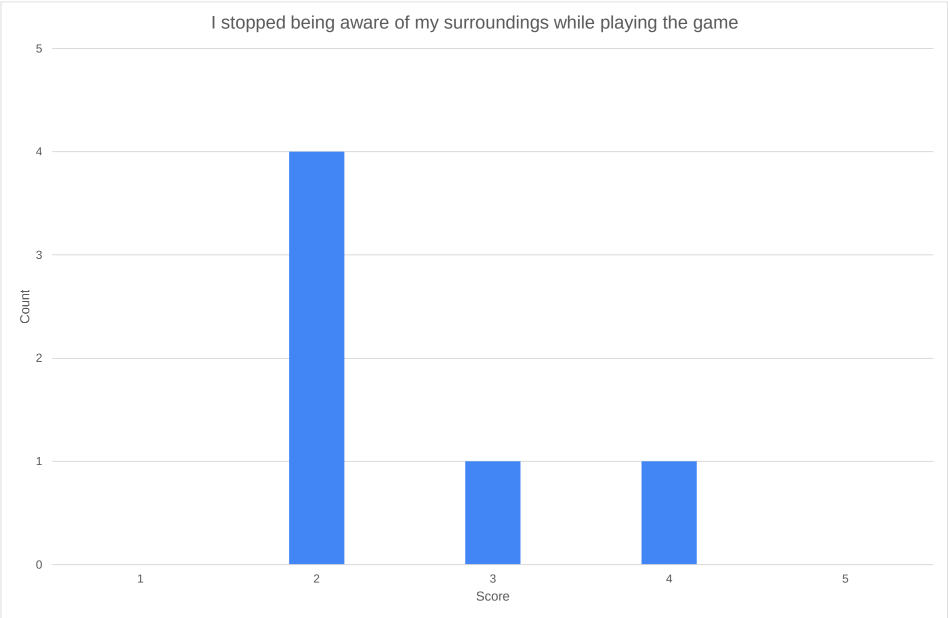

Figure B.4: Answer to the question “I stopped being aware of my surroundings while playing the game”

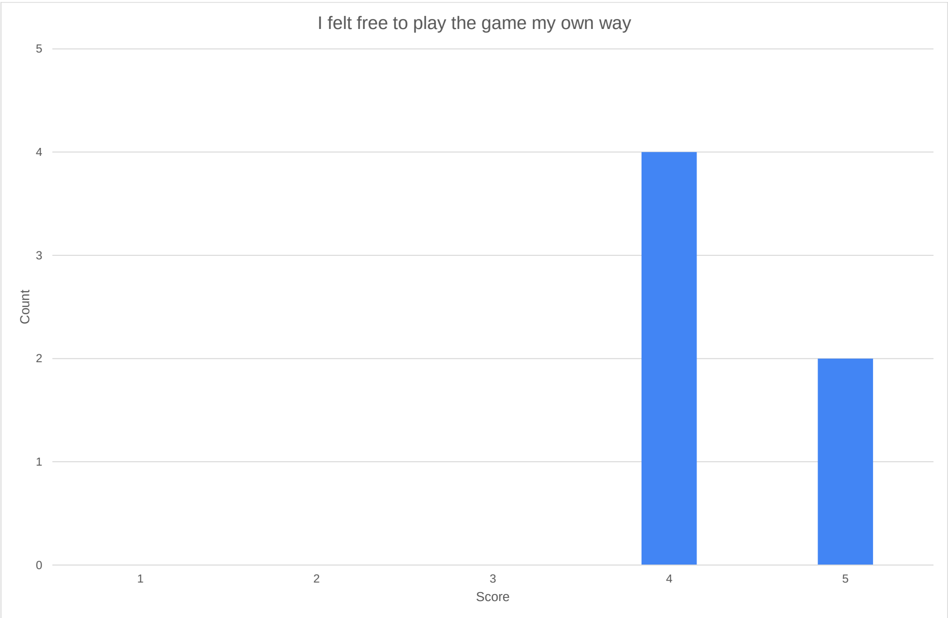

Figure B.5: Answer to the question “I felt free to play the game my own way”

já não me lembrava de algumas coisas porque já se passou algum tempo e o jogo foi uma boa forma de relembrar

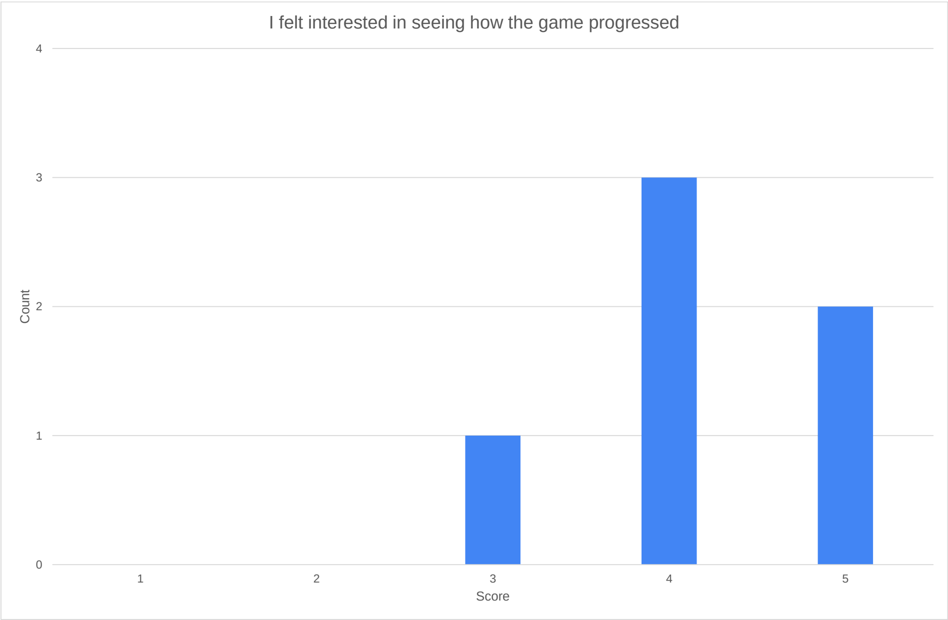

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Figure B.6: Answer to the question “I felt interested in seeing how the game progressed”

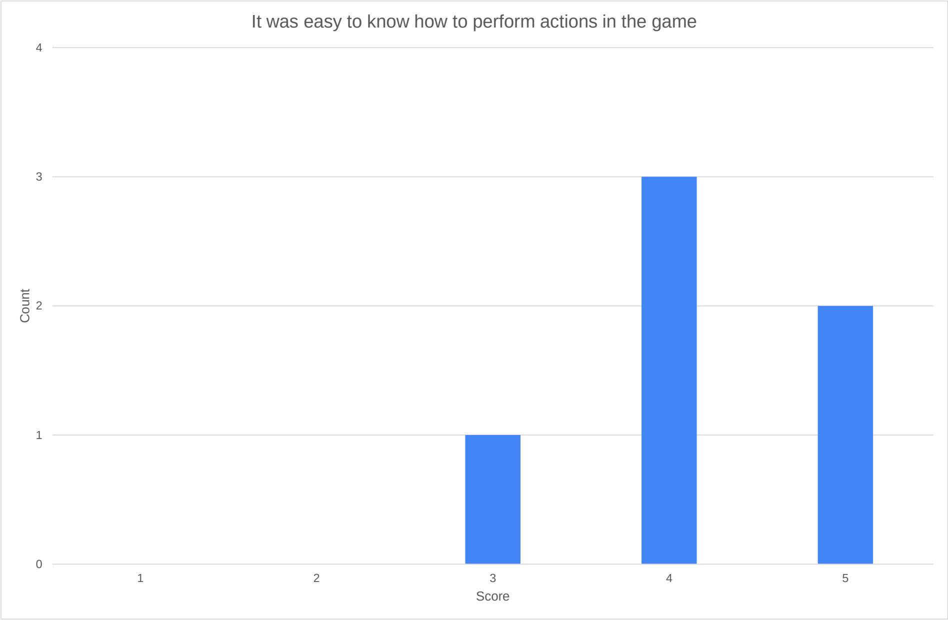

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Figure B.7: Answer to the question “It was easy to know how to perform actions in the game”

Não há muito a dizer estava tudo coerente.

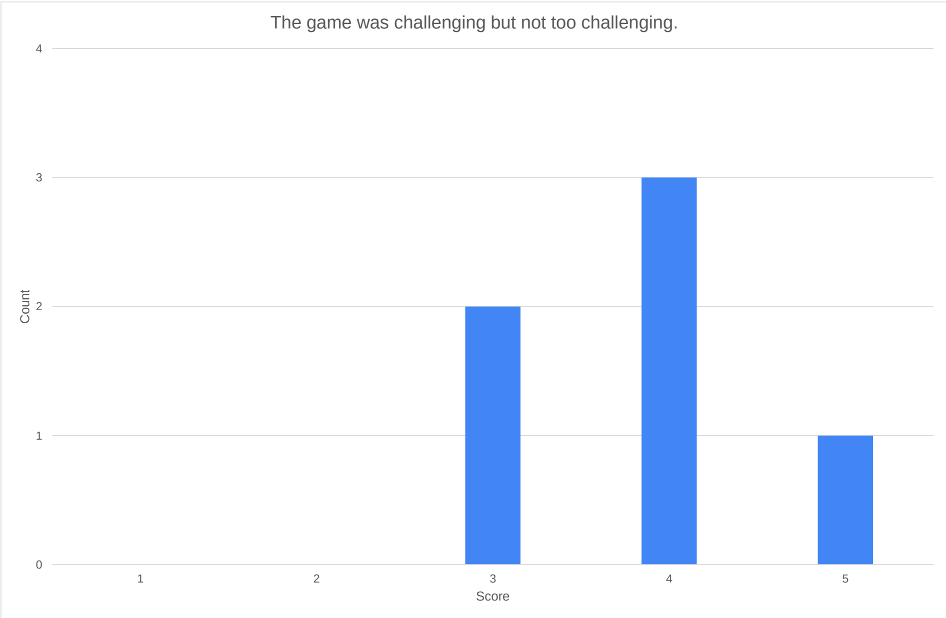

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Figure B.8: Answer to the question “The game was challenging but not too challenging”

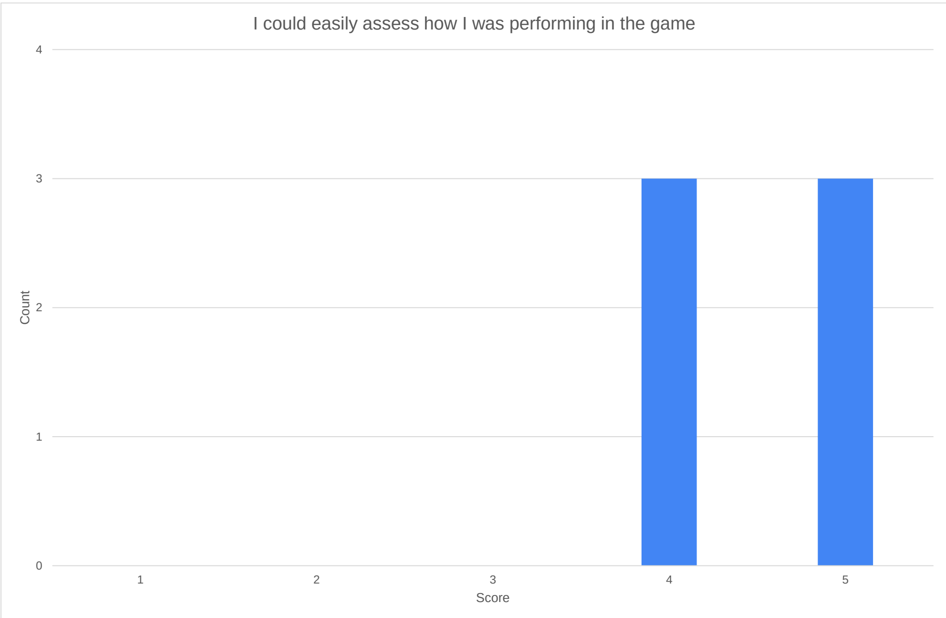

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Figure B.9: Answer to the question “I could easily assess how I was performing in the game”

Lembro-me da professora ter falado dos temas que estão no jogo, principalmente da eficiência

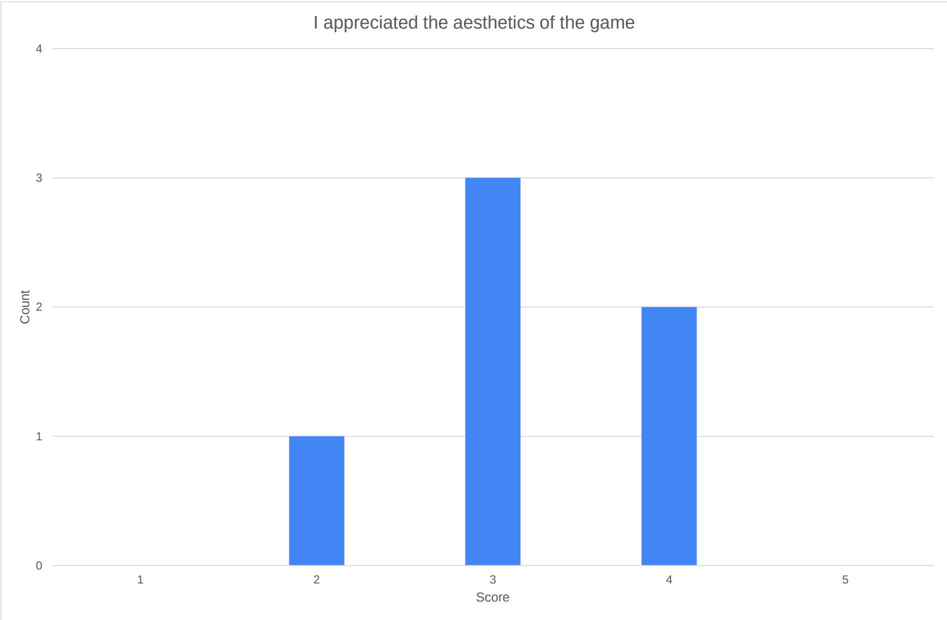

Figure B.10: Answer to the question “I appreciated the aesthetics of the game”

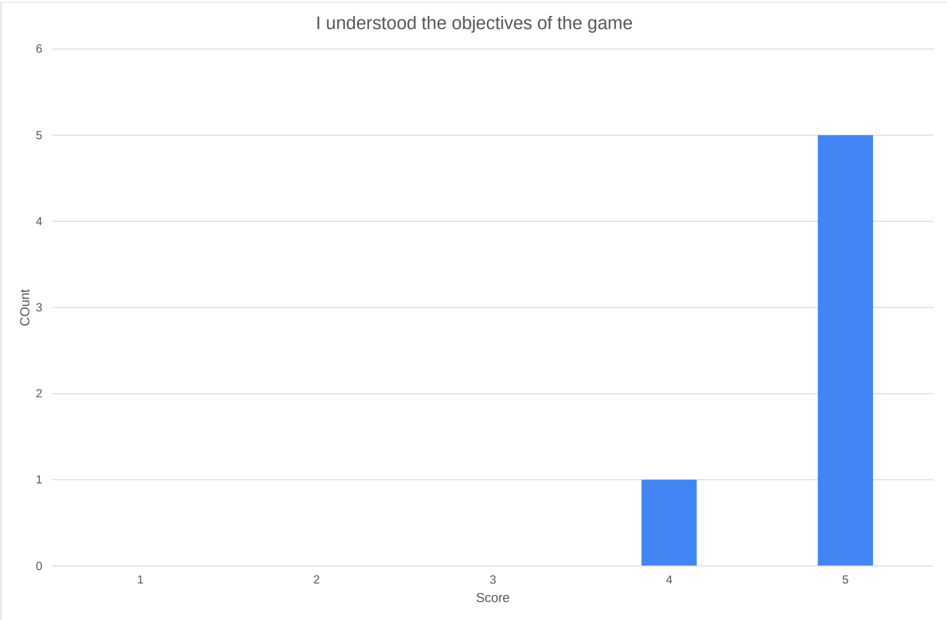

Figure B.11: Answer to the question “I understood the objectives of the game”

Imagina que o exergyX era usado numa tua aula. Das seguintes opções, indica o quão interessado estarias em que elas fossem implementadas.

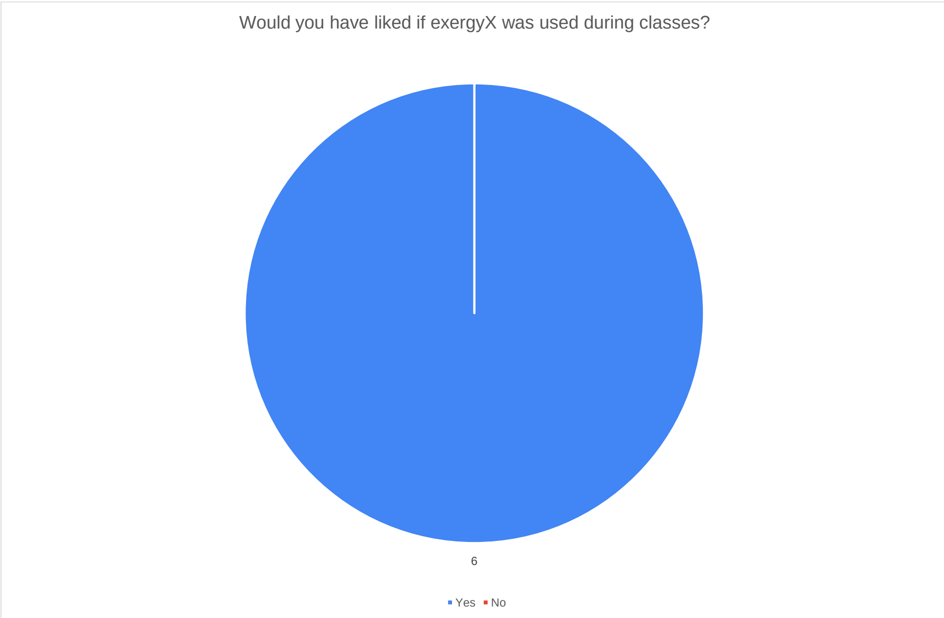

Figure B.12: Answer to the question “Would you have liked if exergyX was during classes?”

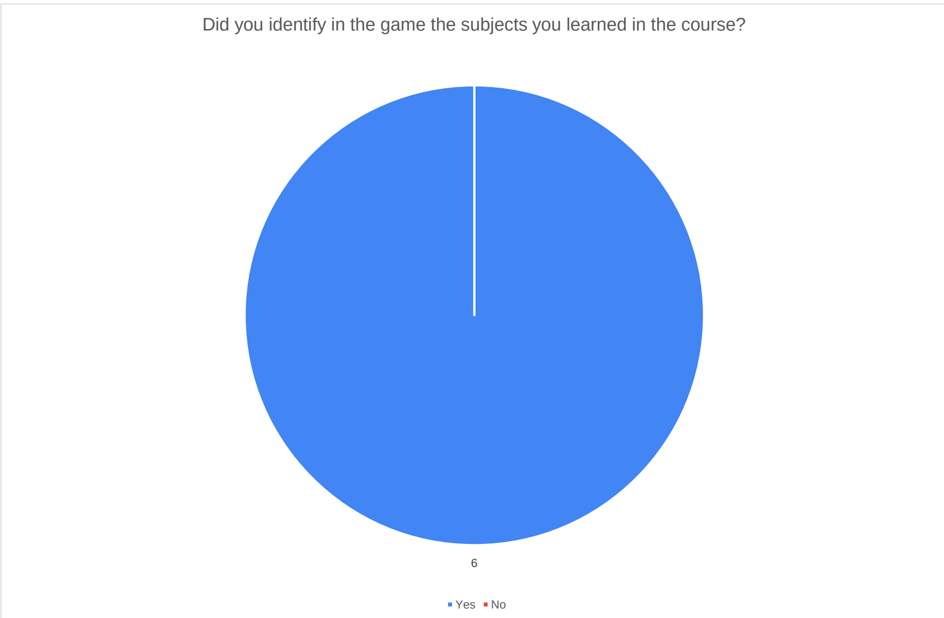

Figure B.13: Answer to the question “Did you identify in the game subjects you learned in the courses?”

Usa esta caixa de texto se quiseres dar mais alguma opinião sobre o jogo.

Acho que tem potencial, mas pode melhorar

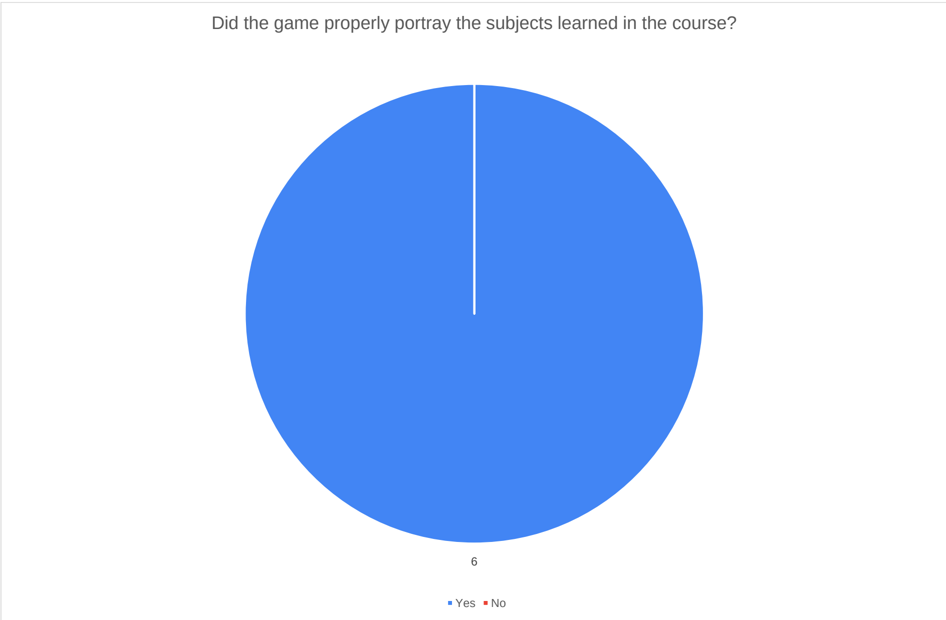

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Figure B.14: Answer to the question “Did the game properly portray the subjects learned in the course?”

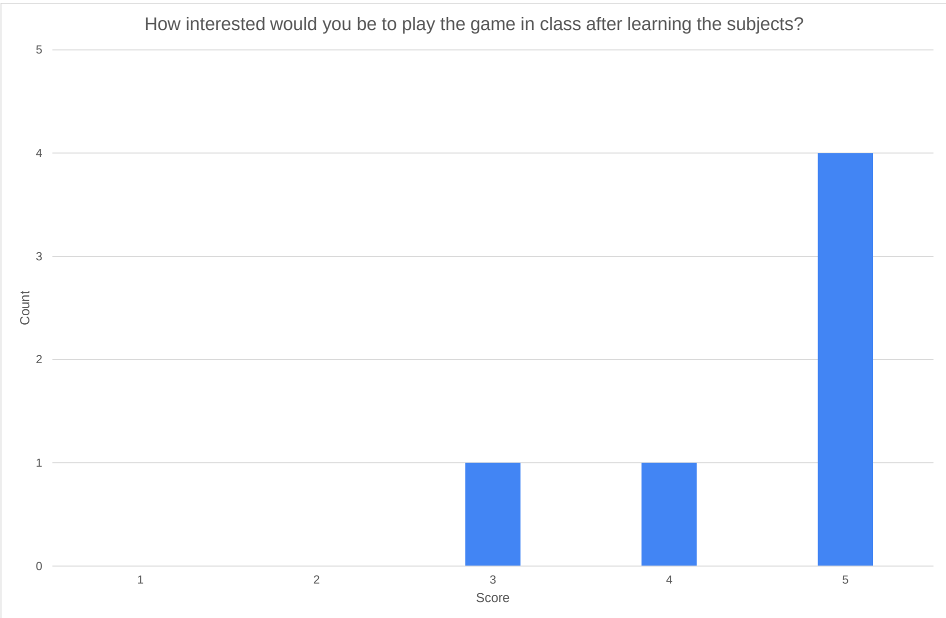

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Figure B.15: Answer to the question “How interested would you be to play the game in class after learning the subjects?”

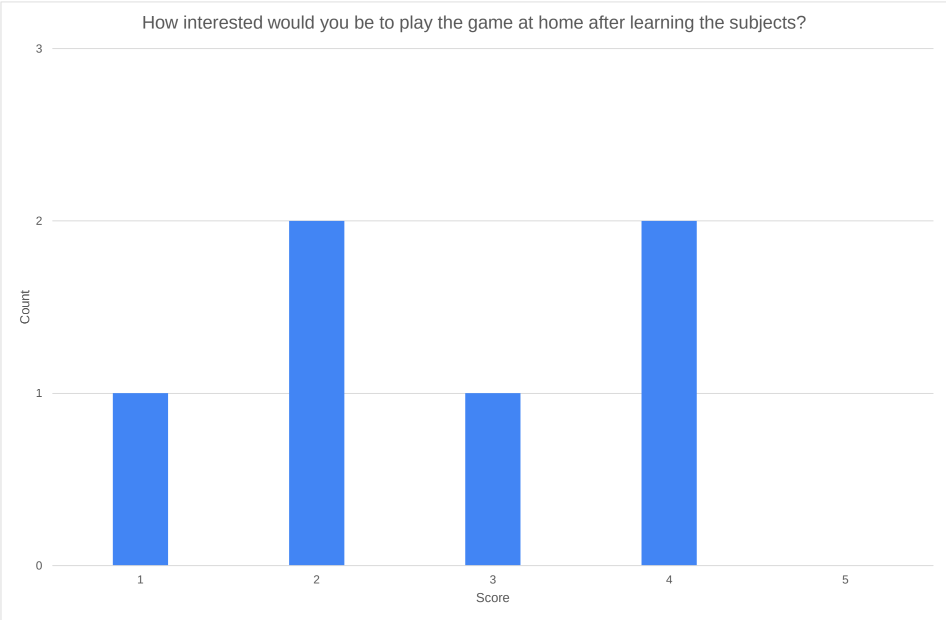

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Figure B.16: Answer to the question “How interested would you be to play the game at home after learning the subjects?”

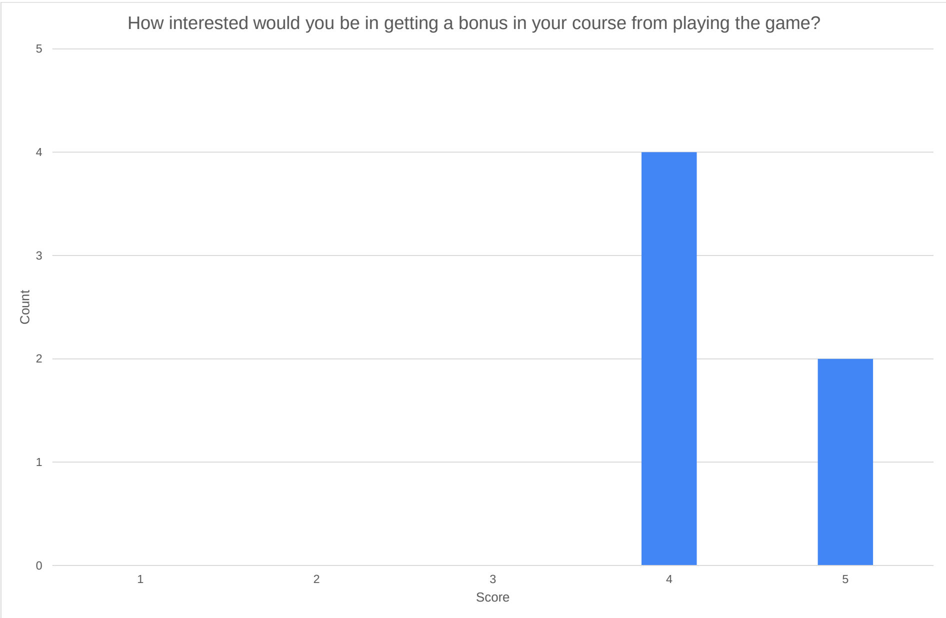

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Figure B.17: Answer to the question “How interested would you be in getting a bonus in your course from playing the game?”

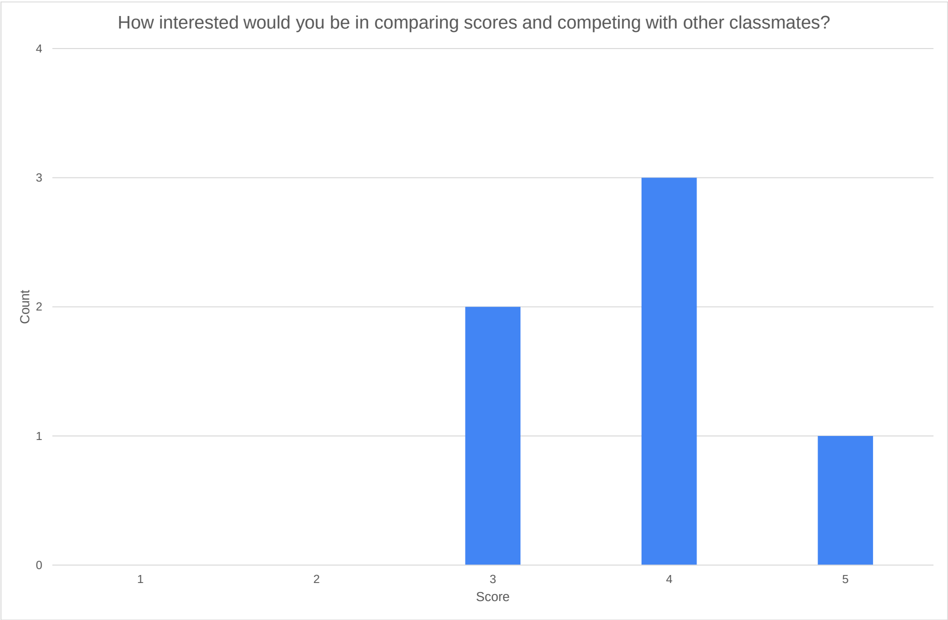

Figure B.18: Answer to the question “How interested would you be in comparing scores and competing with other classmates?”

C User Testing Notes

Test #	User Data	Notes
1	Female, 28yo	Não é óbvio identificar quais dos botões são clicáveis Consegue perceber o significado dos valores nas previsões Não é claro ao que “distribuição por setor” se refere É preciso reforçar que os números das metas entre parêntesis se referem aos objetivos Consegue perceber a que se refere o resto dos dados no ecrã Em termos estéticos está bom Sugestão: Colocar o ano “2050” no mesmo tamanho que o ano atual O ecrã de resultados desaparece com um clique fora, não devia Corrigir "2050 - Resultados (Objetivos)"
2	Male, 26yo	Foi relativamente fácil achar os botões Gráfico está bom Percebeu a distribuição por setor Achou que era relativamente óbvio onde estavam os botões Achou que não havia máximo na potência a instalar, mas não atingiu limites Adotou uma estratégia de tentativa e erro ao analisar os resultados Achou que há tempo suficiente para corrigir erros cometidos antes de 2050 “A animação do ano está gira” Arredondar ecrã de resultados (corrigir o ecrã no geral, retirar crescimento) Sugeriu dar mais contexto ao número da felicidade Em termos estéticos gostou
3	Male, 23yo	Falta shading aos botões para indicar que são clicáveis Apreciou as checkboxes no gráfico para poder ver melhor os valores sobrepostos Sugeriu melhor espaçamento de texto no ecrã principal Achou difícil compreender o que estava a decidir -> Mas não tem conhecimentos sobre o assunto do jogo -> Isto não deverá ser um problema para alunos do curso Nada a apontar em termos estéticos Demorou 2 anos de jogo a perceber que tinha de jogar até 2050

Table C.1: Notes from the game’s user testing