Developing an Educational Game to Teach the Concept of a Black Start of the Power Grid

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Graduation Project

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Start date: 02-09-2024

End date: 31-01-2025

Abstract

A black start is a complex but important process during which power is restored to the grid after a power black out. Education on this topic is thus of great importance for society. However, this topic is not part of the curriculum of the bachelor programme of Electrical Engineering at the University of Twente. This project aims to create an educational game to explain the core elements and the decision-making process in a black start. This will be done with literature research on the topic of black starts and power grids as well as the design of educational games. The educational game will be developed, tested and evaluated.

The game developed is an escape room in which players are divided into two operator teams and a management team. The teams have to work together to solve the puzzles to get the generators back online. Each generator will have to be synchronised to the grid once it has been powered. The players win the game when the city has enough power to bridge the peak power demand of the cold load pickup within the thirty-minute time limit.

The game aims to explain the concepts of synchronisation and cold load pickup during a black start and it aims to be experienced as fun. During the user tests, it became clear that the understanding of the players of the concepts was there, however, the players did not seem confident in their knowledge of the subjects. In future iterations, these concepts should be integrated into more crucial parts of the puzzles. The escape room was experienced as fun. The goal of this project was thus partially achieved.

Acknowledgements

I am very grateful to my supervisor, Nataly Bañol Arias, and my critical observer, Juan López Amézquita, for their guidance and support during this amazing project. They were always happy to answer my questions and share their expertise which was very helpful when brainstorming for better solutions.

I would like to express my appreciation to all the participants who wanted to test the game and provide feedback and suggestions. Finally, I would also like to thank my friends and family for all their help and for keeping me motivated and somewhat concentrated.

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List of Acronyms

Acronym	**Meaning**
GBL	Game-Based Learning
PCL	Priority Customer Load
SUS	System Usability Scale

AI Statement

In the preparation, writing and development of this work, no use was made of generative artificial intelligence tools.

Chapter 1 – Introduction

Power grids transport our daily use of electricity [1]. Power grids generate power and supply it to the places where we use it. To ensure that everyone has reliable access to electricity, the grid is monitored to prevent, mitigate or resolve problems [1]. Power outages – interruptions in the electricity supply [2] – are one of the possible problems, often caused by bad weather, equipment failure or natural disasters [3]. Power outages can result in blackouts. Blackouts cut off the electricity supply completely, thus affecting large areas. Blackouts harm the local economy and human welfare [4]. Essential services such as hospitals and water cleaning companies need power to operate. These essential services have a source of backup power [5] however, these can only be used for a limited amount of time, and therefore, restarting the power grid as soon as possible is vital.

A black start – the start of the power grid without any power to begin with after a blackout – is a difficult task with little room for error [6]. It is therefore important that the people in charge of these operations are well-trained and knowledgeable about the grid in their area so they can handle black starts with the utmost care.

Most people are not aware of the challenges that black starts can cause. Creating awareness and interest in this field should therefore be considered. The topic of black starts is not covered in the bachelor program of Electrical Engineering at the University of Twente [7]. This is partially because there is a lot of required background knowledge in the understanding of power grids needed before black starts can be understood. Additionally, power grid operations can best be understood by doing. Especially in the case of blackouts, this is hard to practice as they are not very common. Teaching the concept of black starts is therefore a complicated matter.

Teachers in the Electrical Engineering field would like to increase the understanding of their students about the concept of black starts. Increasing the knowledge of the subject and helping students retain information better are some of the benefits of active learning methods [8]. Game-Based Learning (GBL) is a form of active learning which motivates and encourages students to solve problems in a different way than regular education [8], [9]. To aid the teachers in developing a method to increase the understanding of their students concerning black starts, an educational game will be developed.

Developing a teaching method in which students learn about the challenges that come with black starts can be beneficial for informing and motivating people to do more research and pursue careers in power system management and operation. To teach people about the concept of black starts and make them enthusiastic about the topic, an engaging way of educating them should be developed. Educational games result in a better understanding of the topic compared to traditional teaching methods [10]. Using a game to teach the concept and procedures during a black start could therefore be more fitting to enthuse and motivate players about the topic. The fun aspect of the concept of power blackouts and black starts might motivate some players to consider a career as a power grid operator.

The game will challenge players to communicate while solving puzzles to get the generators working again. The players will work in three different teams, two operation teams and a management team towards the common goal of restoring the power before the time runs out. The game is targeted at people with minimal to average amounts of knowledge on the topic of black starts.

The research question that will be looked at during the graduation project will be as follows.

Research Question: How can the core elements and the decision-making process of a black start be represented in an effective game to teach university students this concept?

Sub-Research-Question 1: What are the fundamental steps in a black start?

Sub-Research-Question 2: What are the most effective ways to make an educational game?

Sub-Research-Question 3: How can the knowledge of sub-research-question 1 and sub-research-question 2 be combined into an effective game to teach university students about the concepts of a black start?

This paper will consist of literature research that covers information about the approaches to restoring the power grid during a black start as well as challenges that might be encountered. The literature research will also dive into the use of educational games and their effective aspects. Additionally, the difference between board games and digital games will be discussed. The background research will be concluded with a state-of-the-art, exploring the different (educational) games and their various aspects.

Following the background research, the methods, ideation, specification, realisation and evaluation of the game will be discussed. Finally, a conclusion will be drawn.

Chapter 2 – Background Research

2.1 Literature Research

To design an educational game to teach the concept of black starts in power grids, it is important to look at the process of a black start. The foundation of a good educational game is a good understanding of the concept.

Part of the literature research will look at educational games. This is to get an understanding of which aspects of educational games are effective and should therefore be considered to be implemented into the final game.

2.1.1 Black Starts of Power Grids

2.1.1.1 Structure of a Power Grid.

The electricity grid consists of three main categories: generation, transmission and distribution [1]. The generation category focuses on generating the power needed to meet de demand from the customers. The generators can be divided into subcategories: conventional fuel generators and renewable fuel generators. Conventional fuel generators are generators that use coal, oil, natural gas and nuclear power as fuel; these fuels cannot be replenished once they have been used [1]. Renewable fuels use wind, water power, solar power, geothermal heat and tidal waves as energy sources; these sources of energy can be used multiple times.

The transmission category consists of high-voltage power lines, while distribution consists of lower-voltage power lines. Transmission lines are used to move large quantities of electricity over large areas from the power plants to substations. The voltage gets reduced via transformers and can thus be transported over the distribution lines. The distribution lines move the electricity from the substations to the individual customers [1].

2.1.1.2 Approaches to Black Starts.

There are multiple ways to restore the system after a blackout. A bottom-up approach, a top-down approach and a combination of those two. The bottom-up approach restores multiple power generators at once, creating small islands which have to be interconnected at a later point in time [11]. The top-down approach has a restoration plan based on assistance from outside the affected area. The combination approach uses outside sources to build islands which will be connected to outside sources as well as interconnected. The bottom-up approach should be the basic plan in case of a blackout for all power companies [11], [12]. Therefore, this will be the main focus of the literature research as well as the design of the game.

2.1.1.3 Restoring the Grid.

The first step in restoring the grid is the assessment of the problem [11], [13]. Grid operators determine which, if any, generators are still online and asses the possible damage and the location of the generator. The grid operators will try to stabilise the generators so that they will not be part of the blackout. They evaluate if it is possible to increase the generated power load.

The generators that are offline are assessed on their status before the blackout and the possible damage done [11]. Generators that were running before the blackout, can be restarted quicker compared to generators that have not been operating for some time. Damaged generators will be isolated and avoided [14]. Afterwards, the presence of power or generators is evaluated, and the capability of a black start is calculated.

The order in which the generators are powered depends on the type of generator [11]. Hydro generators do not need starting power, so they can easily and rapidly be started. Afterwards, small combustion turbines will be started to generate enough power for the other generators to operate [15]. When there is enough power to start up the big generators, the first ones that are activated are the Drum-Type generators and the Super Critical Steam generators. Finally, the nuclear generators will be started since these have the most start-up requirements and need the largest amount of time to restart, usually more than 24 hours [14]. The speed at which the generators are back online depends on the status of the generator before the blackout as well as the type of generator.

Renewable energy sources, such as wind turbines and solar panels, are usually not started until the grid is fully operating. This is because the output of those generators is dependent on uncontrollable factors, such as weather conditions and locations of the generators, making the power outcome unreliable. In black starts, reliable power is essential in preventing another blackout. With some strict guidelines the renewable energy sources can be used. Large renewable energy facilities can sometimes be used by charging batteries that can be used as black start units [13]; the reason this is not common practise is that it is costly.

2.1.1.4 Powering the Grid.

Once the generators work, the power that they generate can be used to power the Priority Customer Loads. Priority Customer Loads (PCL) are the important parts of the grid that need to be powered first. PCL include medical facilities, governmental and military facilities, public health companies such as water and sewage pumping stations, law enforcement, and telecommunication companies [11]. Once the PCL are powered the non-priority loads can also be powered. The Non-Priority Customer Loads include general customer power and renewable energy generators.

2.1.1.5 Challenges.

Various technical challenges can occur when performing a black start. The two main challenges are the cold load pickup and the synchronisation of the energised islands. Other challenges can occur during a black start, such as fault analysis, transmission capacity and energisation of the transmission lines, but these will not be discussed in detail. The first of the main challenges that will be discussed is a cold load pickup. This is a peak in energy demand after the power has been out [11]. It is caused by the initial power needed to turn electronic devices on. A refrigerator, for example, has to reach a certain temperature before it stops cooling, using a lot of power; once this threshold has been reached, the cooling is stopped until it has warmed up enough that cooling is necessary once again. The power required for the initial cooling of the refrigerator is called the cold load pickup. The cold load after a blackout can be up to ten times as much power compared to normal loads and has to be considered carefully [11].

In the bottom-up approach, the grid is powered in small islands which are each connected to a generator. To fully restore the grid, these islands need to be connected. To do this, the islands both need to be stable, otherwise one larger unstable island will be created, which could lead to another blackout [11], [12]. Islands are stable if they are within the voltage limits and have a frequency within boundaries, as well as enough reserves. Once these conditions are fulfilled, the frequency and voltage of the smallest island will be adjusted to match that of the larger island, to prevent damage and possible blackouts [11]. When the islands are successfully connected, a more stable bigger island is created which can more easily give power to other areas. Connecting the islands is of great importance and should always be done.

2.1.2 Design of Educational Games

The distinction between educational games and serious games is still a debate. Michael and Chen define serious games as "*games that do not have entertainment, enjoyment, or fun as their primary purpose*" [16, p. 21] while Abt defines it as "*an explicit and carefully thought-out educational purpose and are not intended to be played primarily for amusement*" [17, p. 9]. Hendrix and Backlund [18] agree with Abt that educational games are serious games which are used for educational purposes. Serious games do not necessarily have to contain an educational aspect, although the educational aspect is often implied in general use. The term educational games will be used henceforth to clarify the educational aspect of the game.

Education is often seen as a means to the end of academic achievements. According to Biesta [19], education can be categorised into three subdomains: qualification, socialisation and subjectification. The qualification domain covers the topic where knowledge and skill gain are acquired. Socialisation is the domain of the cultural, political and religious aspects of learning. Subjectification talks about whether the learners are responsible and take initiative or if they only do what they are told to do [19]. Educational games can play a role in all these domains as they can teach knowledge, can offer a way for students to interact with each other and can make students take on responsibilities. Educational games can teach students within all three domains which should be kept in mind when designing the game.

2.1.2.1 Why Educational Games Work.

An increase in students' understanding of the subject being taught can be achieved with active learning. Hosseini et al. [8] have investigated various methods for active learning including cooperative learning, computer-based learning, peer-teaching and educational games. They conclude that Game-Based Learning (GBL) is effective as it motivates and encourages students to solve problems in a different way. Chih-Hsiung et al. [9] agree that GBL is effective. Linehan [20] adds onto this that the motivation of the students, which can be created with GBL, is essential for good achievements, and long-term educational outcomes. Shaiakhmetov et al. [21] state that GBL tends to hold students' concentration longer than traditional teaching methods. According to Hosseini et al. [8], GBL might encourage a more diverse group of students with different learning styles to actively learn and participate. Because GBL motivates students, increases students' performance, holds their concentration and allows them to solve problems differently, it can be a useful way of teaching.

2.1.2.2 Challenges of Educational Games.

Educational games are usually regarded as effective ways of teaching, however, some challenges come with the design of educational games. It might seem a good idea to award players with a point system, in the form of money, energy or resources for example. The designers have to keep in mind that awarding players with points can lead to a different learning outcome since points are an extrinsic motivation source for students. Extrinsic motivation can focus students' motivation on merely achieving the rewards instead of focusing on the goal. Hosseini et al. [8] warn that the points given can become the focus of the students' motivation instead of the active and deep learning of the material. The designers should keep the focus point for the students in mind when designing an educational game.

The focus point of the game should be clear, the game mechanics should not distract the students from this focus point. Gui et al. [22] emphasise that it is important that the game does not contain redundant game mechanics as this can lead to unnecessary cognitive load for the students. They state that the student's brain will use energy to process all these unnecessary game mechanics that do not add to the learning of the subject at all. The students will have trouble retaining important information when the game has too many unnecessary game mechanics.

2.1.2.3 Effective Aspects of Educational Games.

Designers now know what to avoid, but knowing what effective aspects to add, is an important part of educational game design. Linehan et al. [20] and Serrano-Laguna et al. [23] agree that to make an effective educational game, it is important to incorporate learning as an essential game mechanic instead of adding the learning process as an addition to the gameplay. Shaiakhmetov et al. [21] add that the learning process should be accelerated by the game and that the game should improve the understanding of the subject. Focusing on making the game 'fun' is essential to making a good educational game; that means, according to Linehan et al. [20], that designing an educational game the same way as one would with a game for entertainment purposes. This seems contradictory to the definition of educational games previously given by Michael and Chen [16] and Abt [17]. However, as long as the primary goal of the game is the learning aspect instead of the game being fun, the game will still fall under the educational game category. Making a game fun is thus an important aspect of the design of the game. To make a game enjoyable, Gee [24] emphasises the game should focus on the outer and growing edge of a player's capabilities so that the games are both slightly frustrating and enjoyable. A good educational game should thus focus on incorporating and accelerating the learning as a process of the gameplay while designing the game itself to be fun to play.

A key aspect of making a game fun are the players’ goals. Swartout and van Lent [25] conclude that the goals are often divided into three categories: short-term goals, medium-term goals and long-term goals. The combination of these different types of goals keeps the players immersed in the storyline. Shaiakhmetov et al. [21] stress the importance of keeping the players concentrated on the game, which can be achieved by an immersive storyline. Schell [26] and Swartout and van Lent [25] agree that to add these goals, it is important that the player can have a sufficient amount of interaction within the game as well as being or having the feeling of being in control. Swartout and van Lent [25] conclude that a balance should be sought between complete players' freedom, which might result in boredom, and complete control of the game, which could lead to players interpreting it as a lecture or movie. Linehan et al. [20] add that a good way to do this is to require the player to make a decision or take a (series of) action(s) to complete a goal, resulting in a different outcome of the game which makes the game responsive according to Loftus and Loftus [27]. However, this can make the game feel like a quiz, which is, game-wise, not a good approach as stated by Szilas [28]. Thus, player goals should be added in such a way that the players feel in control, this can be done by letting them make decisions, for example.

2.1.2.4 Board Games Versus Digital Games.

In the design of educational games, a distinction can be made between digital and non-digital games. Computer or mobile games are usually considered digital games while board and card games fall under the non-digital game category. According to Petri et al. [29] both digital and non-digital games have positive effects on confidence, satisfaction, social interaction and fun. However, there are some differences in the ways the students experience the educational games as each type of game has their advantages.

Digital games have the advantage that they can generally be used by students without the help of a teacher or teaching assistant and are therefore easily used in larger groups of students. Petri et al. [30] found that digital educational games generally have a higher usability, which makes the games more accessible. Petri et al. [29] later expanded this with the information that digital games are usually experienced as easier to learn because the gameplay tends to be self-explanatory, making them more accessible to use in the classroom. Digital games are useful for larger groups that need to quickly be able to play the game, assuming the players have access to devices on which the game can be played.

Non-digital games are often designed for smaller groups and require some explanation before playing. The advantages of non-digital games have more to do with perceived learning and enjoyment. Non-digital games have a more positive evaluation in terms of focused attention as found by Petri et al. [29]. This possibly results in a slightly more positive perception of achieving the learning objectives [29]. Yadollahi et al. [31] and Sousa [32] agree that non-digital games are experienced as being more fun. Petri et al. [30] and Nease and Thomas [33] confirm this while adding that non-digital games generally result in better social interactions. Petri et al. [30] found that "*no significant difference with respect to learning has been observed […] only in terms of professional practice, non-digital games seem to be able to contribute more than digital games*" [30, p. 157]. Non-digital games are more useful for explaining learning goals while being experienced as more fun in comparison to digital games.

2.2 State of the Art

Several games have been designed around black starts of power grids, some with educational intentions others purely entertainment-based. A short overview will be made of each of these categories. Furthermore, games with other topics that might be useful in the implementation and development of the game will be discussed.

2.2.1 Power Grid Games

There are multiple games with the topic of power blackouts and occasionally black starts. Power Blackout is a game in which the players are CEOs of a power grid, who need to cooperate to restore the grid [34]. There is a focus on the negotiating and deal-making skills of the players and less on the technical aspects of a black start. This game is not meant as an educational game, so the players do not learn about the processes involved in a black start.

Power Failure is a competitive game in which players try to build the most effective power grid as soon as possible [35]. The players focus on getting resources and building the generators and not as much on the behind-the-scenes of a black start. The same concept is the main focus of Blackout the Power Game [36]. The difference between these games is that Blackout the Power Game has a greater focus on events that change the course of the game, these events are introduced with the help of impact cards.

Blackout: New Outdoor Game has a different form of gameplay; it is an escape room in which a team of players has to prevent a blackout caused by hackers [37]. This game does not focus on the consequences of a blackout but more on one of the possible causes.

2.2.2 Educational Games

Total Blackout is an educational game under development which focuses on the cooperation between crisis teams [38]. The players will mainly gain experience in decision-making and communication as well as knowledge of the processes within the critical structure chosen by the players. The game seems to be adaptable to various situations and sectors in which crisis teams are present. It is not disclosed yet how in dept the actual processes and decisions that need to be made in the case of an actual blackout are.

BLACKOUT! is another game that is specifically developed for education [33]. It is a digital game in which players are challenged to supply as much power to their clients as possible without causing a blackout. The common goal of the players is to meet the power demand each round of the game; this demand changes every round. The actual goal of the game is unknown for the players until the end of the final turn, this way, the players will focus on what types of power to invest in. The financial status of the players does not count in the final score of the game, however, they need money to operate the powerplants. A blackout will take place when the common goal is not reached, with three blackouts the game is finished and all players lose. The focus of the game is more on power supply than on the process of a black start.

2.2.3 Games with Useful Aspects

Inspiration for the design of certain elements can be taken from a large variety of games. Pandemic and Brass: Birmingham can be a good example of the use of a grid in a game [39], [40]. The grid in this case is a real-world map in which cities are interconnected with lines. Pandemic is also a good example of a cooperation game. Magic Maze also uses a grid, however, this grid is built while playing [41]. Magic Maze is also a cooperation game with communication challenges, of which a few aspects might be useful. Additionally, it has a time limit which adds complexity. This complexity is adaptable, based on how many grid cards are added to the pile. Deckscape: Test Time is a card-based escape room which has different types of puzzles which players have to solve within the time limit, this is a good example of an adaptable puzzle-based game [42]. Escape Room in a Box: The Werewolf Experiment is also a good example of a puzzle-based game, however, in this game, the puzzles are made with physical locks [43].

2.3 Conclusion and Discussion of the Background Research

A black start is the repowering of the electricity grid. There are multiple ways to approach this, the most common approach is the bottom-up approach; with this approach, no power from outside the grid will be used. Black start generators, generators that can start themselves, are used to power parts of the grid – islands – which have to be synchronised to connect them. Within these islands, the order in which the generators are powered depends on the type of generator; the common order to power the generators is by starting with hydro power generators followed by Drum-Type and Super Critical Steam generators, and finally, the nuclear power generators are started. Renewable generators are usually started when the grid is fully operational since these generators do not supply a stable amount of power.

Educational games are an effective way of teaching a concept through active learning. Educational games can be made effective by making the learning goals part of the essential game mechanics. Player goals should be added in a way that makes the players feel in control. Elements that can lead to extrinsic motivation, such as point reward systems, should be avoided. Digital games are generally said to have a higher usability which makes them more accessible. Non-digital games are usually more effective in explaining learning goals and are experienced as more fun.

There are no games that specifically focus on the process that power grid operators have to adhere to in the case of a black start. Some games have a black out as the topic of the game but do not discuss it in detail. There are some educational games which focus on certain aspects of the process, or the process from a different angle such as an economic point of view. Some games can be used as inspiration for certain game elements, such as types of puzzles or game setups. There are, according to this state-of-the-art, no games on the market that fulfil the research question as stated in the introduction.

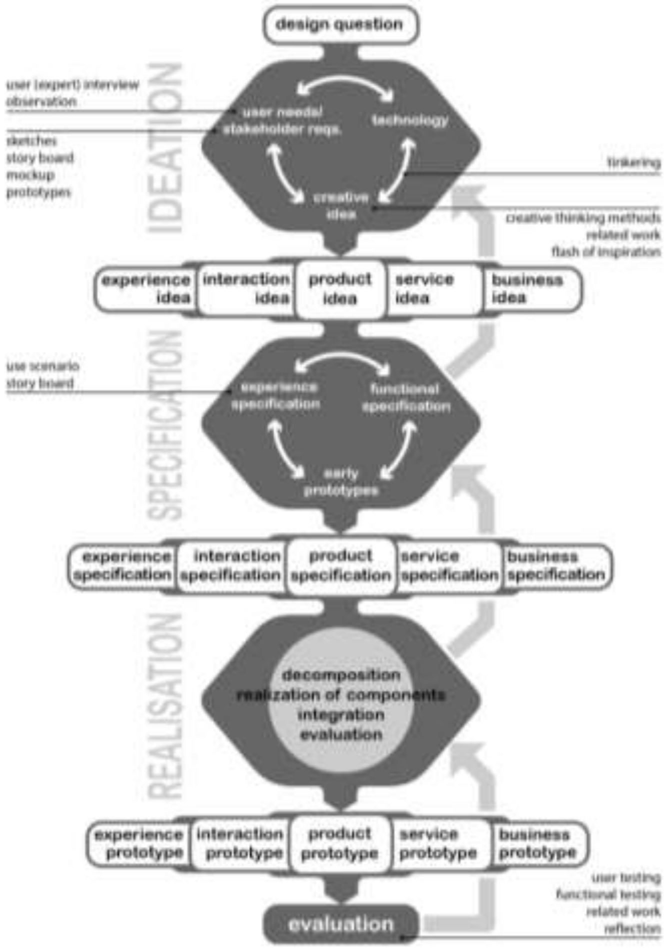
Chapter 3 – Methods and Techniques

3.1 Creative Technology Design Process

The Creative Technology Design Process is an iterative approach to designing a product which uses concepts from human-centred design approaches as well as engineering design principles [44]. The design cycle consists of four phases according to which this project will be structured: Ideation, Specification, Realisation and Evaluation; each of these phases has a start and end point, see Figure 1 [44]. The design process applies a combination of a cyclic design model and a converging and diverging design model. This combination structures a design question into a process with intermediate goals which allows for planning and more user feedback moments [44]. The four stages in the Creative Technology Design Process allow for designing an engineering-based product without neglecting the needs and requirements of the users.

Figure 1

The Creative Technology Design Process **[44]**



3.1.1 Ideation Phase

The ideation phase starts with a design question, this might be a question for a product or an order from a client. In the ideation phase, one should form a clear problem statement, generate ideas, collect relevant information and define stakeholders [44]. Ideas can be generated through brainstorming, lateral thinking or looking into similar projects. Relevant information can be collected with literature research or expert interviews. The stakeholders should be defined as early as possible, this way, they can participate in preliminary user testing or give feedback on prototypes or user scenarios. The outcome of the ideation phase should be a more elaborate project idea, complete with problem requirements.

3.1.2 Specification Phase

In the specification phase, the prototypes are evaluated and improved [44]. With each iteration of the prototype, new functionalities and user demands might occur; these new insights result in new, improved combinations of prototypes. During this process, a lot of prototypes should be made in the low or medium-fidelity category. These prototypes are not fully functional and usually show only parts of the final product. The outcome of the specification phase should be a product specification.

3.1.3 Realisation Phase

During the realisation phase, the chosen prototype will be developed into a working product. All aspects of the product specification will be integrated into one prototype. There will also be functionality tests in this phase. The final stage of the realisation phase should be a product prototype.

3.1.4 Evaluation Phase

The evaluation phase includes user evaluations on different levels. Additional functionality tests can be done in this phase. The designer should evaluate if the original design requirements, from the ideation phase, are met in the product prototype [44]. The goal of the user evaluation is to see if the users are satisfied with the design choices and user requirements as incorporated into the product prototype. The product prototype is placed in the context of the existing products. There should also be an evaluation and reflection of the progress – both personally and academically – made during the entire process.

3.2 Brainstorming

3.2.1 Thinking Hats

Parallel thinking is an important aspect of brainstorming as it allows the designers to look at a problem from the same side at the same time. Using the six thinking hats during a brainstorm session helps with parallel thinking. The six thinking hats – each their own colour – represent six different ways of looking at the problem and solution, see Figure 2. The white thinking hat represents neutral and objective thinking, focusing mainly on the objective facts [45]. The red hat looks at the problem from the emotional side. The black hat allows for cautious and careful thinking. The yellow hat is used for optimistic thinking and hope. The green hat indicates creativity and new ideas [45]. Finally, the blue hat is used for organisation and control of the problem as well as organising the other thinking hats. During a brainstorm session, designers can use these hats to look at the problem from different angles. The hats can be picked or assigned at all times during the brainstorm session.

Figure 2

The Six Thinking Hats

3.2.2 Important Aspects of Brainstorming

During a brainstorming session, it is important to keep an open mind and be open to new ideas even if they might not be feasible or good. The 'bad' ideas can allow for a new perspective and possibly very good ideas. Avoiding criticism is, therefore, one of the most important rules during a brainstorm session [46]. During a brainstorm, the participants should be encouraged to build upon each other's ideas. Diverging in thinking as much as possible is also important as it allows for more creative approaches to ideas.

3.2.3 Creative Idea Generation

There are different ways to generate creative ideas such as using the silence, random connections or scamper method. With the silence method, the designer(s) sit in silence; their only goal is to generate as many creative ideas as possible [47]. How the designer approaches the brainstorm session is up to them. The random connections method is a bit more structured, this method encourages designers to connect random objects. These random objects will be used to create as many new ideas as possible. The designers will try to make connections between the original problem and the ideas, allowing them to look at the problem from a perspective they might not have thought of originally [47]. The scamper method also builds upon existing products. The designers pick a product and apply the seven possible change approaches: substitute, combine, adapt, modify, purpose, reverse and rearrange [47].

3.2.4 Organising a Brainstorm Session

A brainstorm session can be organised in different ways, where the task is approached in different ways. The lotus flower method starts with a theme or a question, around this question, eight ideas will be generated – like the petals of a lily flower – [46]. These eight ideas form their own lily, with all eight ideas. This way, a lot of different ideas can be generated.

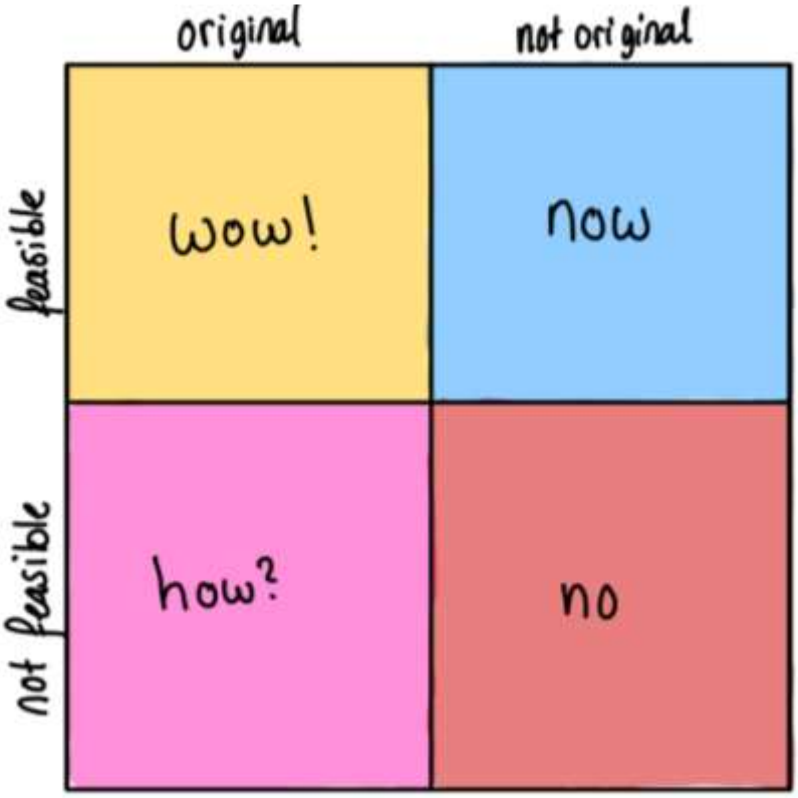
With the brain writing technique, each person has a piece of paper on which they write an idea; after a few minutes, the pieces of paper are passed to their neighbours, who add something to the paper related to the initial idea. This will be repeated until the person has their piece of paper back.

A How, Now, Wow Matrix can be used to organise ideas into four categories. A table will be used where the leftmost column is feasible and not feasible and where the top row is original and not original. All the ideas will be divided into one of the categories, see Figure 3. The ideas from the Wow category can be expanded upon, and a final prototype can be chosen using dot voting; each person gets five dots which they can divide however they want among the Wow ideas, the idea with the most dots is generally the favourite.

Another way to initiate a brainstorming session is with the superhero brainstorm. With this method, the designers imagine that they are a superhero and that they could solve the problem without a connection to reality. This can result in some wild ideas that might motivate the designers to see if they can make it a feasible idea.

Figure 3

How, Now, Wow Matrix



3.3 Product Requirements

3.3.1 MoSCoW Method

The MoSCoW method is a technique used to prioritise different aspects of a product, such as user requirements, tasks or acceptance criteria [48]. MoSCoW stands for Must have, Should have, Could have and Will not have this time. Things in the must have category are there because the product will not be able to function without it, either because of safety, legality or usability. The Should have category has things that are important to have, but it is possible to have the product without this aspect. Could have is that category used for things that would be nice to have but are not as impactful when they are left out [48]. The Will not have this time category consists of things that will not be implemented (in this version of) the product. The MoSCoW method helps designers prioritise different aspects of a product, usually within a specific time frame.

3.4 User Testing

Preceding any user testing, a consent form will have to be filled in by the upcoming participant. Attached to this consent form will be an information letter. These can be found in Appendix A.

3.4.1 Focus Groups

Focus groups can be used to get in-depth information on what users think about a product. The advantage of focus groups is that they can be conducted with multiple participants at once, allowing the participants to add to the answers of the other participants giving them a different point of view. Focus groups can be conducted in three structure levels, similar to the structure types of an interview: unstructured – asking the participants questions which are not written down previously, allowing for personalised questions –; semi-structured – the questions are thought of beforehand, however, the focus group leader can change, leave out or add questions as they see fit –; and structured – all questions are thought of beforehand and no questions can be added, changed or removed. Semi-structured focus groups allow for the most flexibility based on the users, by for example asking follow-up questions based on the answer to previous questions while providing a clear framework for the questions that should be asked.

3.4.2 System Usability Scale

The System Usability Scale (SUS) is a way of testing the usability of a product using the Likert Scale in questionnaire format [49]. The questionnaire consists of ten questions which will ask about the usability of the product. The standard format of the SUS can be found in Appendix B. The SUS is mostly used for quick and simple evaluations of the usability of a product, usually in large groups of users [50].

The SUS gives a score to the usability of the product, making it easily interpretable using percentages, grades or acceptability [50]. The odd questions are scored as the number given minus one; the even questions are scored by subtracting the scored number from five. This way a score between 0 and 4 will be obtained for each question. These scores will be added and multiplied by 2.5, resulting in a score between zero and one hundred. Higher scores mean that the product is more usable than it would be with a lower score. Scores above 70 are characterised as good and scores of more than 85 are excellent [50].

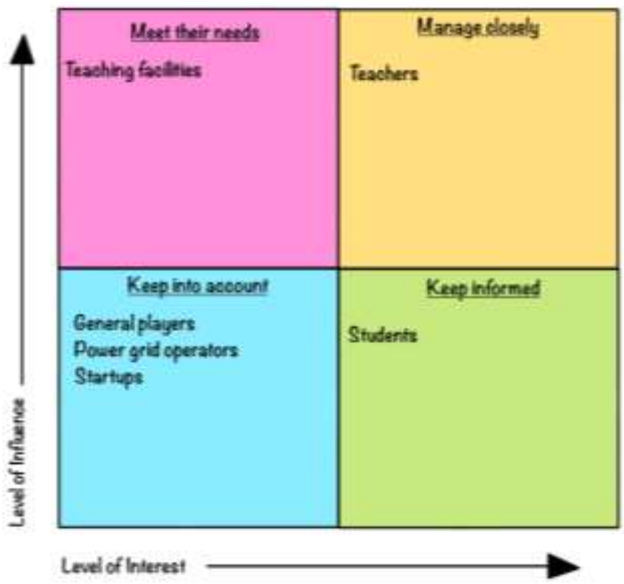
Chapter 4 – Ideation

4.1 Stakeholders Identification and Needs

In the design of a product, it is important to keep the different stakeholders in mind. The different ways in which the design can impact the stakeholders is something that should be assessed and for which solutions should be sought. The stakeholders for this game can be categorised into two groups, direct and indirect stakeholders. Direct stakeholders are the people who are directly affected by the product. The indirect stakeholders are the people who might have something to do with the product. Stakeholders might be affected by only a part of the product. The stakeholders can also be divided by their level of influence they have on the final product. A stakeholder matrix can be created to keep track of the different stakeholders and their influence on the project [51], see Figure 4.

Figure 4

Stakeholder Matrix



The direct stakeholders for the game are the teachers, students and general players. Teachers are the people who will use the game to teach their students about the concepts of a black start. They need the game to be educational, so their goal of teaching the students can be accomplished with the help of a tool, in this case, a game. They also need the game to be fun, to keep their students engaged. Students are also direct stakeholders as they are the ones playing the game. They need the game to teach them something about black starts while keeping them engaged by being enjoyable. The final group of direct stakeholders are the players who play the game outside of a teaching environment. They mainly need the game to be enjoyable, they might want to learn about black starts using the game, so knowledge increase is also something they consider important. The most important aspects for the direct stakeholders are that the game is enjoyable and teaches the players something about black starts.

The indirect stakeholders are the teaching facilities, startups interested in developing the product further and power grid operators. Teaching facilities, such as universities or schools, are the indirect stakeholders of the game because they will have to buy the games. They need the game to be affordable, so they can offer it to their teachers. They might also experience some effect of the game on their students and/or teachers; teachers might, for example, tell the teaching facilities that they enjoy teaching more and are therefore less prone to burn outs. Startups are also indirect stakeholders of the game. They could have an interest in developing the product further, making them partially responsible for an effective educational game. Since there are no startups in this process yet, they will fall under the indirect stakeholder category. The power grid operators are the final group of indirect stakeholders because they might come in contact with the game, however, when they are playing the game, they will be considered direct stakeholders. Colleagues of the power grid operators might be motivated to work with them because they played the game and enjoyed it which motivated them, among other factors, to pursue a career in power grid engineering. The power grid operators therefore need the game to be educational and reflect the accurate situations during a black out. The most important aspects of the game for the indirect stakeholders are that the game is affordable and educational.

4.2 Brainstorm sessions

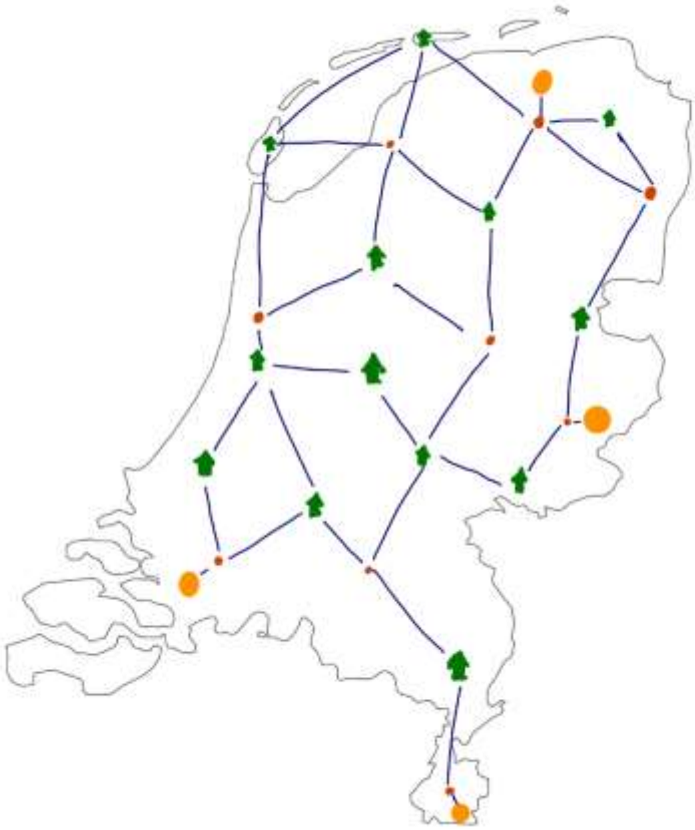
4.2.1 The first Brainstorming Session

During the first brainstorm session, no brainstorming techniques were used. This resulted in a brainstorm session that got stuck on one idea. The idea was to make a grid with each player being a different power supplier, see Figure 5.

The players were supposed to work together to get the grid back online keeping the aspects of a black start in mind, which would become clear through gameplay and game rules. While this idea is not necessarily ‘bad’ it probably would not be a very fun game when Schell’s definition of fun “*fun is pleasure with surprises*” [26, p. 26] is used. Game elements to make it more fun would be a time limit, to increase urgency, or event cards to make things a bit more difficult and surprising. The first brainstorm session was not a success since it only generated one idea.

Figure 5

An Example Map for the First Idea



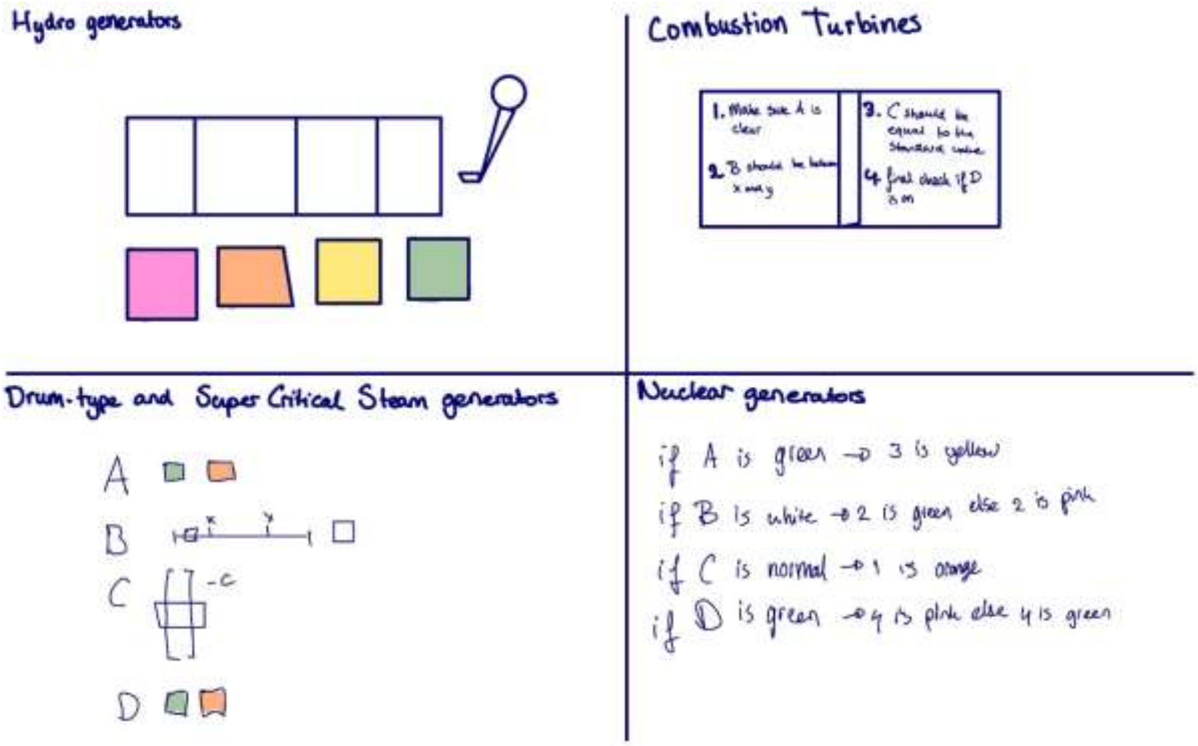
4.2.2 The Second Brainstorming Session

Based on the previous brainstorm session, brainstorming techniques were needed to approach the session with a new point of view. The idea generation that was used was a combination of silence and scamper in combination with the lotus flower brainstorming approach. Existing games were taken as the existing products and around these, ways to make the game educational, or have the topic of black starts, were thought of. These ideas were generally better than the game from the first brainstorm session, since the game aspects that make the game fun – and thus the needs of the stakeholders – were kept in mind during this brainstorm session. The second brainstorming session was more effective compared to the first session. This brainstorm session resulted in a longer list of possible ideas which can be found in Appendix C. Some of the ideas will be discussed shortly.

One of the possible ideas was to make a puzzle-based game, in which players divided into four groups each representing a different power generator, and had to collaborate to solve the puzzles, see Figure 6. The puzzles should be designed in such a way that they can only be solved by communication between the different teams, and they should only be solvable in one order – the order in which the generators are brought back online after a blackout.

Figure 6

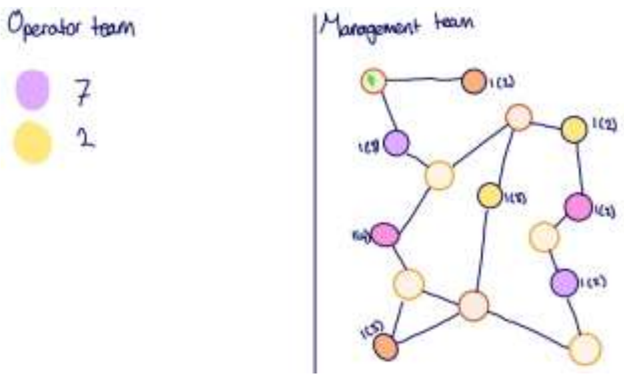
The Puzzle Game



Problems with communication were one of the other initial ideas. In this game, the players are divided into two groups, the management and the operator team. The management team can see the grid and all the resources, see Figure 7. The operator team can see the problems at the generators. They need to collaborate to get the power back online, talking, however, is not allowed. By powering loads, more resources will be generated, making it easier to repair the other generators.

Figure 7

The Communication Problems Game



4.3 Converging

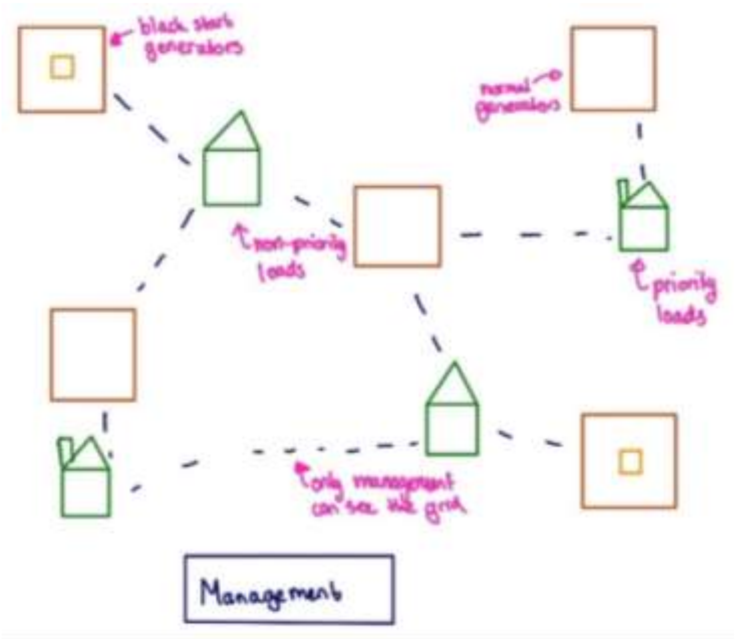
The results of the two brainstorming sessions were presented to the client. During this feedback session, a final idea was picked to expand upon. The favourite idea was to make an escape room in which the players have limited time to get a grid back online. The choice for this game was based on the expected amount of fun for the players, the amount of adaptability to the needs of the players, the possibilities to incorporate learning and the possibility of communication during the entire process.

4.4 The Initial Game Idea

The initial game idea for the chosen game was to make an escape room. In the escape room, a group of five or more players is tasked with getting the grid back online within a time frame. The players are divided into three groups: two operator groups and a management group. The players are divided equally over the groups, but if that cannot be done, the management group will have the least amount of people; with five players for example, the management group will consist of one player. The management team is the only team which has an overview of the grid and how the generators and loads are interconnected, see Figure 8. The operator groups are the ones doing the puzzles at the generators, part of the information about the puzzles is in the hands of the management team. The management team will have to communicate with the operator teams to solve a puzzle and get the generators running in the right order. During the game, the players will learn about power grids, cold load pickup, synchronisation between power islands and communication.

Figure 8

The Initial Game Idea: an Escape Room



Chapter 5 – Specification

For the final game, there are a few aspects that need to be considered. Product requirements should be set to prioritise which aspects of the game should be implemented first to make sure that the most important aspects are present in the final game. The different puzzle types that will be implemented in the game should be considered.

5.1 Product Requirements

To make a functional educational game, it is important to take some aspects into account. Most importantly, incorporating the correct learning concepts should be considered, to ensure that the students learn the topics that the teachers think are important. The important learning concepts should therefore be defined. Next to the learning concepts, the users have other needs which need to be met, these need to be defined as well. These requirements should be sorted on importance using the MoSCoW method. Prioritising is important to keep the goals feasible within the project time.

5.1.1 Product Requirements

The designers and the client have defined product requirements. These were based on discussions and possible player scenarios. Some of the requirements were based on feasibility, others on the goal set for the product.

5.1.2 MoSCoW

5.1.2.1 Must Have.

The escape room is an educational game, therefore it must teach the students something. For this game, the learning goals are that the students have an understanding of cold load pickups and of the synchronisation of the islands that are created during the bottom-up approach of a black start procedure. The escape room must combine the theory of black starts with some physical or visual aspects within the game, for example in the form of a puzzle. The escape room must have at least two puzzles, this way, all teams have something to do.

5.1.2.2 Should Have.

Educational games should be fun, even though it is not their main priority. Therefore the requirement that the game should be fun is placed in the Should Have category. The escape room should have more than two puzzles, this will increase the strategy needed to plan which puzzles, and thus generators, to solve first. The level of puzzles should be slightly challenging for the players. The puzzles should not be too easy or too hard, which is difficult to achieve since this is subjective. The game should take between 30 and 60 minutes.

5.1.2.3 Could Have.

The escape room could explain non-priority concepts such as voltage levels, transmission capacity or finding the causes of the black out with the help of puzzles. The escape room could also be made adaptable to differences within the user groups, for example by adding multiple difficulty levels. To do this, a lot of user testing has to be done to establish the different levels that are needed.

5.1.2.4 Will Not Have.

In future iterations of the escape room, other user groups could be taken into consideration. The game can be beneficial for younger players to get to know the concept of power grids or even the fundamentals of electricity distribution. General players could also be taken into consideration, then the development should focus more on players of all ages with little knowledge of power grids. Expert players could also be an interesting group to tailor the game to, this version could explain niche concepts or focus on the communication aspect.

5.1.3 Risk Matrix

A risk matrix can be made to create an overview of the risks and possible failures that can occur during the testing process, see Table 1.

Table 1

Risk Matix

Likelihood /impact	Minor	Marginal	Critical	Catastrophic
Certain				
Likely		One of the puzzles does not work properly.		
Possible	Someone gets hurt by sharp aspects of the puzzle. Someone gets hit by a ping-pong ball.	Mental problems or stress because of the topic. The puzzle malfunctions. The players have low engagement or enjoyment.	The puzzles are too easy or too difficult. The players do not understand the instructions.	
Unlikely	The players find a loophole.		The players are unable to solve the puzzle.	One of the puzzle pieces gets lost.
Rare				A puzzle falls on a player.

5.2 Game Overview

The escape room consists of four puzzles – nuclear, hydro, combustion and renewable generators –, a management station and a city as the final part, see Figure 9. Before the game, the group will be split into three teams, two operator teams of at least one person per team, and one management team of at least one person. The management team informs the operator teams of the order in which the puzzles have to be solved – the hydro and combustion generators first. The teams will solve their respective puzzles with the help of the management team. The team that finishes first with their puzzle will move on to the nuclear generator, and the other team will go to the renewable generator. When the second generator is powered, the synchronisation between the generators will take place by switching two levers at the right time. Every generator after that will have to be synchronised with the rest of the generators through the same process. When all the puzzles are solved, the city will be powered. This is done at the end to take the cold load pickup into account. The walkthrough of the escape room is illustrated in Figure 10.

Figure 9

Overview of Puzzles and Other Game Aspects

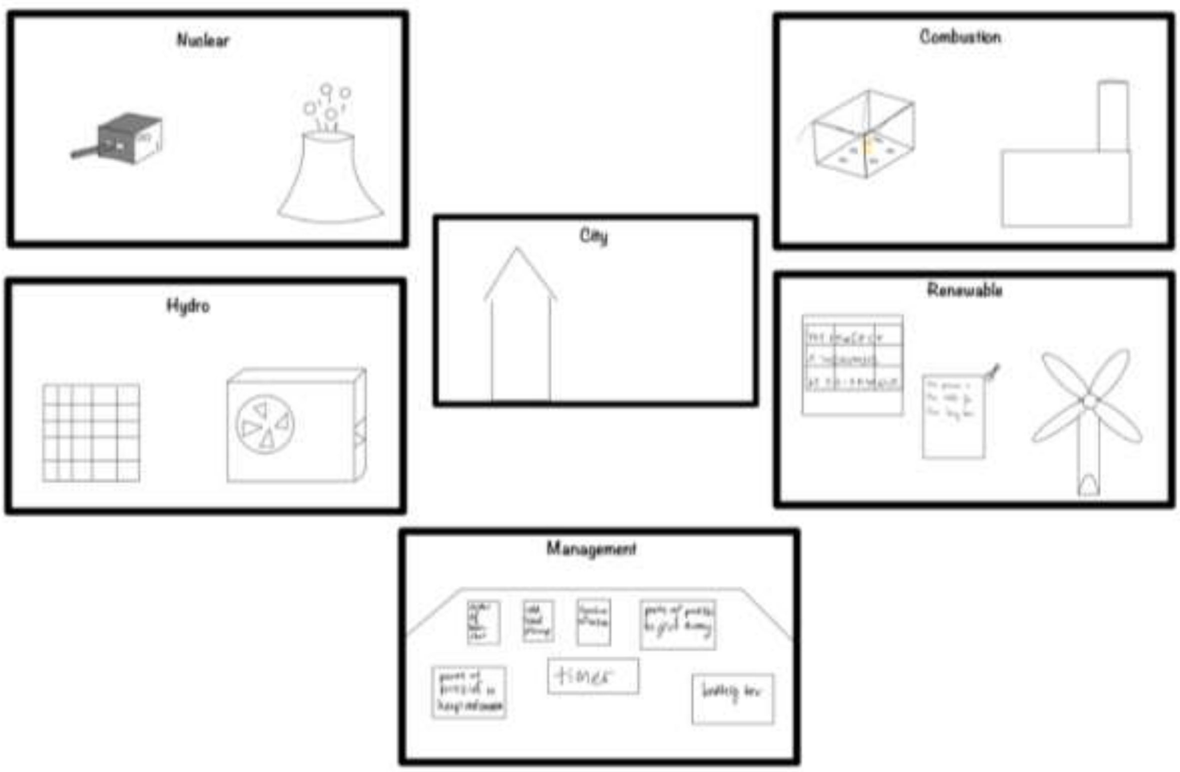
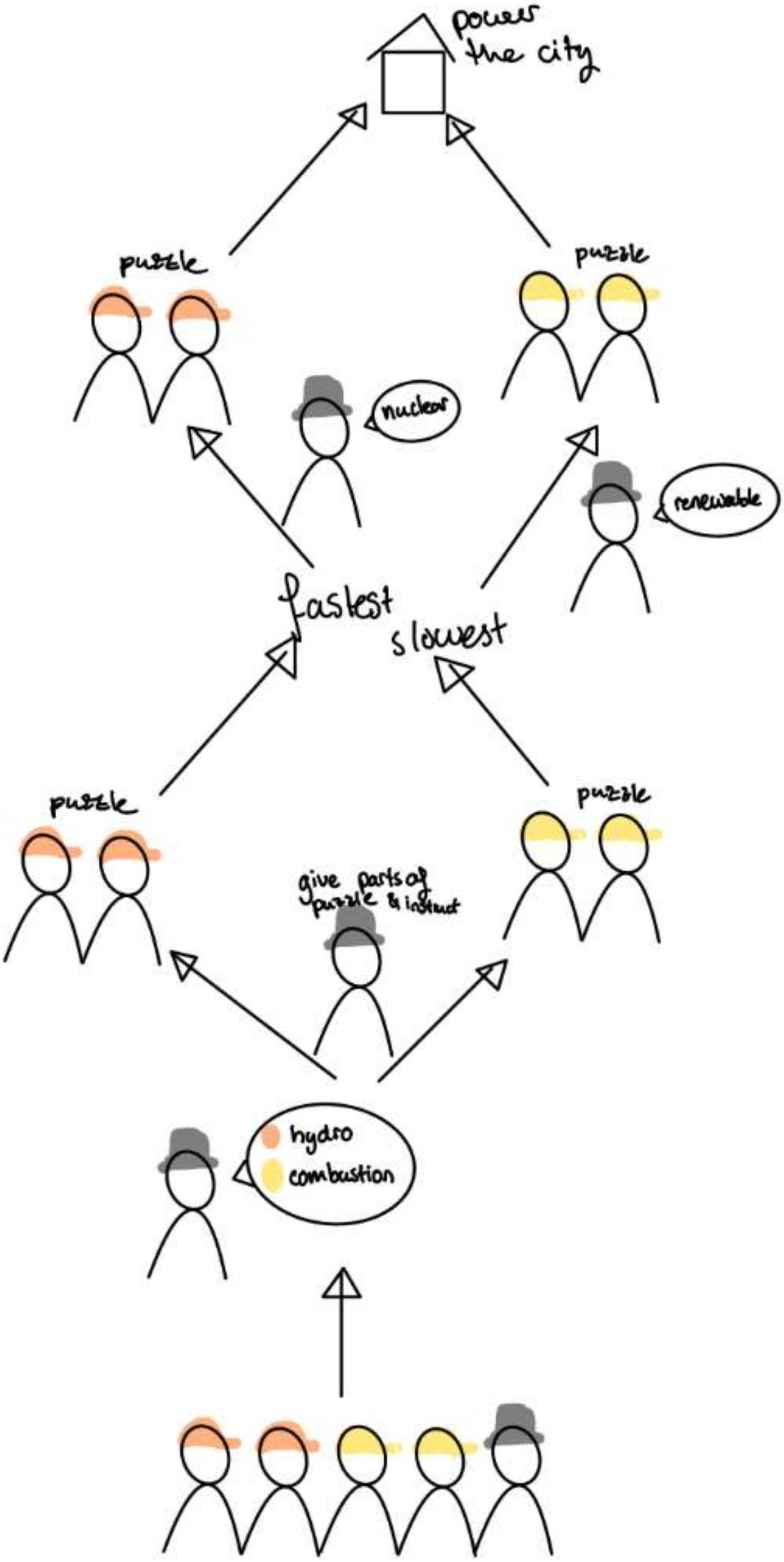


Figure 10

Flow of the Game



5.3 Puzzle Types

Different types of puzzles should be considered for the different generators. The diversity in the puzzles overlaps with the different types of generators, making the players understand that each generator has its own regulations. Different puzzles will be designed for all generators. The final solution of each generator will give the players some ping pong balls which represent the amount of energy the generators supply when they are operational. The ping pong balls can be used in the final part of the puzzle, supplying a city with power.

5.3.1 Hydro Generator

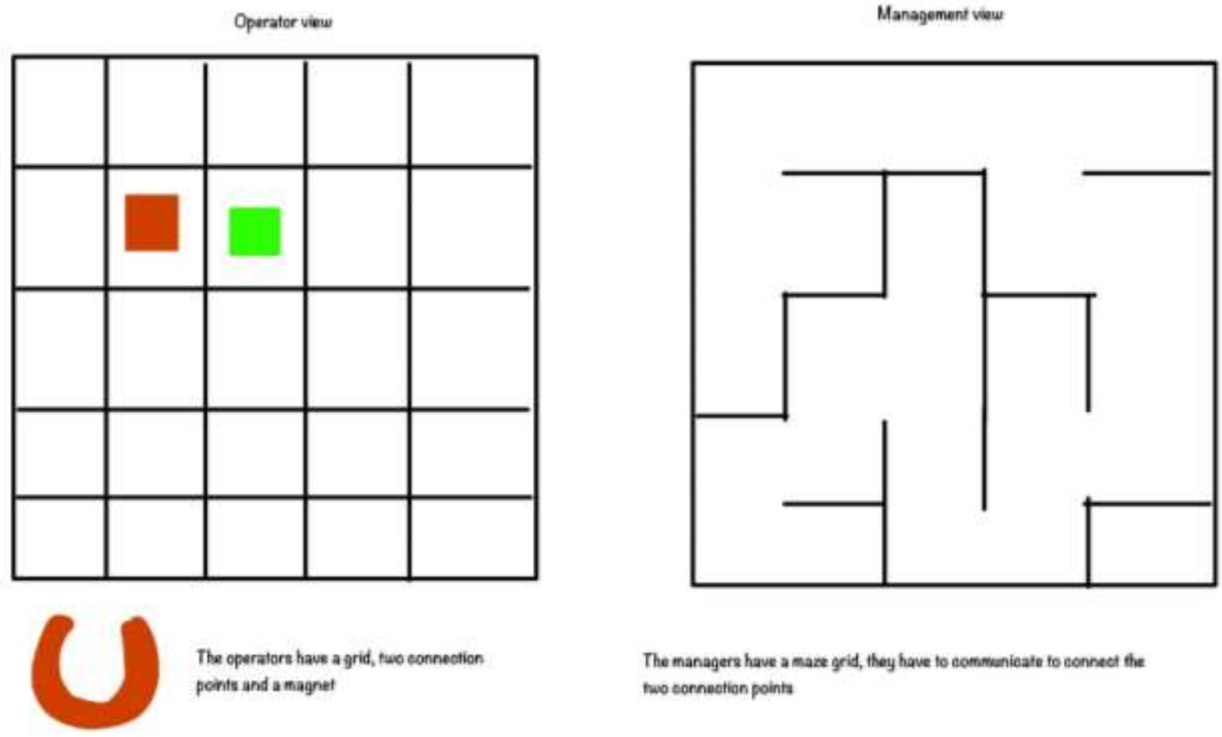
The hydro generator is the first generator that will be activated, therefore it has to be solvable on its own. The puzzle for this generator gives the key to unlock the energy balls from the generator.

5.3.1.1 Magnet Maze.

Magnets can be used to solve an invisible maze. The management team will have access to the maze, see Figure 11. The operator team has access to the two points that have to be connected. They will have to communicate with each other to solve the puzzle. The result of the puzzle is a key that can be used to unlock the wheel of the hydro generator.

Figure 11

Magnet Maze

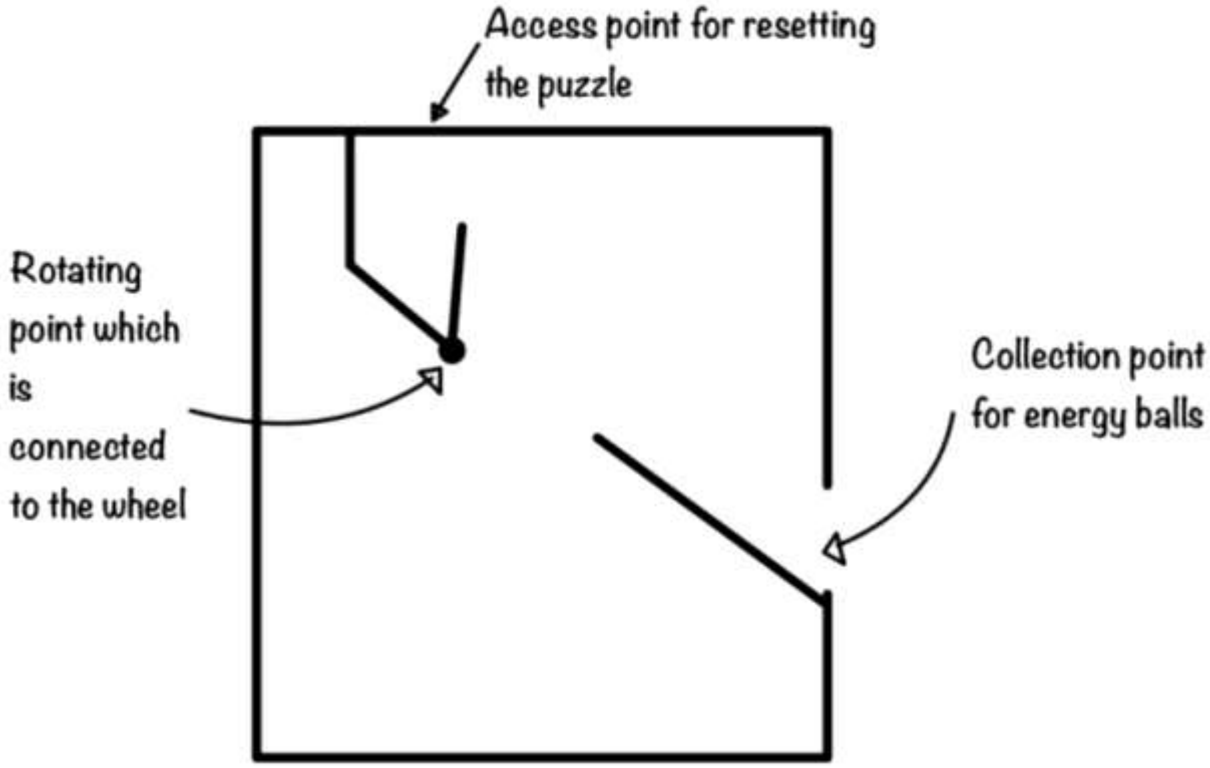


5.3.1.2 Wheel.

The wheel is the final stage of the hydro generator as it is a physical representation of a gate valve of the hydro generator. A key is needed to unlock the wheel which can be obtained by solving the Magnet Maze. When the wheel is unlocked, it can be turned. With the turning of the wheel, a trapdoor will rotate to create a slide from which the energy balls leave the generator, see Figure 12.

Figure 12

Hydro Wheel



5.3.2 Combustion Generator

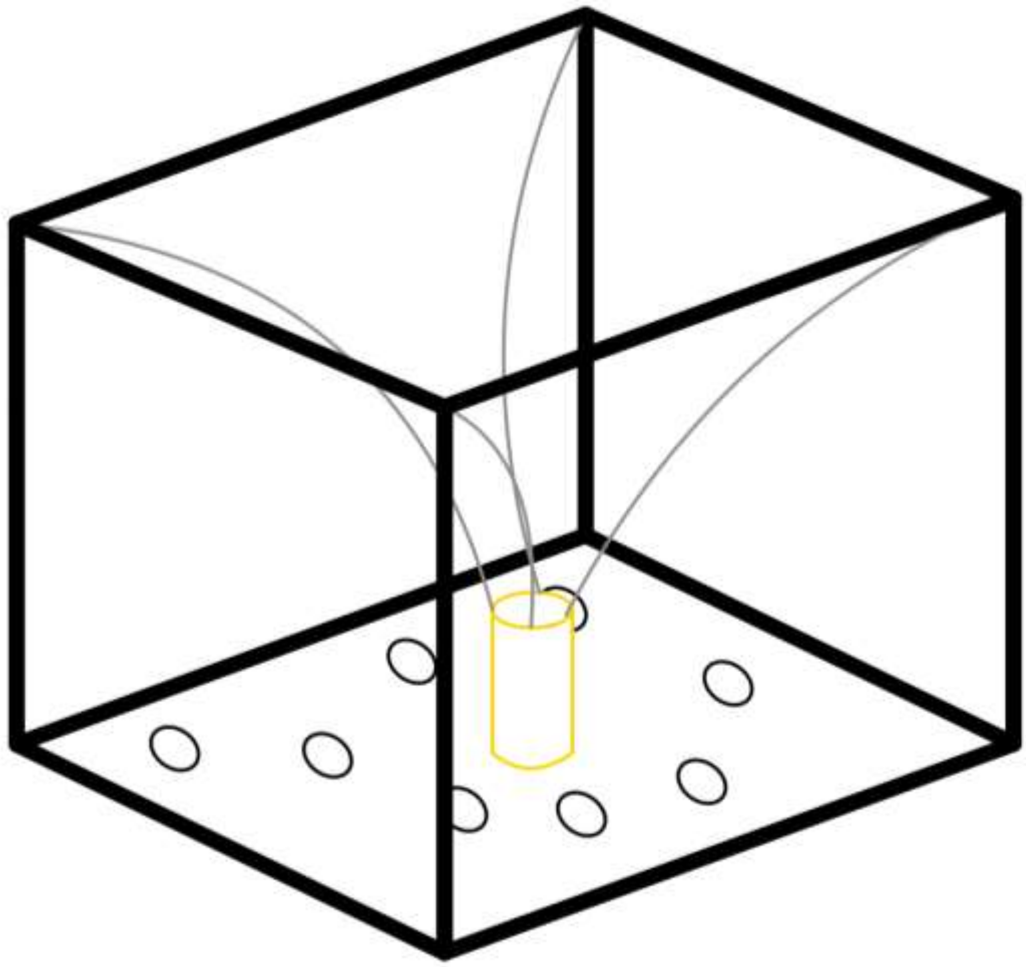
The Combustion Generator can be started simultaneously with the hydro generator. The puzzles for this generator should therefore be possible to solve independently.

5.3.2.1 Magnet Fishing.

Magnet fishing focuses on communication within the operation team. The players move the magnet using the four strings to the different stations, where they uncover the numbers in the right order to get the code, see Figure 13.

Figure 13

Magnet Fishing



5.3.2.2 Smoke Outlet.

The smoke outlet holds the energy, this can be released by unlocking the lock using the key acquired from the previous puzzle. The lock will move away from the opening of the smoke outlet allowing the energy to flow down.

5.3.3 Nuclear Generator

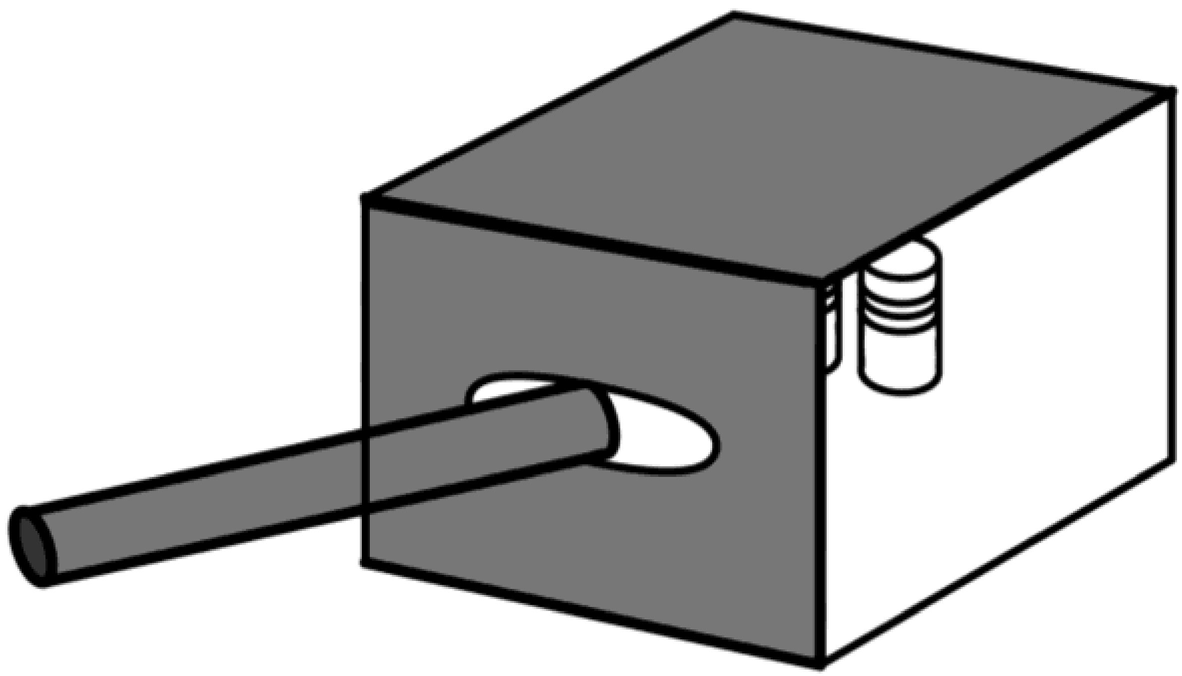
The nuclear generator can be activated by using energy from previous generators to 'shoot' at the targets containing the key.

5.3.3.1 Nuclear Shoot.

The key for the cooling tower of the nuclear generator can be found in one of the targets in the generator, see Figure 14. The management team has an elastic which can be attached to the pipe so that it can be used to shoot energy (ping pong balls) from one of the previous generators at the targets. Once this is done successfully, the key will drop from the target.

Figure 14

Nuclear Shoot

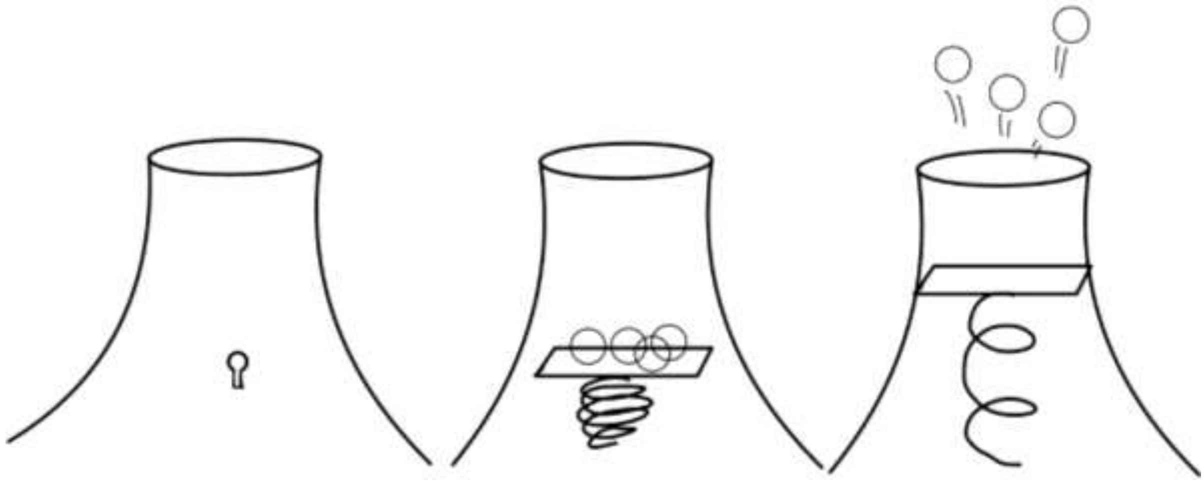


5.3.3.2 The Cooling Tower.

The key from the previous puzzle can be used to unlock the spring mechanism in the cooling tower, this results in the ping pong balls flying out of the top to represent smoke, see Figure 15.

Figure 15

The Cooling Tower



5.3.4 Renewable Generator

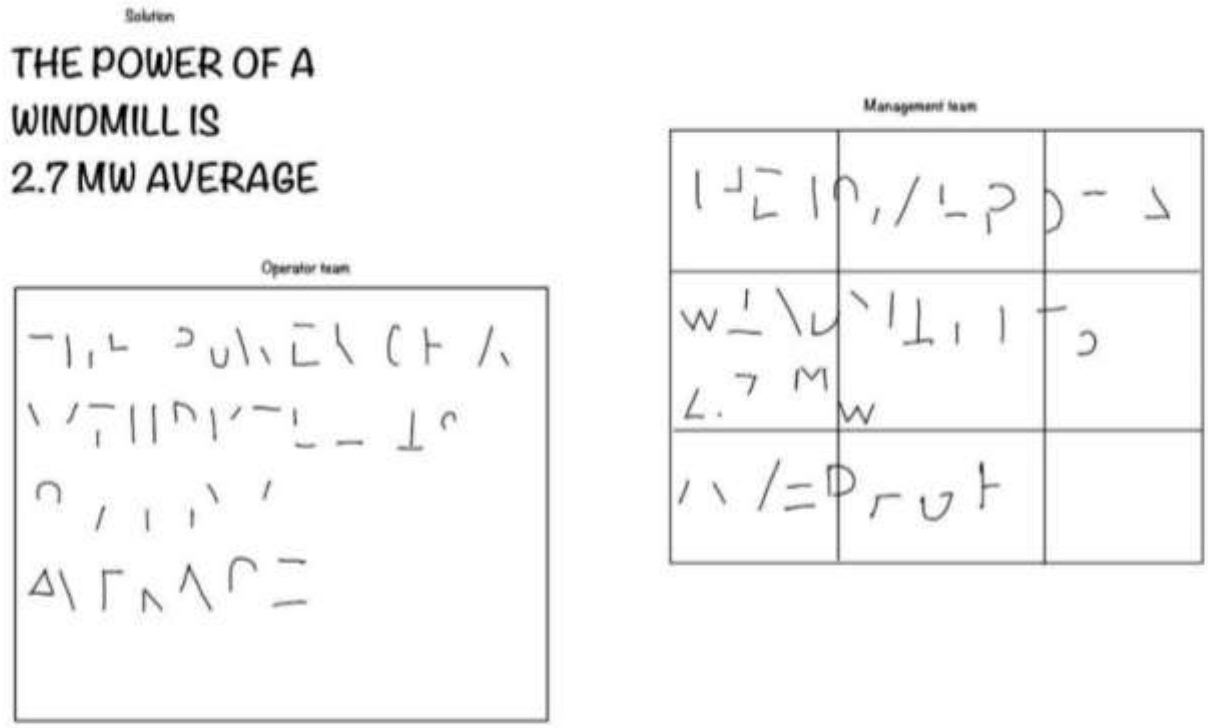
5.3.4.1 Light Puzzle.

In the light puzzle, the players have to combine pieces of paper with different symbols on them. In the first iteration, two sheets of paper were used. This version of the puzzle could be solved within fifteen seconds, which was too fast. There was also an error in the text, the usage of voltage instead of power. For the second iteration, one of the sheets was cut into nine pieces, see

Figure 16. This was better as it was more challenging and it took a bit longer. When the pieces are combined correctly, the solution as shown in the top left corner will be formed. With the pages combined and held to the light, the players can see the message with the average amount of power, 2.7 mega watts, generated by a windmill [52].

Figure 16

Light Puzzle

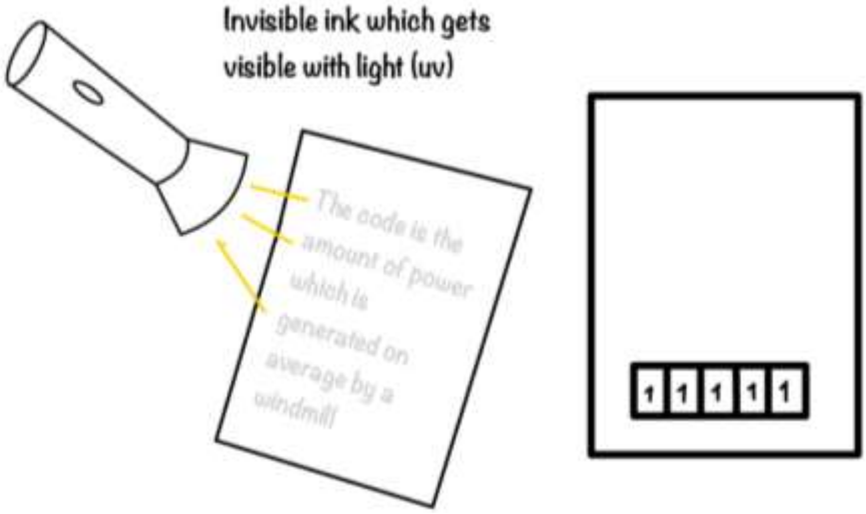


5.3.4.2 Invisible Ink

With the UV torch, the message on the blank page can be read, see Figure 17. The message that appears is that the amount of power generated by the average windmill is the solution for the key box. The average amount of power needs to be converted from mega watts to giga watts.

Figure 17

Invisible Ink

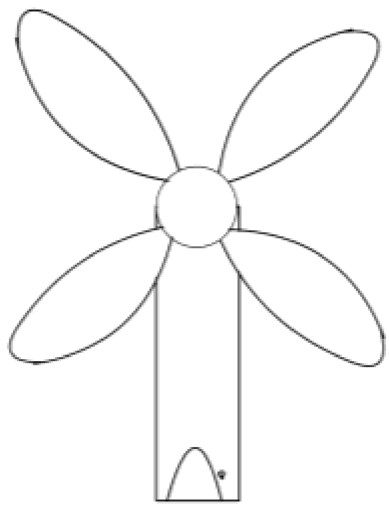


5.3.4.3 Windmill.

The key from the key box can be used to open the door at the bottom of the windmill, see Figure 18. The door can be opened and the energy balls will fall out.

Figure 18

Windmill



5.4 Other game aspects

5.4.1 Management Team

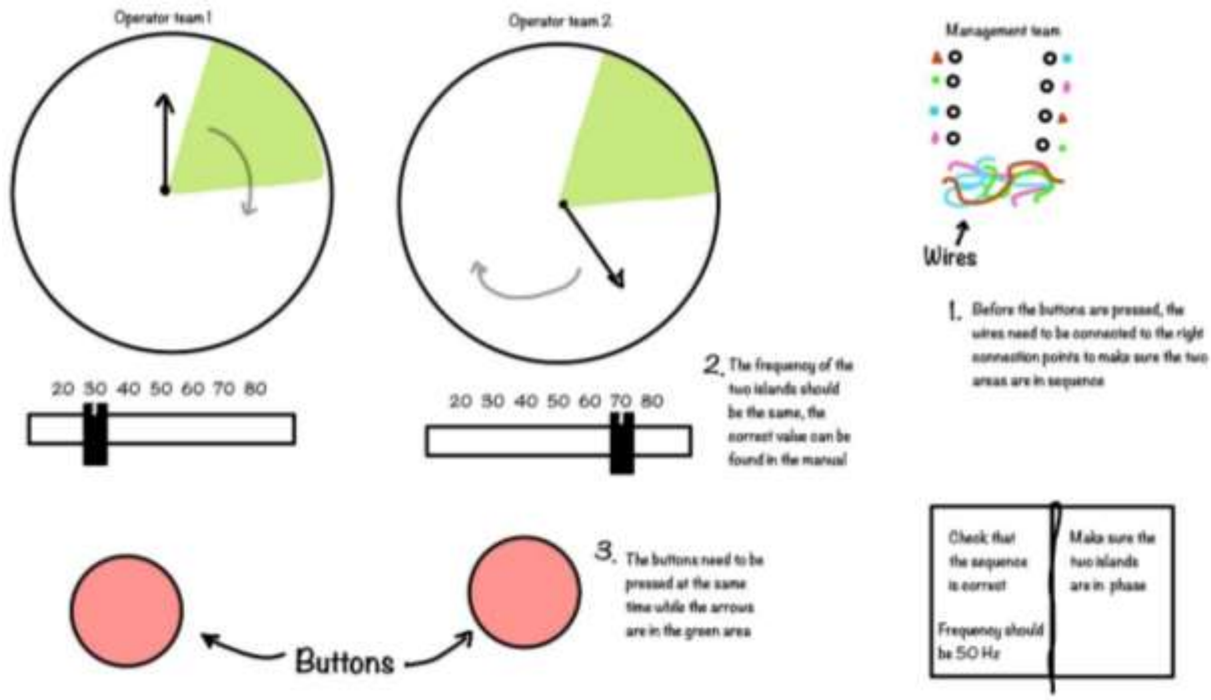
The management team has a desk with a screen around it. On the desk, there is a lot of information and parts of puzzles. The parts of the puzzles also contain some decoy pieces to make the game a bit more challenging and encourage communication. Some of the puzzle pieces can be given to the operator teams while others have to stay behind the screen. The team will have to control the two operator teams as well as help them with the puzzles. They are also the ones responsible for explaining the synchronisation and cold load pickup part of the game.

5.4.2 Synchronisation

The synchronisation between the newly powered generator and the already powered generators can be done with the synchronisation puzzle, see Figure 19. This puzzle consists of two radars which are spinning and two buttons. A part of the circle under the radar is coloured green, when the hands are over this green part, the button has to be pressed. The management team has one radar and the operation team has to operate the other one. Once this is done correctly for both groups, the generator is solved correctly. When the button is pressed at the wrong time, a time penalty will be given.

Figure 19

Synchronisation

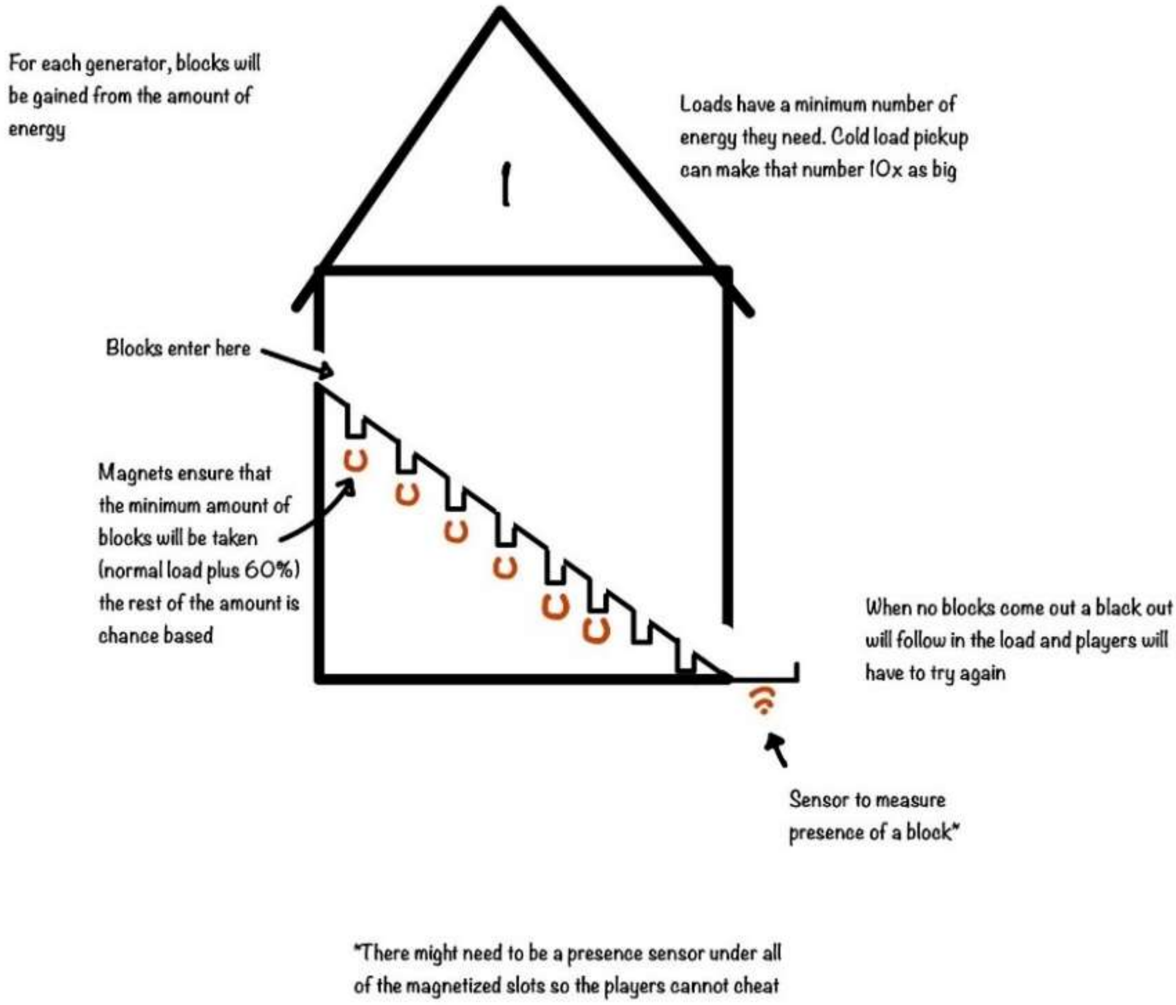


5.4.3 Cold Load Pickup

The concept of the cold load pickup will be explained with one final load that the players need to supply with energy. Within this part of the game, the players will supply the house with the energy ping pong balls they have acquired during the rest of the game, see Figure 20. The ping pong balls will roll down a slope which is narrow at the start, this way all the slots will be filled. After the first 60% of the slots are occupied, the slope will broaden and split into two parts; one side will continue with slots in the same way as before, and on the other, no slots will be placed.

Figure 20

Cold Load Pickup



Chapter 6 – Realisation

In the realisation phase of the escape room, the puzzles were built. Each puzzle was tested by the researcher or another participant to ensure that the puzzle was possible to solve, that there were no major flaws and to ensure that there were no loopholes. The details of each puzzle will be discussed below.

6.1 Hydro generator

6.1.1 Magnet Maze

The first version of the Magnet maze was made out of cardboard, hot glue and duck tape. The maze was based on one of the earlier sketches for the explanation of the puzzle, see Figure 21. The walls were made of strips of cardboard that were glued to the bottom plate. A small hole was cut in one of the spaces to allow the magnet to get in and out of the puzzle. The entire puzzle was covered in silver duck tape, both for aesthetic reasons as well as structural integrity. A grid was drawn over the duct tape to allow for easier communication. This version was made to test whether the game was fun and if the mechanics worked.

Figure 21

Magnet Maze First Version

The second version of the maze was made because the key which is needed for the wheel, did not fit through the maze. The second version was also made to be a bit more sturdy to ensure that it would not break during the game. The bottom plate is made out of wood in which the maze walls were milled, see Figure 22. Aluminium strips were bent into shape in a hand-operated break press and put into the slits and glued down. The top plate is made of an aluminium sheet on which a grid is milled, this is mounted on the side walls of the maze, see Figure 23. The height of the maze on the inside is two centimetres to allow the key to move through easily with enough strength on the magnet to make sure that it moves, see Figure 24. A shell for the magnet on the outside of the maze is made out of a plastic tube in which a hole was drilled. To (re)set the puzzle, the key with a magnet attached to it can be inserted through the hole, after which the other magnet can be used to move the key back to its original position.

During user testing, it became clear that this puzzle was too easy, therefore, an extra step was added to this puzzle. The management team got access to four different mazes, see Appendix D. On the back of the Magnet Maze, the word Jellyfish was written to indicate which maze was the correct one.

Figure 22

The Inside of the Magnet Maze

Figure 23

The Milling Process of the Top of the Magnet Maze

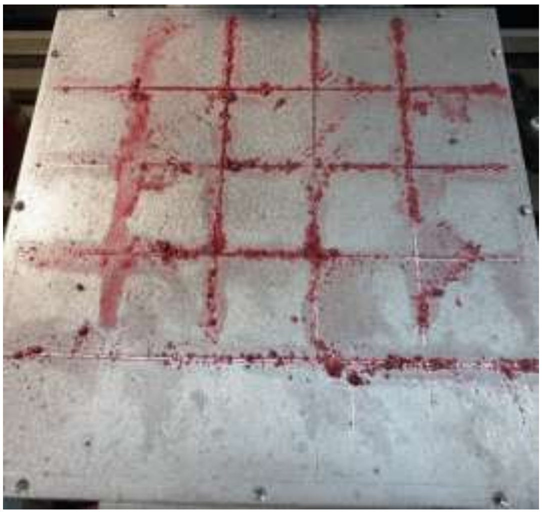


Figure 24

The Magnet Maze

6.1.2 Wheel

In the initial design of the puzzle, the lock was placed on the wheel itself. During the building process, this was discovered to be not the most practical way to approach this problem. The lock was moved to the top of the box, where it was used to block the slope from going down. This way, the wheel cannot be turned without unlocking it.

The wheel is made of a 30 by 30 wooden box, with on the inside a slope, see Figure 25. At the top, a hole was cut to allow the ping pong balls to be put in before the start of the game. This hole was later closed as it was too easy for the players to open it. A lock was placed that holds the slope in its place, ensuring that the ping pong balls cannot fall down. The key from the magnet maze can be used to turn the lock. The axis of the wheel is connected to the axis of the hinge, to which the side of the slope is attached. When the wheel is turned, the slope rotates downwards and the ping pong balls will roll down to the exit of the puzzle. The box is sealed with an aluminium sheet, to give the impression of a metal box which might be present at the generator, see Figure 26. The wooden part is painted silver with spray paint to give the same effect. To (re)set the wheel, the ping pong balls are rolled up the slope – hold the wheel slightly tilted backwards to make it easier – the slope is then rotated upwards to its initial position and the lock gets locked.

Figure 25

Wheel Inside

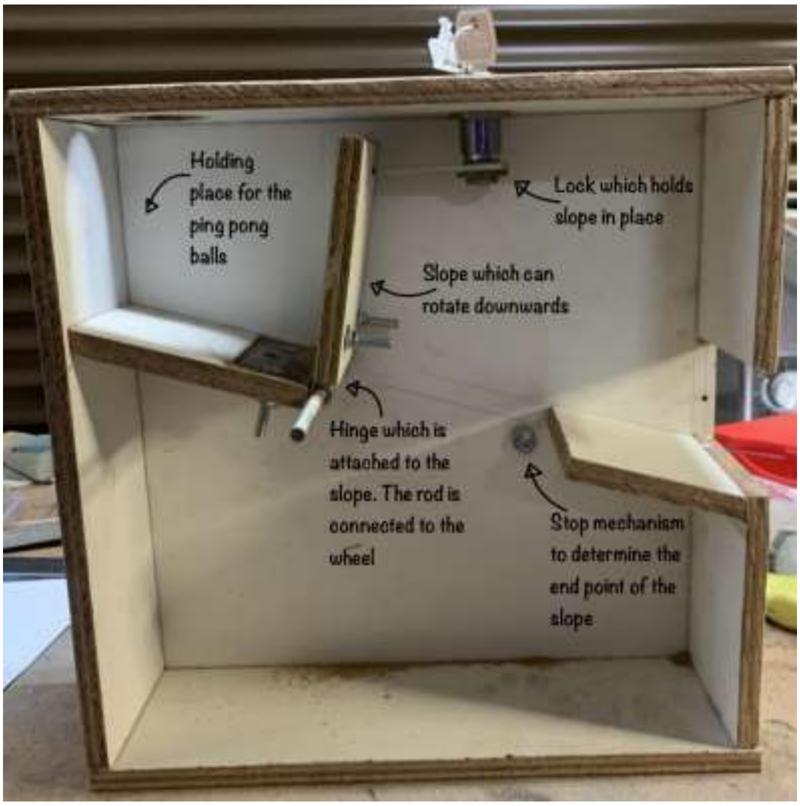


Figure 26

The Outside of the Wheel

6.2 Combustion Generator

6.2.1 Magnet Fishing

The original idea for this puzzle was altered to make the realisation process more achievable. The new goal was to move the key from one point to the exit. The magnet fishing pool was created by making a box with a hole in the bottom, a nail to put the key on and a Plexiglas plate on top. Four holes were drilled into the side so the strings could go through which were attached to the magnet. The initial test showed that this was too easy so the nail was replaced with a hook.

The pilot test showed that this was still too easy, therefore most of the top was obscured, so only the key could be seen. Additionally, the strings were locked to the top with a combination lock, see Figure 27. The code for the combination lock can be obtained by solving a different part of the puzzle. A rebus was made with the rebus tool from Rebus Club [53]. The rebus solves to “The fuel in the combustion generator is propane, the code is the amount of power per kilogram of fuel”, see Figure 28. The management team has a table with different fuel types and their properties, with this information they can calculate the answer, see Table 2. To (re)set the puzzle, the top plates can be removed to put the key back on the hook. The top can be reattached and the rings on the strings can be locked with the combination lock.

Figure 27

Magnet Fishing

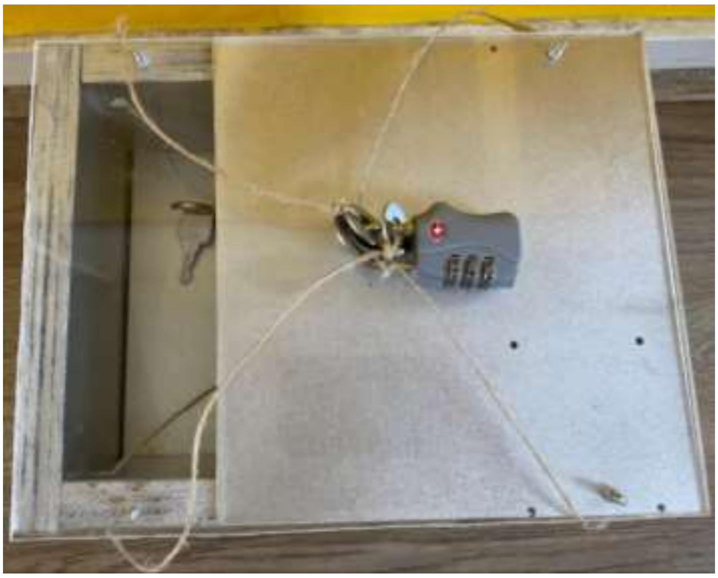


Figure 28

The Rebus for the Magnet Fishing Puzzle

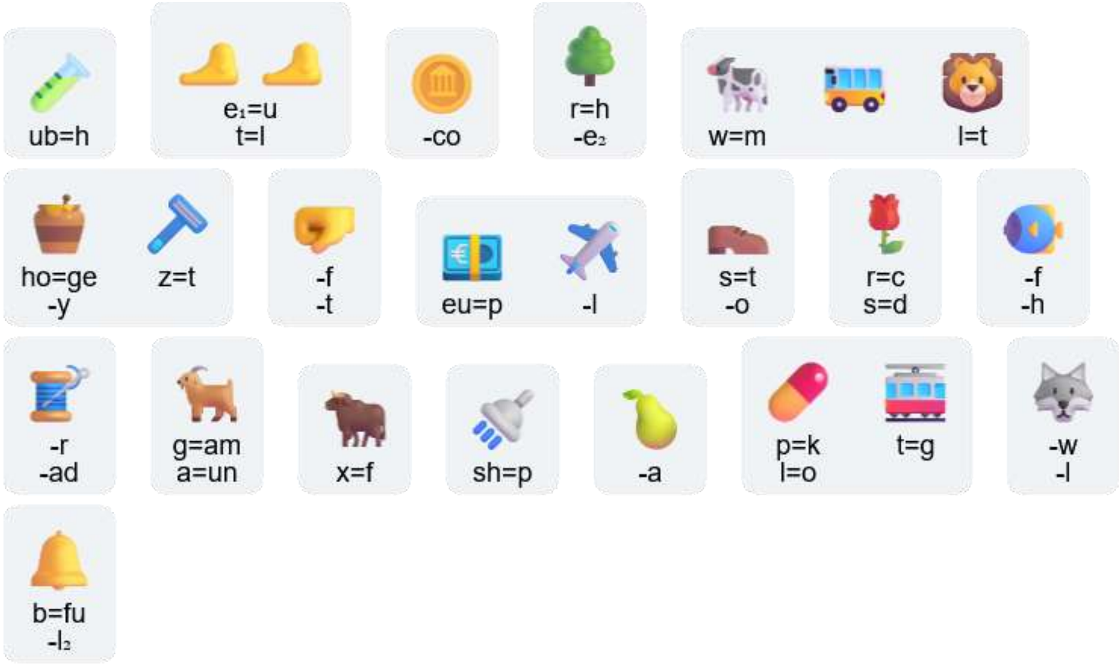


Table 2

Fuel Properties

Fuel type	1kg = [x]L	kWh/L
Propane	1.97	7.0
Diesel	1.18	10.0
LPG	1.82	7.5
Gasoline	1.37	10.5

6.2.2 Smoke Outlet

The smoke outlet consists of a chimneypiece and a slide piece in a box, see Figure 29. The chimney is attached above the slide. The lock holds the ping pong balls in place. When the key is turned the ping pong balls will slide down. To (re)set the smoke outlet, the top of the chimney is removed and filled with ping pong balls.

Figure 29

The Smoke Outlet

6.3 Nuclear Generator

6.3.1 Nuclear Shoot

For this puzzle, a rectangular box was created with a platform on one side, see Figure 30. On the platform three metal pipes were attached to keep the pins in place, see Figure 31. On the opposite side of the box, a PVC pipe was attached at two points so it could rotate sideways. In the pipe, two slits were cut out for the elastic to go through, see Figure 32. The elastic can be attached to a metal ring. On the right side of the box, a circle was cut out for the players to look through and possibly retrieve some energy balls. The back of the box has a hinge to allow for resetting the puzzle. The back has a small gap to allow the players to retrieve the key but not the energy balls. To (re)set the puzzle, the back hinge can be opened by removing a pin with a magnet, this allows access to the inside of the box. The pins can be placed on top of the metal pipes and a key can be hidden in one of the pins. All remaining energy balls should be removed as well as the shooting elastic. When the puzzle is reset, the back hinge will be locked again.

Figure 30

Nuclear Shoot

Figure 31

Targets on Platform

Figure 32

Shooting Part

6.3.2 The Cooling Tower

The shell of the cooling tower was 3D printed with a model from Gamer [54]. Underneath a spring mechanism had to be made. The first iteration consists of a spring which is attached to a plate and held down by a lock. This resulted in the plate being askew and the ping pong balls falling off. The second iteration has a spring which has guide rails so the spring will go straight up. The lock kept the problem of pressing the plate down on one side, and the guide rails resulted in the spring not going up at all. In the third iteration, the lock is changed to have a U-shape, so that it distributes the force over the whole plate, see Figure 33. A piece of rain pipe is secured on top of the plate to ensure the balls stay on the plate and can be refilled easily. The rain pipe also serves as a guide rail to make sure the spring goes up. In theory, this iteration was functional, however, the lock was not strong enough to keep the spring down.

Figure 33

The Third Iteration of the Spring Mechanism for the Nuclear Generator

For the fourth iteration, the idea of springs was discarded and rubber bands were used to create a firing mechanism. A catapult mechanism was designed to shoot the ping pong balls up. A PVC pipe with a diameter of 5 cm was used to guide the balls upwards. A ring was made to fit around the pipe, it can be attached with three screws tightened so they will not interfere with the velocity of the ping pong balls, see Figure 34. To this ring, a rubber band can be attached. On the side of the PVC pipe, two slits are made to allow the elastic to contract fully while keeping sufficient tension. The elastic passes through two screw eye hooks which are attached to a wooden disk to ensure even pressure on the balls. The lock has a pin attached to it which holds the elastic in place and rotates up to release the elastic, see Figure 35. To (re)set the puzzle, the wooden disk is pulled back and the elastic is hooked underneath the pin. The ping pong balls are added from the top and the cooling tower is placed over the contraption. The final cooling tower can be seen in Figure 36.

Figure 34

Firing Mechanism

Figure 35

Locking Mechanism

Figure 36

Cooling Tower

6.4 Renewable Generator

6.4.1 Light Puzzles

The light puzzles were made by printing the text onto paper. For the jigsaw puzzle, parts of the text were traced on one piece of paper and the rest on a different piece of paper. One of these pieces of paper was cut into nine pieces. For the UV puzzle, the text was traced onto a sheet of paper with a pen with invisible ink. Afterwards, all pieces of paper were laminated

6.4.2 Windmill

The windmill is a piece of PVC pipe in which a metal rod with a metal windmill is attached, see Figure 37. The windmill is placed on a box in which a slide is built. With a key, the slide can be lowered down so the balls will roll out of the bottom. To (re)set the puzzle, the slide can be placed into position by pushing it up with a metal rod, and the slide can be locked in place by locking the lock. The ping pong balls can be added from the top by removing the windmill.

Figure 37

Windmill

6.5 Management Team

For the management team, a screen was built so their part of the puzzle can be kept secret, see Figure 38. The screen consists of three pieces of wood attached with hinges so it can be adapted to different types of desks and can stand on its own. The puzzle pieces for the management team are parts of the puzzles as described above.

Additionally, the management team has some information sheets with partially useful information. The extra sheets for the management can be found in Appendix D. These sheets contain information for the nuclear shoot puzzle as this puzzle was found to be too hard during the user tests. They also contain some general information on the structure of power grids, synchronisation, cold load pick up and renewable energy.

Figure 38

Management Screen

6.6 Synchronisation

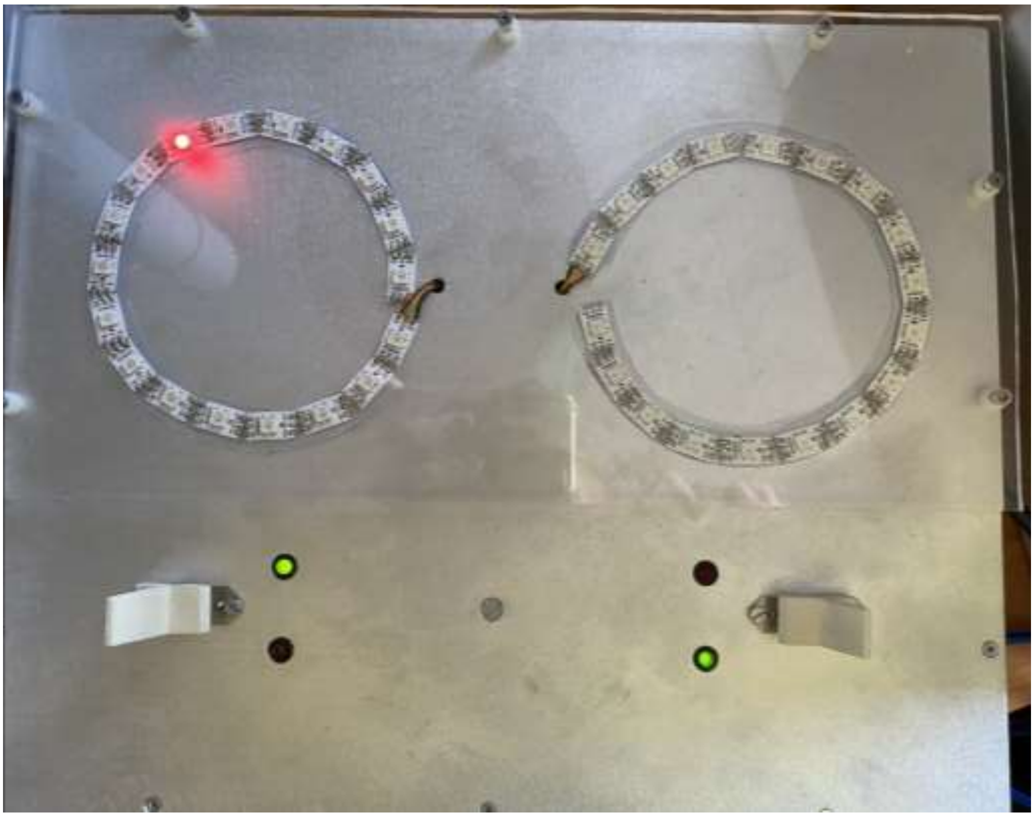
The synchronisation puzzle consists of two strips of programmable LEDs soldered in a circle. Each team has a switch and two LEDs, a red and a green one, which show the state of the synchronisation part. A first iteration of the code was made using the Wokwi simulator [55]. This programme allows for testing code without having to build the physical circuit. With the simulation working, the circuit was reproduced physically, see Figure 39. The Arduino code can be found in Appendix E.

The LED rings were glued onto a metal sheet underneath which was a box containing all the electronics. A Plexiglas sheet was attached on top of the LED rings to protect it from damage – with some spacer screws to avoid breaking the lights. On the side of the box, a hole is cut to allow the Arduino and the LED rings to get power from an outlet.

During the building process, it became clear that the initial goal of adding different parameters – as described in the specification – such as frequency to the synchronisation puzzle would not fit within the scope of this project. For future improvements, it would be good to add these parameters as it might make the players more aware of what they are doing compared to the real world.

Figure 39

Synchronisation



6.7 Cold Load Pickup

During the realisation process, it became clear that the initially designed cold load pickup device was not optimal. The slope on the inside of the house would become too long, making it impractical for classroom settings. The divider between the second part of the process would be unreliable or unnecessarily complex to make. Instead, a device was designed as can be seen in Figure 40.

To visualise the cold load pickup a device similar to a marble run was designed. The energy balls can be thrown in at the top. As they move down, they pass holes which fit one energy ball this way. The first hole represents the average load of the city, the next six holes represent the first sixty per cent of the cold load pickup, see Figure 41. In total, seven balls will fall down while the others roll over the top of them. After this, the energy balls will drop down a piece of stovepipe which has a width of 10 centimetres. At the bottom of this pipe, a partition is made to divide the balls into two categories, see Figure 42. One is the energy balls used in the cold load pickup, the other is the amount of energy balls which are not used.

The probability of the energy balls ending up on either side of the end is fifty per cent. The data is split into four different measurements. In each measurement, the device was turned ninety degrees to account for the slight angle on which it was tested. For all the results the average, standard deviation and skewness of both the right (not used) and the left (used) parts were calculated. The results of the test can be found in Appendix F.

Figure 40

Cold Load Pickup

Figure 41

Average for Cold Load Pickup

Figure 42

Sorting of Energy

Chapter 7 – Evaluation

7.1 Goal of the Evaluation

The goal of the evaluation is to understand the experience of the players while playing the escape room. The main aspects that will be observed are if the game teaches the players the concept of black start and if the game is fun to play. To assess if the goal has been reached, interview questions were composed. The questions can be found in Appendix G.

To determine if the escape room teaches the players something they will be asked during the focus group if they think they learned something from the escape room, and what they learned. After a few other questions, the participants will be asked to explain the concept of a cold load pickup and the concept of synchronisation. Finally, they will be asked if they think their understanding of a blackout has increased.

To ascertain if the escape room was fun, the players will be asked if they had fun. Later they will be asked about their favourite and least favourite part of the escape room. The participants will be asked what they would do if they had a magic wand which could change anything in the game without limitations. This question allows for some creative freedom for the players and can result in more ways for the players to enjoy the experience as they usually focus on the part that they think is missing.

The research question will be answered positively when all the goals have been achieved. When only part of the goals have been achieved, the research question will have been answered with mixed success. If both results of the goals have not been classified as satisfactory, the research question will have been answered negatively. In the latter cases, the ideation process should be revisited based on the feedback from the players to find improvements that will help achieve the goals.

After each test, the suggestions that are feasible to implement will be considered. This will result in slightly different versions during each of the user tests. These improvements will be made to be able to create the most efficient product possible. With the major problems solved, the experience will be better for the new players.

7.2 Procedure of the User Testing

To ensure consistency between the user tests, a procedure was set up. The session starts with allowing the participants to read the information letter and sign the consent forms. Then the players will be told some information about the playing of the escape room. After the first user test, a training speech was composed to make sure that the necessary information had been explained. The speech can be found in Appendix H. After the information, the players could pick a team. Based on the team, they got an accessory – a hat for the manager, and a fluorescent vest for the operators – to immerse them in their role. With their outfits on, they could start playing the game.

During the game, the players had to figure most things out on their own. The researcher was present to observe the players while playing. The communication aspect of the game made the observing of the players easier; because the players had to communicate with each other about the things they had available, the researcher could identify the parts that were noticed quickly as well as the things that were not noticed as quickly or even not at all. The other objective of the researcher was to give hints when needed and to make quick repairs if things broke or did not work in the way they were supposed to. The final task of the researcher was to keep track of the time and notify the players if they had solved the escape room in time.

After the game, a focus group was conducted during which all players were asked to answer the questions as can be found in Appendix G. The players were encouraged to answer all questions and to add on to or discuss with the other participants. The System Usability Score was not used since the focus group provided more in-depth answers than would have been possible with the SUS. After the focus group, the players were thanked for their participation.

7.3 Findings

7.3.1 Pilot test

With the physical part of the escape room finished, a pilot test was conducted to get an estimate of the time limit the players should get as well as to get an idea of how difficult and balanced the puzzles were. It became clear that five people were too many as most of the puzzles did not necessarily need two people to be completed, and especially in small places, the need for someone to communicate between the management team and the operation team was not necessary. The choice was made to decrease the amount of players to three. The magnet fishing puzzle from the combustion generator was too easy, so a rebus and a question with a combination lock were added.

7.3.2 User tests

A total of three user tests were conducted. Each test was done with a group of three players, who were all part of their own ‘team’. The players found the escape room generally self-explanatory, they found it clear what needed to be done to solve the puzzles. Sometimes hints were given when the players were stuck on one puzzle for too long. Each test consisted of an introduction of approximately five to ten minutes, then they had thirty minutes to solve the escape room. If the players were almost done at the thirty-minute mark, they could keep playing to solve the puzzles since they might be able to get some bonus time from the leftover power. After the game, the focus group was conducted, which took ten to thirty minutes depending on the amount of feedback they provided.

The puzzles were generally experienced as fun. The puzzles that were not so enthusiastically received were the light puzzle and the nuclear shoot. The players found the light puzzle slightly too difficult because it took a long time to solve and because the puzzle pieces could be used from multiple angles. The nuclear shoot was also quite difficult as most players did not use the elastic in the most efficient way which made hitting the targets more difficult. Additionally, aiming at the targets might have been too challenging since they could not see the trajectory of the ping pong ball properly.

The first user test resulted in insightful feedback. The main issue was that the management team did not have enough to do and therefore felt out of control in solving the escape room. Some suggestions were made on how to improve this, and the feasible ones to realise were implemented. The management team had too little to do, and they felt that their task was to hand over the things they had behind the screen without having to solve some sort of puzzle. For the magnet maze, multiple mazes were given; each of the mazes had a different abstract symbol of a water animal, at the back of the puzzle, the name of the correct animal was written. The management team was also given extra information pages – including information on the nuclear shoot, as this puzzle was found to be solved wrong in both the pilot and the user test while also taking too much time -, as can be found in Appendix D. Dots were added to the top right corners of all information sheets and paper puzzle pieces to indicate the correct way in which they should be used. The information sheet with the order of the generators was removed. This helps as the management team now has to determine the order of the generators by critical thinking which makes the players more aware of the situation in real life.

Another main point of feedback was that the educational aspect was not fully clear. Some suggestions were made to include more and more clear information in the introductory speech. Therefore the speech was rewritten as a training briefing allowing for the information to be given in a fun and informative way, see Appendix H.

During the other user tests, it became clear that the management had enough to do with the iterations. They did not like that there was so much text in the documents, which shows that the balance between underwhelming and overwhelming the management team is a delicate subject. The operation team found the nuclear shoot too painful as there is quite some force needed when pulling the elastic back. The players also stated that they would have been more aware of the goal of the escape room if the puzzles had been more related to the generators or the topic. Another suggestion the players had would be to have some sort of reward for doing the synchronisation, as it was easy to forget this since it was not necessary to be completed before they could go on with another puzzle.

The goal of the escape room was to teach students about the concepts of a black start, to estimate the effectiveness of the escape room in this aspect, a few questions were asked. Most players were able to explain the concept of a black start and synchronisation. They did not seem confident in their answers and sometimes explained only part of the concept. This might be the case because the puzzles did not need those concepts to be fully understood to solve the puzzles; the puzzles did not help with the understanding of the concept as it was not a crucial step in the process of solving the escape room.

The other important part of the escape room was that it should be fun. The players experienced the escape room as fun. They stated that they would like to have it as a part of the curriculum. They liked the puzzles and their level – difficult enough that it was just a bit frustrating, but easy enough that they felt they could solve them. The players – from the second and third user tests – experienced the differentiation in the two teams as a good concept that encourages players to communicate and work together.

Overall, the escape room was a mixed success. The main goal was partially achieved; the players gained some knowledge on the topic of black starts, cold load pickups and synchronisation but usually, they did not have a very deep understanding. The escape room could be used as an introduction to the topic but not as the main explanation of this complex concept. The sub-goal, of the escape room being fun, was achieved. Only the first user group managed to solve the escape room in time, therefore, the time limit might have to be increased by five minutes. With future iterations, the escape room could be successful in explaining the concepts of a black start, cold load pick up and synchronisation to the players.

Chapter 8 – Discussion and Future Work

8.1 Key Findings

The main goals that were evaluated during the user test were if the game is fun and if it is educational on the topic of black starts. It was found that the players enjoyed the escape room and found it fun to play. The main goal of evaluating if the players had learned something about the concepts of black starts, cold load pickup and synchronisation was harder to specify. The players indicated that they learned something, but they generally hesitated slightly when answering. They could explain the concepts when asked, but usually not in a very confident way.

The escape room can therefore be classified as a mixed success on the goal of creating an educational game to teach university students about the concept of a black start. To make the escape room a success, the puzzles should focus more on these important concepts and make them a crucial element of solving the game. At this stage, the game might be used as an introduction to the topic of black starts but should not solely be used as the teaching material.

8.2 Limitations

8.2.1 Time Limitations

The main limitation in the design and realisation of the escape room was the amount of time. Designing components is a time-consuming process, especially because multiple iterations are generally necessary. During the realisation of the puzzles, these designs might have to be changed again. The building process itself also takes time. The project planning had too little time dedicated to the realisation of the project. Limiting the amount of changes that could have been made to improve the general product.

8.2.2 Physical Limitations

During the realisation process, it became clear that the escape room became quite big. A big box with wheels underneath was constructed to be able to move all parts in one go. The box was 90x60x120 cm. The box was too large to move from and to testing locations, so the testing location was changed to the house of the researcher.

8.2.3 Testing Limitations

Due to the size of the escape room components, the testing location was moved from the university to the house of the researcher. This impacted the amount of participants as it increased the time investment for the participants by half an hour. The time investment for just playing the game was already quite long – approximately one hour – which made requiting participants more difficult. Additionally, a time slot needed to be found in which three participants were available. This was made a bit easier as the number of participants dropped from five to three following the pilot test. The limitations of the testing conditions might have impacted the type of participants.

8.2.4 Subject Limitations

The goal was to create an educational game on the concept of a black start. A black start is a complex concept to explain. Designing an educational game that is perceived as fun which explains a difficult concept is a great challenge. The main limitation of the subject was that the researcher was no expert on this concept.

8.3 Future Work

8.3.1 Physical Improvements

There are several physical aspects which could be improved. The most important improvement would be to make an automatic timer, this way, it is not necessary for an operator to be there, which would decrease the workload of the teachers. They will be able to focus more on the learning and understanding of the subject and help their students where necessary. The other improvement that should be done is the addition of more LEDs, these could be useful in the visualization of certain aspects. The LEDs would be useful on each generator to indicate if it has been solved or not. The cold load pickup might also become clearer with lights indicating the different levels. Furthermore, it would be nice to make the escape room a bit more visually appealing, especially the cold load pickup. If the escape room gets a permanent space, it might be beneficial to give the management team their own space and decorate accordingly to improve the immersion of the players.

8.3.2 Subject Improvements

The most important improvement for the goal of the escape room would be to make the important concepts crucial for the completion of the game. This way, the players will need to understand the concept before they can solve the escape room. How the improvements should be made is something that needs to be tested with participants. This might be solved by making these concepts more into puzzles, so for example filling in words in a sentence that explains the concept and once that has been done correctly, the generators can be synchronised. One possible solution might be to tailor the games more so that they explain these concepts better, however, this will likely make the game less fun. Another solution would be to have a form of reward for synchronising the generators which can be used for solving the next puzzles. The problem with this might be that the generators are not solved in the right order – if one team solves two puzzles in the time the other team solves one, the problem will appear that the puzzle parts will not match. Therefore, the puzzle parts that can be retrieved from the synchronisation should be identical but should not be usable more than once. With user testing, the best way to make the important concepts crucial parts of the completion of the game can be found.

8.3.3 Scale Improvements

One of the primary improvements that should be implemented is the scalability of the escape room. Currently, it can be played with three to five players; in a curriculum setting, it would be beneficial to increase the number of players to at least ten. This could be done by adding more generators, to create more operation teams and increase the size of the management team. Another approach might be to increase the level of the puzzle, requiring multiple people to solve it. When the game is played on a bigger scale, communication becomes more important and therefore a separate room for the management team might become necessary.

When the amount of players is increased, it becomes more important for the teacher and teaching assistants to know how the game is supposed to be played. Therefore a guide should be made complete with hints that can be used when players get stuck.

Chapter 9 – Conclusion

The goal of this graduation project was to create an effective educational game that represents the core elements and decision-making process of a black start. To do this, the fundamental steps in a black start and the most effective ways to create an educational game should be identified.

A black start is the repowering of the electricity grid. There are multiple ways to approach this, the most common approach is the bottom-up approach; with this approach, no power from outside the grid will be used. Black start generators, generators that can start themselves, are used to power parts of the grid – islands – which have to be synchronised to connect them. Within these islands, the order in which the generators are powered depends on the type of generator; the common order to power the generators is by starting with hydropower generators followed by Drum-Type and Super Critical Steam generators, and finally, the nuclear power generators are started.

Educational games are an effective way of teaching a concept through active learning. Educational games can be made effective by making the learning goals part of the essential game mechanics. Player goals should be added that make players feel in control. Elements that can lead to extrinsic motivation, such as point reward systems, should be avoided. Non-digital games are usually more effective in explaining learning goals and are experienced as more fun. Digital games are generally said to have a higher usability which makes them more accessible. There are no educational games on the market that represent the core elements of a black start.

Based on the research background, the Creative Technology Design Process was used to design this game [44]. This iterative approach consists of four phases: ideation, specialisation, realisation and evaluation. The initial game idea – an escape room – was the conclusion of the brainstorming sessions in the ideation phase. In the specification phase, this idea was considered and thought out further, elaborated upon and made more concrete. To make sure that the game would meet the end goal, product requirements were established. The prototype for the escape room was made in the realisation phase. The ideas from the specification phase were used as guidelines, but unexpected outcomes resulted in several new brainstorming sessions for elements of some puzzles and generators. To ensure that the goal had been reached, the product was tested with students in the evaluation phase. Three players – two operation teams and a management team – worked together to solve all the puzzles and give power back to the city within thirty minutes. The goal of explaining the concepts of a black start was partially met, the participants could usually explain the concepts of a cold load pick up and synchronisation of the generators but not without hesitating. The participants did not feel confident in their knowledge of these concepts, so this is something that should be improved upon in future developments. The players did experience the game as fun, which is an important aspect of an effective educational game.

This escape room might start to pave the way for further improvements of educational games on the topic of black starts and make students enthusiastic about this topic. With this interest, more people might develop an interest in becoming a power grid operator. More people in this field will increase the innovation in the power grid giving future generations cleaner and more stable power grids.

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Appendices

Appendix A Information Letters and Consent Form

Information Letter Developing an Educational Game to Teach the Concept of a Black-Start of the Power Grid

The goal of the project is to design an educational game to teach university students about the concepts and procedures in case of a black start. The game has to include realistic scenarios, including their challenges. The players will be divided into three teams, two operator teams and a management team. The players will work together by solving puzzles within the time limit. The game will last approximately 30-60 minutes, depending on the players. During the game, observations will be made by the researcher. The game will be video recorded for observation purposes; meaning that the researcher will be able to observe all parts of the game afterwards to make sure no information is missed. The video will afterwards be destroyed.

After the game, a focus group will be held. In the focus group, questions will be asked regarding their experiences of the game; whether the game was clear, fun and if they learned something from it. The focus group will take 15 to 30 minutes. The focus group will be audio-recorded and transcribed. The transcriptions will be anonymously used for the evaluation of the puzzles. The audio recording will afterwards be destroyed, the transcriptions will be archived as focus group results in the final report.

Participation is entirely voluntary, and your response will be treated anonymously. Participants are free to stop during the game without providing a reason. Participants may request to have their answers deleted at any time without providing a reason.

The audio recordings will be destroyed after transcription. The transcription and interview notes will be kept until the end of the graduation project and will be destroyed afterwards.

There are no expected risks of participating in this study. The research project has been reviewed by the Ethics Committee Information and Computer Science.

If you have any questions about the survey or research, feel free to contact the researcher, Mette Laros, at m.u.j.laros@student.utwente.nl.

Additionally, you can contact the Secretary of the Ethics Committee of the Faculty of Electrical Engineering, Mathematics and Computer Science at the University of Twente through ethicscommittee-cis@utwente.nl

Information letter Puzzles

The goal of the project is to design an educational game to teach university students about the concepts and procedures in case of a black start. The game has to include realistic scenarios, including their challenges. The participants will be asked to solve a puzzle. This will take approximately between 5 to 15 minutes, depending on the player. During the game, observations will be made by the researcher. The game will be video recorded for observation purposes; meaning that the researcher will be able to observe all parts of the game afterwards to make sure no information is missed. The video will afterwards be destroyed.

After the game, a focus group will be held. In the focus group, questions will be asked regarding their experiences of the puzzle; whether the puzzle was clear, fun and if they learned something from it. The focus group will take 10 to 20 minutes. The focus group will be audio-recorded and transcribed. The transcriptions will be anonymously used for the evaluation of the puzzles. The audio recording will afterwards be destroyed, the transcriptions will be archived as focus group results in the final report.

Participation is entirely voluntary, and your response will be treated anonymously. Participants are free to stop during the game without providing a reason. Participants may request to have their answers deleted at any time without providing a reason.

The audio recordings will be destroyed after transcription. The transcription and interview notes will be kept until the end of the graduation project and will be destroyed afterwards.

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Consent form Developing an Educational Game to Teach the Concept of Black-Start of the Power Grid

Author: Mette Laros

Last edited: 11-11-2024

Consent Form for Developing an Educational Game to Teach the Concept of Black-Start of the Power Grid

YOU WILL BE GIVEN A COPY OF THIS INFORMED CONSENT FORM

Please tick the appropriate boxes

es o

Taking part in the study

I have read and understood the study information dated [11/11/2024], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.

I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.

I understand that taking part in the study involves taking part in a focus group with written notes and audio recordings which will be transcribed as text. The audio recording will afterwards be destroyed.

I understand that taking part in the study involves playing a game which will be observed with written notes and video recordings to review the observations. The video recording will afterwards be destroyed.

Use of the information in the study

I understand that information I provide will be used anonymously in the graduation report of Mette Laros

I understand that personal information collected about me that can identify me, such as [e.g. my name], will not be shared beyond the study team.

I consent to be audio recorded during the interview.

I consent to be video recorded during the game.

Future use and reuse of the information by others

I give permission for the anonymised interview transcriptions and notes that I provide to be archived as “focus group results” so it can be used for future research and learning.

Signatures

______________________ ______________________ ________

Name of participant [printed]

Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

____Mette Laros_________ ___________________ ________

Researcher name [printed] Signature Date

Study contact details for further information: Mette Laros m.u.j.laros@student.utwente.nl

Contact Information for Questions about Your Rights as a Research Participant

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee Information & Computer Science: ethicscommittee-CIS@utwente.nl

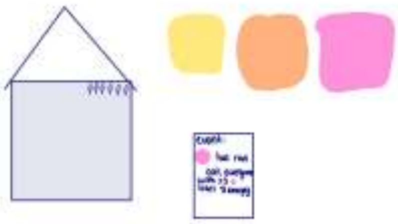
Appendix B System Usability Scale
Figure 43

System Usability Scale **[49]**

	Strongly disagree				Strongly agree
1. I think that I would like to use this system frequently	1	2	3	4	5
2. I found the system unnecessarily complex	1	2	3	4	5
3. I thought the system was easy to use	1	2	3	4	5
4. I think that I would need the support of a technical person to be able to use this system	1	2	3	4	5
5. I found the various functions in this system were well integrated	1	2	3	4	5
6. I thought there was too much inconsistency in this system	1	2	3	4	5
7. I would imagine that most people would learn to use this system very quickly	1	2	3	4	5
8. I found the system very cumbersome to use	1	2	3	4	5
9. I felt very confident using the system	1	2	3	4	5
10. I needed to learn a lot of things before I could get going with this system	1	2	3	4	5

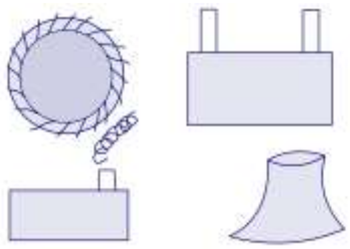
Appendix C Brainstorming

Survival of the fittest



- Collect cards and invest in categories
- Event cards make you gain or lose energy
- Person with the energy supply that lasts the longest wins

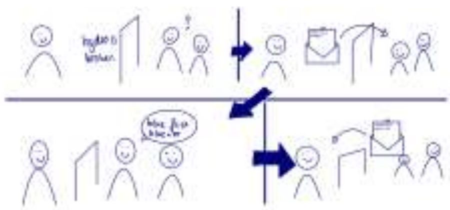
Generator dating simulator



- Match the generators in the right order
- Based on the specifics of the generators

Computer error

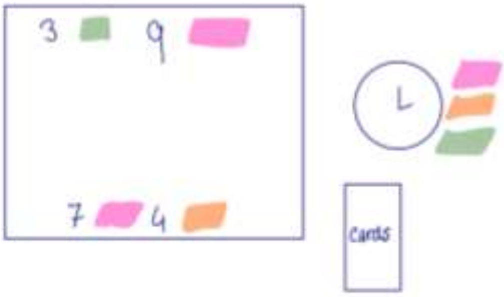
- Computer and operators try to communicat
- Communication using fake code
- Try and fix a generator



Resource management

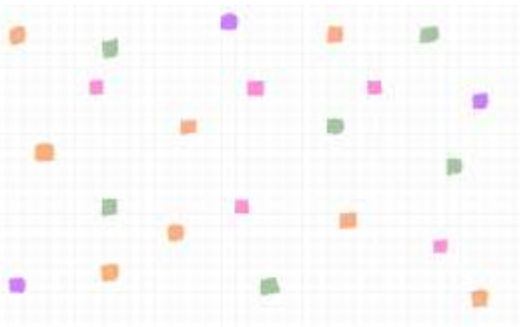
- Collect and trade resources as quick as possible to comply with the needs of your part of the grid
- Different resources can be obtained in different areas of the map

Broken generator



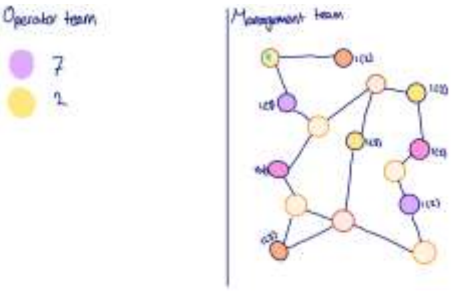
- Turn cards
- Hand in the right cards to fix the generator
- Hand in cards to gain extra time
- Cooperate with other players to trade cards

Build your own grid



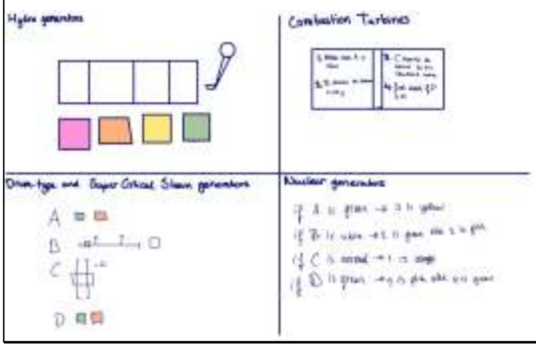
- Make the grid between the blackout generators (purple), generators (pink), priority loads (orange) and non-priority loads (green)
- Make as efficient as possible
- Costs based on cards
- Different terrains → different difficulties turn extra cards to see if you need to hand in extra cards

Communication problems



- Management team sees the grid and resources
- Operator team sees the problems
- They can only communicate without words because the power is down
- When the loads are powered, they generate more resources

Puzzles

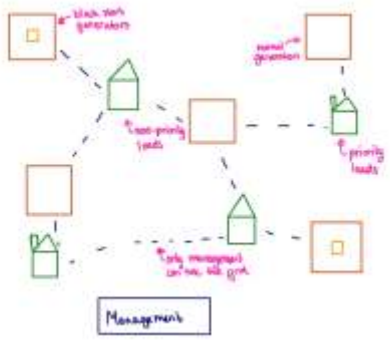


- 4 players or groups are a different generator
- They have puzzles that they can only solve when they communicate and work together
- The puzzles are only solvable in the right order of generator starts

Blackout

- Players are power grid operators
- They have to restart the grid
- They work together to do this as fast as poss

Escape room



- Communication between management and operators
- Management has some info operators other info
- Race against the clock
- Puzzles

Appendix D Management Team Information Pages

Structure of Power Grids

The electricity grid consists of three main categories: generation, transmission and distribution. The generation category focuses on generating the power needed to meet de demand from the customers. The generators can be divided into two subcategories: conventional fuel generators and renewable fuel generators. Conventional fuel generators are generators that use coal, oil, natural gas and nuclear as fuel; these fuels cannot be replenished once they have been used. Renewable generators use wind, water power, solar power, geothermal heat and tidal waves as energy sources; these sources of energy can be used multiple times.

The transmission category consists of high-voltage power lines, while distribution consists of lower-voltage power lines. Transmission lines are used to move large quantities of electricity over large areas from the power plants to substations. The voltage gets reduced via transformers and can thus be transported over the distribution lines. The distribution lines move the electricity from the substations to the individual customers.

Synchronisation of Multiple Generators

When a generator is powered, it creates a small island of power. To connect two islands into a bigger island, both islands need to be stable because unstable islands can cause another blackout. Islands are stable if they are within the voltage limits and have a frequency within boundaries, as well as enough reserves. Once these conditions are fulfilled, the frequency and voltage of the smallest island will be adjusted to match that of the larger island, to prevent damage and possible blackouts [11]. When the islands are successfully connected, a more stable bigger island is created which can more easily give power to other areas. Connecting the islands is of great importance and should always be done.

To synchronise the islands, the levers need to be switched at the right moment; when the LEDs are green. When one island is switched at the right moment, the other island has to be switched correctly within a round. Not switching the islands on the right time can cause another blackout and will therefore cost you time.

Cold Load Pickup

In the case of a power blackout, there will be a peak in the energy demand when the power is restored to the loads. This concept, called a cold load pickup, is caused by the initial power needed to turn electric devices on. A refrigerator, for example, has to reach a certain temperature before it stops cooling, using a lot of power; once this threshold has been reached, the cooling is stopped until it has warmed up enough that cooling is necessary once again. The cold load after a blackout can be up to 10 times as much power compared to normal loads and has to be considered carefully.

The standard energy demand for the city is equal to [1/2] energy balls. When restarting the grid this can increase to [12] energy balls. The amount of cold load pickup depends on how many devices are plugged into the net and how much energy they need. The energy demand usually gets at least six times as big, the amount of extra energy needed is a fifty per cent chance. To visualise this, the first [7] energy balls will be used with an almost 100% chance, and the other [5] energy balls will have a fifty per cent chance of getting used.

The amount of energy which is not needed during the restart of the city can be used for another city, thus giving you a bit of extra time.

Benefits and Pitfalls of Renewable Energy

Renewable energy becomes increasingly valuable as people become more aware of the effect of traditional energy production on the climate. Governments place more importance on the usage of renewable or green energy which can lead to some complications in the event of a black start.

The downside of renewable energy is that it is not a reliable energy source, meaning that the amount of energy depends on the weather conditions. Windmills generate less power when the winds are not as strong. During a black start, the energy supply should be stable to prevent additional power blackouts. Renewable energy sources are therefore mostly added to the grid when the grid has become stable. Hydropower is exempt from this general rule as the flow of water is quite consistent when the water supply is sufficient.

New ways of storing renewable energy are being developed. Stabilising the energy of renewable sources is also a topic for which new solutions are being sought. These new developments could aid in the usage of renewable energy during a black start.

CATAPULT ENERGY TECHNOLOGY

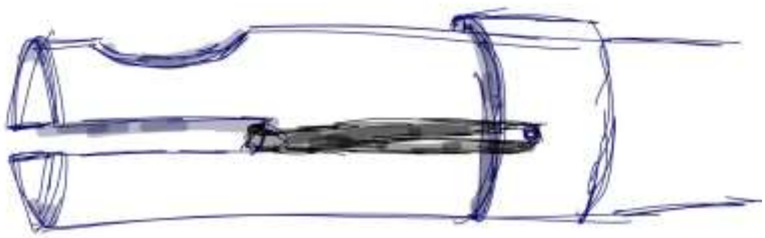
Introduction
Catapult technology is a way to shoot energy. By increasing the tension, a higher success rate will be achieved. The energy travels in an arc, which makes encasing the projectile for the initial part of its journey difficult making aiming the projectile correctly can be challenging.

Usage
The goal is to create the highest possible energy velocity. This can be done by lowering the scoop all the way down. Furthermore, the energy should be aimed precisely at the target.

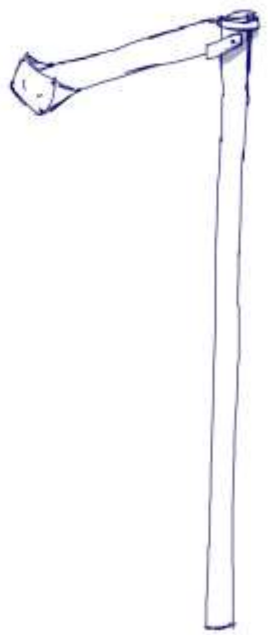
SLINGSHOT ENERGY TECHNOLOGY

Introduction
Slingshot technology can be used to shoot energy. More force will result in a higher success rate of creating more energy. By guiding the elastic portion, the projectile can be steered in the right direction. To aim the projectile more precisely, the projectile travels partially through a case.

Usage
The goal is to create the highest velocity of the energy as possible. This can be done by increasing the tension on the elastic part as well as by hitting the energy in the middle.

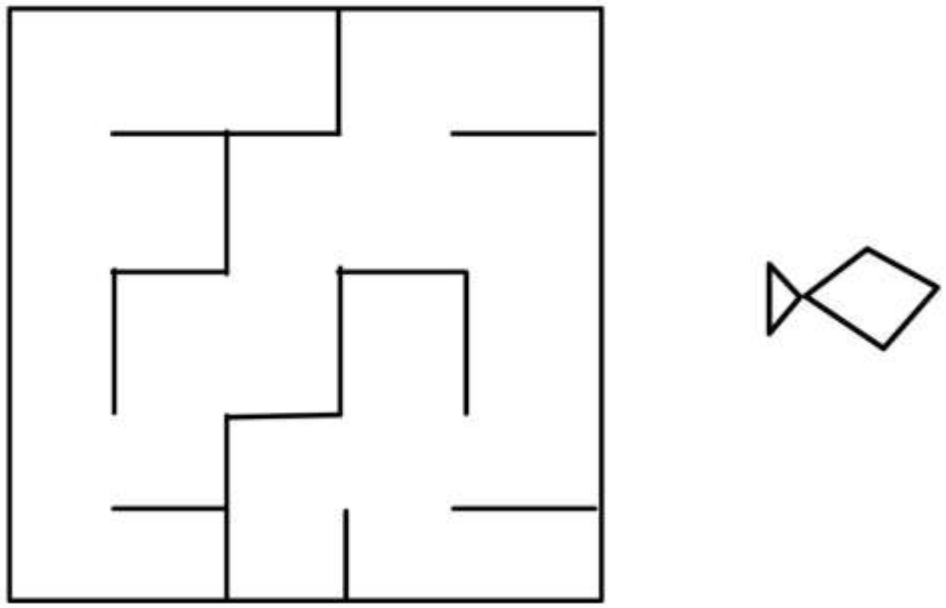


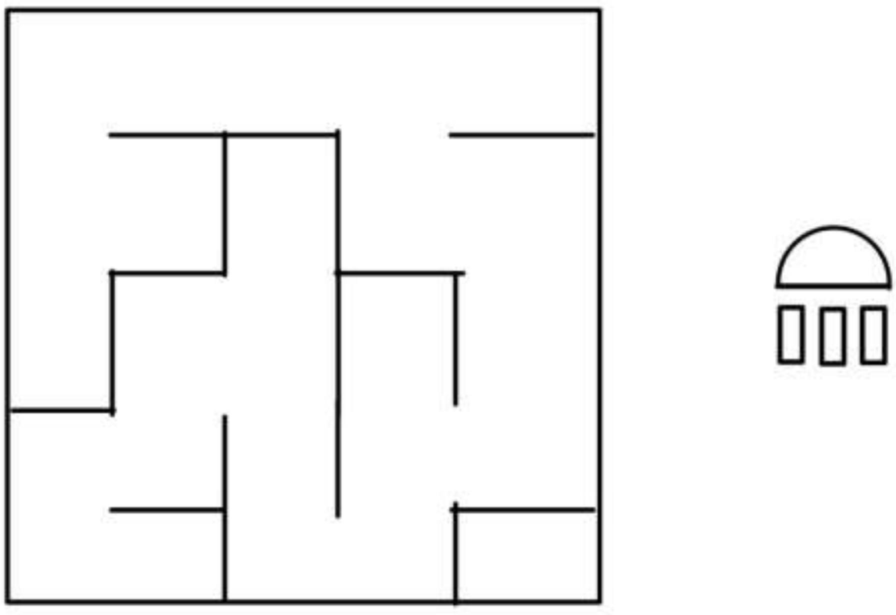
SLING ENERGY TECHNOLOGY

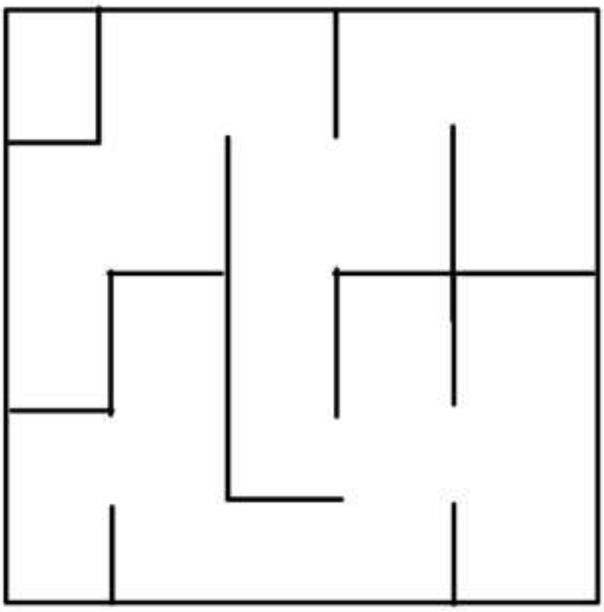


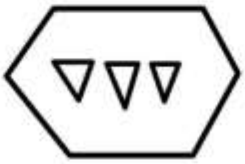
Introduction
Sling technology is a way of shooting energy. By spinning at a high velocity, a higher success rate can be achieved. Aiming with this technology is the most complex part as the sling should be released at precisely the right moment.

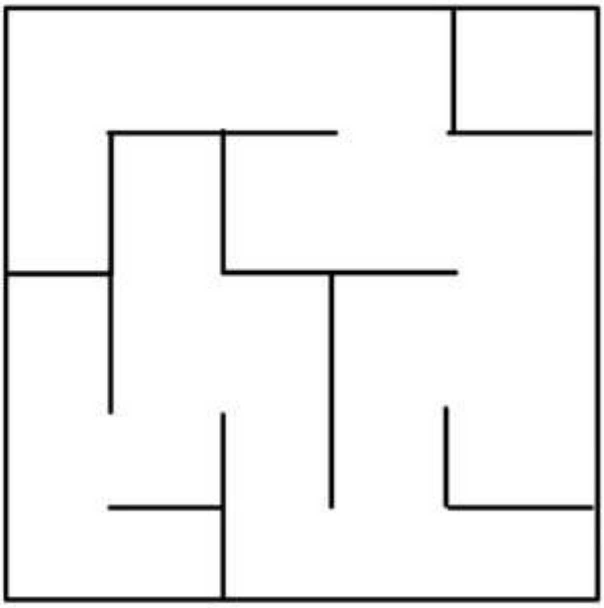
Usage
The goal is to accurately aim the energy with enough force at the target. This can be done by rotating the base quickly and letting it go at the right moment. To operate this machine, one should have the right credentials.

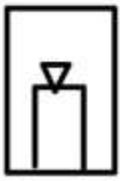












Appendix E Arduino Code Synchronisation

```
#include <FastLED.h>
#include <crgb.h>

#define numberLeds1 18
#define numberLeds2 18
#define ledPin1 6
#define ledPin2 5
#define buttonPin1 2
#define buttonPin2 4
#define greenLedPin1 13
#define greenLedPin2 8
#define redLedPin1 12
#define redLedPin2 7

CRGB leds1[numberLeds1];
CRGB leds2[numberLeds2];
bool greenLed1 = false;
bool greenLed2 = false;
bool prevTimePassed1 = false;
bool prevTimePassed2 = false;
bool timePassed1 = false;
bool timePassed2 = false;
bool correctButtonPressed1 = false;
bool correctButtonPressed2 = false;
bool stopProgramme1 = false;
bool stopProgramme2 = false;
bool hasRun = false;
bool restartGame = false;
bool tooLong1 = false;
bool tooLong2 = false;
bool buttonHasRun1 = false;
bool buttonHasRun2 = false;
bool restartInABit = false;
bool restartHasRun = false;
int buttonState1 = 0;
int buttonState2 = 0;
int speed = 100;
int level = 3;
int i = -1;
int j = -1;
int o = -1;
int limit = 50;
unsigned long underGameOver;
unsigned long upperGameOver;
unsigned long gameOver;
unsigned long restart;
```

```
unsigned long buttonPressTime1;
unsigned long buttonPressTime2;
unsigned long previousMillis1 = 0;
unsigned long previousMillis2 = 23;
const long interval1 = 66;
const long interval2 = 55;
const long buttonTime = 450;
const long intervalCountdown = 10500;
const long restartCountdown = 2000;

void setup() {
  FastLED.addLeds<WS2812B, ledPin1, GRB>(leds1, numberLeds1);
  FastLED.addLeds<WS2812B, ledPin2, GRB>(leds2, numberLeds2);
  FastLED.setBrightness(100);
  Serial.begin(9600);
  pinMode(greenLedPin1, OUTPUT);
  pinMode(greenLedPin2, OUTPUT);
  pinMode(redLedPin1, OUTPUT);
  pinMode(redLedPin2, OUTPUT);
  pinMode(buttonPin1, INPUT);
  pinMode(buttonPin2, INPUT);
}

void loop() {
  unsigned long currentMillis1 = millis();
  unsigned long currentMillis2 = millis();
  unsigned long currentMillisCountdown = millis();
  buttonState1 = digitalRead(buttonPin1);
  buttonState2 = digitalRead(buttonPin2);

  if (buttonState1 == HIGH) {
    if (buttonHasRun1 == false) {
      buttonPressTime1 = currentMillis1 + buttonTime;
      buttonHasRun1 = true;
    }
    if (buttonPressTime1 == currentMillis1) {
      digitalWrite(redLedPin1, HIGH);
      digitalWrite(greenLedPin1, LOW);
      correctButtonPressed1 = false;
      restartGame = true;
      tooLong1 = true;
    }
    if (tooLong1 == false) {
      if (greenLed1 == true) {
        digitalWrite(greenLedPin1, HIGH);
        digitalWrite(redLedPin1, LOW);
        correctButtonPressed1 = true;
        stopProgramme1 = true;
```

```
      } else if ((stopProgramme1 == false) || (greenLed1 == false)) {
        digitalWrite(greenLedPin1, LOW);
        digitalWrite(redLedPin1, HIGH);
        digitalWrite(greenLedPin2, LOW);
        digitalWrite(redLedPin2, HIGH);
        correctButtonPressed2 = false;
        correctButtonPressed1 = false;
        stopProgramme1 = false;
        stopProgramme2 = false;
        restartGame = true;
      } else if ((stopProgramme1 == true) && (buttonState2 == false)) {
        digitalWrite(greenLedPin1, HIGH);
        digitalWrite(redLedPin1, LOW);
      } else if ((stopProgramme1 == true) && (correctButtonPressed2 == false))
{
        digitalWrite(greenLedPin1, LOW);
        digitalWrite(redLedPin1, HIGH);
        stopProgramme1 = false;
        stopProgramme2 = false;
        correctButtonPressed1 = false;
        correctButtonPressed2 = false;
        digitalWrite(greenLedPin2, LOW);
        digitalWrite(redLedPin2, HIGH);
        restartGame = true;
        leds1[numberLeds1 - 1] = CRGB(0, 0, 0);
        leds2[numberLeds2 - 1] = CRGB(0, 0, 0);
        FastLED.show();
      }
    }
  }
  if (buttonState1 == LOW) {
    buttonHasRun1 = false;
  }
  if (buttonState2 == HIGH) {
    if (buttonHasRun2 == false) {
      buttonPressTime2 = currentMillis2 + buttonTime;
      buttonHasRun2 = true;
    }
    if (buttonPressTime2 == currentMillis2) {
      digitalWrite(redLedPin2, HIGH);
      digitalWrite(greenLedPin2, LOW);
      correctButtonPressed2 = false;
      restartGame = true;
      tooLong2 = true;
    }
    if (tooLong2 == false) {
      if (greenLed2 == true) {
        digitalWrite(greenLedPin2, HIGH);
```

```
        digitalWrite(redLedPin2, LOW);
        correctButtonPressed2 = true;
        stopProgramme2 = true;
      } else if ((stopProgramme2 == false) || (greenLed2 == false)) {
        digitalWrite(greenLedPin2, LOW);
        digitalWrite(redLedPin2, HIGH);
        digitalWrite(redLedPin1, HIGH);
        digitalWrite(greenLedPin1, LOW);
        correctButtonPressed1 = false;
        correctButtonPressed2 = false;
        stopProgramme1 = false;
        stopProgramme2 = false;
        restartGame = true;
      } else if ((stopProgramme2 == true) && (buttonState1 == false)) {
        digitalWrite(greenLedPin2, HIGH);
        digitalWrite(redLedPin2, LOW);
      } else if ((stopProgramme2 == true) && (correctButtonPressed1 == false))
{
        digitalWrite(greenLedPin2, LOW);
        digitalWrite(redLedPin2, HIGH);
        stopProgramme1 = false;
        stopProgramme2 = false;
        correctButtonPressed1 = false;
        correctButtonPressed2 = false;
        digitalWrite(greenLedPin1, LOW);
        digitalWrite(redLedPin1, HIGH);
        restartGame = true;
        leds1[numberLeds1 - 1] = CRGB(0, 0, 0);
        leds2[numberLeds2 - 1] = CRGB(0, 0, 0);
        FastLED.show();
      }
    }
  }

  if (buttonState2 == LOW) {
    buttonHasRun2 = false;
  }
  if ((timePassed1 == !prevTimePassed1) && (correctButtonPressed1 == true) &&
(stopProgramme1 == true) && (restartGame == false)) {
    leds1[i] = CRGB(0, 255, 0);
    FastLED.show();
  }
  if ((timePassed2 == !prevTimePassed2) && (correctButtonPressed2 == true) &&
(stopProgramme2 == true) && (restartGame == false)) {
    leds2[j] = CRGB(0, 255, 0);
    FastLED.show();
  }
  if (currentMillis1 - previousMillis1 >= interval1) {
```

```
    previousMillis1 = currentMillis1;
    prevTimePassed1 = timePassed1;
    timePassed1 = !timePassed1;
  }
  if (currentMillis2 - previousMillis2 >= interval2) {
    previousMillis2 = currentMillis2;
    prevTimePassed2 = timePassed2;
    timePassed2 = !timePassed2;
  }


  if ((timePassed1 == !prevTimePassed1) && (correctButtonPressed1 == false) &&
(stopProgramme1 == false)) {
    if ((i < numberLeds1) && (stopProgramme1 == false)) {
      i++;
      if (i <= numberLeds1 - level) {
        greenLed1 = false;
        leds1[i] = CRGB(255, 0, 0);
        FastLED.show();
        if (timePassed1 == !prevTimePassed1) {
          timePassed1 = prevTimePassed1;
          leds1[i] = CRGB(0, 0, 0);
        }
        return;
      }
      if (i >= numberLeds1) {
        i = -1;
      } else if (i > numberLeds1 - level) {
        greenLed1 = true;
        leds1[i] = CRGB(0, 255, 0);
        FastLED.show();
        if (timePassed1 == !prevTimePassed1) {
          timePassed1 = prevTimePassed1;
          leds1[i] = CRGB(0, 0, 0);
        }
        return;
      }
    }
    return;
  }

  if ((timePassed2 == !prevTimePassed2) && (correctButtonPressed2 == false) &&
(stopProgramme2 == false)) {
    if ((j < numberLeds2) && (stopProgramme2 == false)) {
      j++;
      if (j <= numberLeds2 - level) {
        greenLed2 = false;
        leds2[j] = CRGB(255, 0, 0);
        FastLED.show();
```

```
        if (timePassed2 == !prevTimePassed2) {
          timePassed2 = prevTimePassed2;
          leds2[j] = CRGB(0, 0, 0);
        }
        return;
      }
      if (j >= numberLeds2) {
        j = -1;
      } else if (j > numberLeds2 - level) {
        greenLed2 = true;
        leds2[j] = CRGB(0, 255, 0);
        FastLED.show();
        if (timePassed2 == !prevTimePassed2) {
          timePassed2 = prevTimePassed2;
          leds2[j] = CRGB(0, 0, 0);
        }
        return;
      }
    }
    return;
  }
  if (((stopProgramme1 == true) || (stopProgramme2 == true)) && (hasRun ==
false)) {
    gameOver = currentMillisCountdown + intervalCountdown;
    underGameOver = gameOver - limit;
    upperGameOver = gameOver + limit;
    hasRun = true;
  }
  if (((currentMillisCountdown >= underGameOver) && (currentMillisCountdown <=
upperGameOver)) && ((stopProgramme1 == false) || (stopProgramme2 == false)) &&
(!((stopProgramme1 == false) && (stopProgramme2 == false)))) {
    digitalWrite(redLedPin1, HIGH);
    digitalWrite(redLedPin2, HIGH);
    digitalWrite(greenLedPin1, LOW);
    digitalWrite(greenLedPin2, LOW);
    for (int k = 0; k < numberLeds1; k++) {
      leds1[k] = CRGB(255, 0, 0);
      leds2[k] = CRGB(255, 0, 0);
    }
    stopProgramme1 = false;
    stopProgramme2 = false;
    correctButtonPressed1 = false;
    correctButtonPressed2 = false;
    restart = currentMillisCountdown + restartCountdown;
  }
  if ((stopProgramme1 == true) && (stopProgramme2 == true)) {
    digitalWrite(redLedPin1, LOW);
    digitalWrite(redLedPin2, LOW);
```

```
    digitalWrite(greenLedPin1, HIGH);
    digitalWrite(greenLedPin2, HIGH);
    for (int k = 0; k < numberLeds1; k++) {
      leds1[k] = CRGB(0, 255, 0);
      leds2[k] = CRGB(0, 255, 0);
      FastLED.show();
    }
    restartInABit = true;

  }

  if ((currentMillisCountdown == restart) || (restartGame == true)) {
    hasRun = false;
    correctButtonPressed1 = false;
    correctButtonPressed2 = false;
    stopProgramme1 = false;
    stopProgramme2 = false;
    restartGame = false;
    buttonHasRun1 = false;
    buttonHasRun2 = false;
    restartInABit = false;
    restartHasRun = false;
    greenLed1 = false;
    greenLed2 = false;
    prevTimePassed1 = false;
    prevTimePassed2 = false;
    timePassed1 = false;
    timePassed2 = false;
    tooLong1 = false;
    tooLong2 = false;
    buttonState1 = 0;
    buttonState2 = 0;
  }
  if ((restartInABit == true) && (restartHasRun == false)){
    restartHasRun = true;
    delay(7000);
    for (int l = 0; l < numberLeds1; l++) {
      leds1[l] = CRGB(0, 0, 255);
      leds2[l] = CRGB(0, 0, 255);
      FastLED.show();
    }
    delay(1000);
    for (int m = 0; m < numberLeds1; m++) {
      leds1[m] = CRGB(0, 0, 0);
      leds2[m] = CRGB(0, 0, 0);
      FastLED.show();
    }
    delay(700);
```

```
    for (int n = 0; n < numberLeds1; n++) {
      leds1[n] = CRGB(0, 0, 255);
      leds2[n] = CRGB(0, 0, 255);
      FastLED.show();
    }
    delay(1500);
    restartGame = true;

  }
}
```

Appendix F Cold Load Pickup Data

The average data from all measurements combined.

Skew Left	0,814272	Skew Right	-0,81427
Standard Deviation Left	0,104073	Standard Deviation Right	0,104073
Average Left	5	Average Right	5

Skew	-0,17025		0,170255	
SD	1,699673		1,699673	
average	4,666667		5,333333	
measurement	L	%L	R	%R
1	6	60	4	40
2	3	30	7	70
3	5	50	5	50
4	7	70	3	30
5	7	70	3	30
6	4	40	6	60
7	5	50	5	50
8	3	30	7	70
9	1	10	9	90
10	5	50	5	50
11	4	40	6	60
12	5	50	5	50
13	4	40	6	60
14	2	20	8	80
15	7	70	3	30
16	7	70	3	30
17	4	40	6	60
18	7	70	3	30
19	3	30	7	70
20	5	50	5	50
21	4	40	6	60

Skew	0,322532		-0,32253	

SD	1,484615		1,484615	
average	5,714286		4,285714	
measurement	L	%L	R	%R
1	6	60	4	40
2	4	40	6	60
3	7	70	3	30
4	4	40	6	60
5	3	30	7	70
6	9	90	1	10
7	6	60	4	40
8	4	40	6	60
9	7	70	3	30
10	8	80	2	20
11	6	60	4	40
12	6	60	4	40
13	6	60	4	0
14	5	50	5	50
15	5	50	5	50
16	8	80	2	20
17	4	40	6	60
18	5	50	5	50
19	6	60	4	40
20	6	60	4	40
21	5	50	5	50

Skew	-0,04685		0,046851	
SD	1,731396		1,731396	
Average	4,380952		5,619048	
Measurement	L	%L	R	%R
1	7	70	3	30
2	4	40	6	60
3	5	50	5	50

4	4	40	6	60
5	5	50	5	50
6	3	30	7	70
7	6	60	4	40
8	5	50	5	50
9	6	60	4	40
10	2	20	8	80
11	5	50	5	50
12	5	50	5	50
13	4	40	6	0
14	1	10	9	90
15	5	50	5	50
16	4	40	6	60
17	8	80	2	20
18	3	30	7	70
19	2	20	8	80
20	6	60	4	40
21	2	20	8	80
Skew	-0,24588		0,245879	
SD	1,540092		1,540092	
Average	5,238095		4,761905	

Measurement	L	%L	R	%R
1	5	50	5	50
2	8	80	2	20
3	6	60	4	40
4	7	70	3	30
5	4	40	6	60
6	5	50	5	50
7	4	40	6	60
8	7	70	3	30
9	6	60	4	40
10	5	50	5	50

11	3	30	7	70
12	6	60	4	40
13	2	20	8	0
14	3	30	7	70
15	6	60	4	40
16	7	70	3	30
17	5	50	5	50
18	4	40	6	60
19	7	70	3	30
20	6	60	4	40
21	4	40	6	60

Appendix G Interview Questions Evaluation

- Did you have fun?
- How did you experience the game?
- Did you learn something during the game, if so what did you learn?
- What did you like?
- What did you not like?
- If you had a magic wand which could change things about the game without limitations, what would you change?
- Would you like to play this game as part of the electrical engineering curriculum at the University of Twente?
- Can you explain what a Cold Load Pickup is?
- Can you explain what synchronization is?
- Do you feel like this game increased your understanding of the concept of a blackout?

Appendix H Training Speech

You are here today to learn how you can bring power back in case of a power blackout. The goal of this 'training session' is to bring power back to a city. This might seem easy, but there are a few things to keep in mind during this process. You will need multiple generators to power this city. When connecting these generators together on the power grid, they must be synchronised. This means that the voltage, frequencies and phases of the energy are the same. Synchronisation should therefore happen after each new generator that is added to the grid.

Before supplying the power to the city, it is important to be aware of the cold load pickup. This is the concept that when the power has been off, the initial power demand is higher than what is usually used. For example, when a fridge has been off for multiple hours it has to actively start cooling a lot before the desired temperature has been reached. This peak in energy is called a cold load pickup and can be up to ten times as much energy compared to the normal load. How much extra power is needed depends on how many devices are connected to the grid. It is important that you have at least the maximum amount of power before supplying it to the load to avoid another blackout.

You will have to give power to the load as quickly as possible, the time limit is thirty minutes. This time is flexible, meaning that there are certain things that can influence the total amount of time. When the generators are not synchronised, or if a mistake is made in the synchronisation, you will lose time. The energy that is not used after the cold load pickup can give you extra time, so keep going even if the time is up.

During the black start procedure, you will be divided into three groups, one management 'team' and two operation 'teams'. The management team will sit behind the screen.

Some other things to remember are that no screws or bolts have to be removed. All puzzles should stay in their place except for the puzzle at the hydro generator. Each generator consists of one puzzle which will give you a key to open the generator so the energy can be collected. The keys can only be used for their respective generators so please don't mix them across generators.