GAMIFICATION IN THE FRAMEWORK OF A REAL-TIME MULTIBODY SIMULATION

Lappeenranta–Lahti University of Technology LUT

Master's Programme in Mechatronic System Design, Master's thesis

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Anna Nikitina

Examiners: Professor Aki Mikkola

Suraj Jaiswal, D.Sc.(Tech.)

ABSTRACT

Lappeenranta–Lahti University of Technology LUT
LUT School of Energy Systems
Mechanical Engineering

Anna Nikitina

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Simulation is a tool for assessing the quality of the developing product. Multibody system dynamics is an approach used for simulation of mechanical systems that allows the real-time simulation. When the simulation is running real-time, the use cases for it are expanded into marketing, training and maintenance, supporting the whole life cycle of the machine. The data obtained from the simulator used for these purposes can be then fed back into the research for continuous model improvement. However, the novelty of the simulator wears off easily for users, and they lose motivation to continue operating the simulator. Gamification is an approach used to increase user engagement and involvement that can be implemented on top of the existing system, including mechanical simulations.

This research focused on creating the gamified system on top of an existing excavator model created with Mevea software, as well as addition of hydraulic circuit parametrisation. The literature review helped establishing the systematised framework for gamification implementation. Based on it, game elements were implemented: leveling, continuous feedback and performance metrics. Leveling included tutorial with operation instructions, and independent soil loading exercises. Continuous feedback was provided by the meters on the screen, and the performance metrics were presented by the written feedback in the end of the exercise. The parametrisation was implemented using the spline editor that changed the shape of model's hydraulic valves characteristic curves. The user experience survey was conducted in order to collect the opinion about the gamified system.

The results of user survey showed that users enjoyed the gamified model and felt that it helped them to improve their excavator operation skills. Users also stayed motivated to try the simulator again. Unlike in previous research, the parametrisation was randomised even without user input, providing more diverse data for analysis. However, the data about the influence of hydraulic valves on the overall operation was not conclusive and requires further investigation.

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Lappeenranta, January 17, 2022

Anna Nikitina

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Symbols and abbreviations

Abbrevations

3D	Three dimensions
DOF	Degree of freedom
HIL	Hardware-in-the-loop
PBL	Points, badges and leaderboards
R&D	Research and development

1 Introduction

Simulation has been a well-known tool used in product development for many years, even before the computational power of the personal computers was enough to handle complex multibody or Monte-Carlo simulations. Stefan Thomke describes 90s as the turning point for the car manufacturing industry in terms of prototyping, decreasing the lead times as costs mostly due to the emerging computer-aided technologies. With the wider introduction of computer-aided technologies, especially simulation, the time and resource consuming physical prototyping step was eliminated, while increasing the amount of the iterations the design goes through. (Thomke 2001, p. 21)

Simulation has clear advantages compared to prototype-based development and allows the companies to develop and test the concept before they can be physically built. The simulation can serve different purposes, but the focus of this work lies on real-time simulation, which is a special case of conventional simulation. Real-time simulation means that all the software modules need to compute their operations within pre-defined time step. At the same time, to influence the simulation, a synchronous connection to the real world via Hardware-in-the-Loop or Man-in-the-Loop simulation is needed. (Korkealaakso 2009, pp. 15–17).

However, the usage of simulation is not limited to only product development these days but can be used throughout the whole product lifecycle: in research and development (R&D), service, marketing, and sales (Alaei et al. 2018, pp. 3–5). In real-time simulation of mechatronic systems, multibody dynamics approach is well known and used, with the development of early methods starting in 1980s, but only in 21st century the computers became powerful enough to execute the multibody codes efficiently and reliably.

Simulation also allows the designers and engineers to collect the user feedback early in the design process, which decreases the time and amount of the design iterations, as the customer can better communicate the needs. Collecting user feedback early in the design process also ensures that the users receive the product needed which is more likely to perform well in the market. If the machine operation is complex and the building process is long, it is also possible to start training the operators even before the machine is built, as well as market it to wide audience. (Alaei et al. 2018, p. 1).

The data produced during the simulation runs can be analysed and used for improving the performance of the machine. However, to use the data in proper analysis, the data need to be consistent yet there should be enough of it. This can be achieved by running multiple simulation runs with the same operator, but certain variability still must be introduced to ensure at least few different operation modes are covered. It can be challenging to encourage the user to complete enough runs to provide enough data for analysis, however, a designer can use the natural competitiveness and psychological aspects of the human nature to their advantage with the help of gamification.

Gamification is known as “the use of game design elements in non-game contexts”. The first documented use of the concept was seen in 2008, and since then this has been a vibrant trend both in computer sciences academia, as well as in various industries. In its core, gamification is based on creating “activities motivated by curiosity, motivation and reflection”. Gamification is well separated from serious games and playful design, as shown in Figure 1, because it is separated both on the axis of playing-gaming and whole-parts. This means that unlike playing, gaming and gamification always uses a set of rules and restrictions, while unlike serious games, gamification is a part or elements included into ready system. Serious games are purpose-built systems, designed and implemented as games from their inception, using not only certain parts of the gaming process, but incorporating the gaming features all at the same time. Gamification is usually built on top of the existing systems, or with minimal changes to the main mechanics of the existing system, and it includes limited amount of game features. This makes gamification attractive for the use in training, health, news and “other purposes”, as it does not mean that completely new system has to be developed. (Deterding et al. 2011, p. 2)

“Other purposes” is a broad definition, which allows us to connect the real-time simulation and the gamification. Real-time simulation, especially user-centric, includes at least one

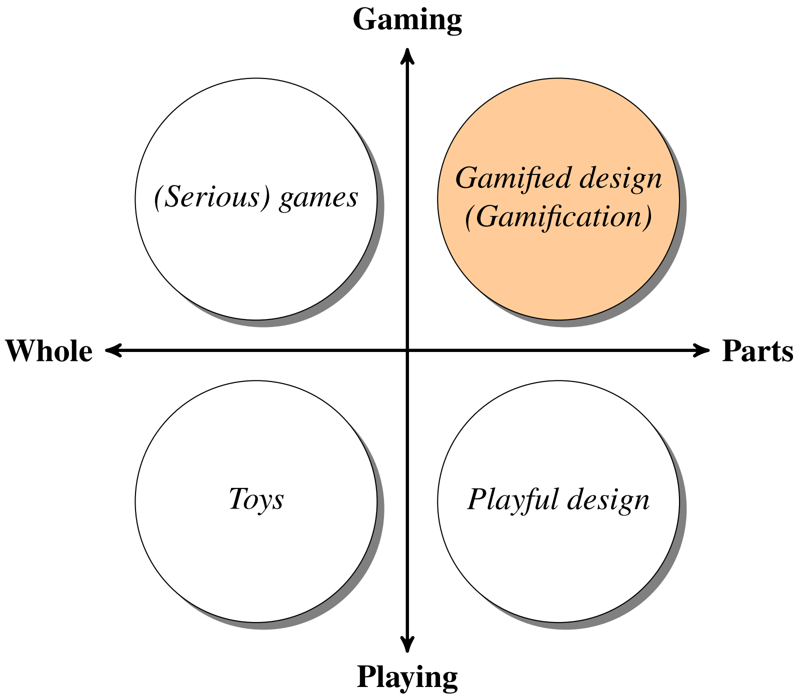

Figure 1. Place of gamification in relation to similar concepts (Deterding et al. 2011, p. 5)

gamification feature mentioned in Table 1 by default: fantasy in the form of visualisation of the machine and the environment. However, even though one element is enough in some cases to call a system "gamified", it is still preferred to have several features from different levels to distinguish the gamified object from a non-gamified one. (Deterding et al. 2011, p. 4)

Table 1. Levels of game design elements (Deterding et al. (2011, p. 4))

Level	**Description**	**Example**
Game interface design patterns	Common, successful interaction design components and design solutions for a known problem in a context, including prototypical implementations	Badge, leaderboard, level
Game design patterns and mechanics	Commonly reoccurring parts of the design of a game that concern gameplay	Time constraint, limited resources, turns
Game design principles and heuristics	Evaluative guidelines to approach a design problem or analyze a given design solution	Enduring play, clear goals, variety of game styles
Game models	Conceptual models of the components of games or game experience	Mechanics, dynamics and aesthetics; challenge, fantasy, curiosity; game design atoms; core elements of game experience
Game design methods	Game design-specific practices and processes	Playtesting, playcentric design, value conscious game design

Certain steps have already been made to connect real-time physics-based simulation and gamification (Jaiswal et al. 2021, pp. 7–9; Islam 2017, pp. 23–33); however, no consistent approach has been designed yet that help the designer achieve the needed quality of the data received from the gamified simulation. For example, in one study it was pointed out that even though the users could choose from three excavator bucket sizes (small, medium, and large), they never chose the small bucket, as it was deemed unsuitable for the task (Islam 2017, p. 44). This meant that the data for this option was completely missing, so it was impossible to evaluate its true feasibility.

1.1 Research questions

As the previous section outlined, there seems to be a lack of understanding how to connect the fields of mechanical simulations and gamification, despite the obvious benefits of connecting them. Therefore, to establish this connection in the research, the following research questions can be posed:

- How to implement gamification to a mechanical simulation in a standardised way?
- How to measure the effectiveness of a gamified system?
- What are particular ways of ensuring user satisfaction with the gamified simulator?
- How to implement a parametrisation system that can be used for R&D purposes without removing the fun element of the gamified system?
- How to improve the data gathering for R&D processes?
- How to ensure the quality of the user generated data and its usability for R&D processes?

With these questions in mind, the research process can commence, taking into account the constraints outlined in the following section.

1.2 Research objectives and constraints

This research focuses on implementation of gamification features in real-time physics-based simulation. The research uses the existing platform of LUT University that includes Mevea real-time simulation software, and simulation models developed in earlier projects. The current state of the simulator project is shown in Figure 2.

Figure 2. Simulator in the Laboratory of Intelligent Machines

The main objective of this study is to increase the amount user data collected for R&D purposes. This can be done in a number of ways, but this research will focus on gamification as the engagement method and multibody system dynamics as a modelling approach. The hydraulic actuators will be modelled using lumped fluid theory and the controls are done using physical joysticks and pedals. The systematic approach for gamification will be used to ensure the ability to implement gamification to future simulations.

Another objective of the research is to find out what specific gamification techniques work well in the simulation of heavy machinery and are most appealing to the target audience. These findings can be used to create future gamification projects and increase the engagement in the existing and future R&D simulation projects.

The last but not the least objective of the research is utilisation of gamification in enabling bigger variations of parameters selected by the users. It was pointed out in the previous research that users tend to stick with the similar parameter choices all the time, resulting in not enough statistically significant data about the given variation. Combining the gamification techniques that increase engagement and simple user interface for parameterisation may result in larger diversity of selected parameters and more statistically significant results.

2 Gamification and multibody system dynamics

This section is divided into the subsections touching the two main techniques in use in this research: gamification and multibody system dynamics. The gamification section looks into the definition of gamification, where is it used, what does it consist of, the benefits and disadvantages of gamification, as well as the systematic way of implementing the gamification into an existing system. The rest of the chapter gives a brief overview of the multibody system dynamics and hydraulic modelling approach used in the model under review.

2.1 Gamification overview

The gamification is rapidly developing field: Gartner, the leading technology consulting company, claimed that by 2014 about 80% of the big international companies will have gamification implemented at least in one area of their business. Consequently, this is a hot topic for academic research as well. The reviews of the papers on gamification outline the most lucrative fields for gamification. For example, 2014 research by Seaborn and Fels tells that the most researched application fields of gamification are:

- Education with 26% of papers
- Health and wellness (13%)
- Online communities and social networks (13%)
- Crowdsourcing (13%)
- Sustainability (10%) (Seaborn and Fels 2015, p. 27)

Another research conducted in 2019 by Koivisto and Hamari included larger scope of articles and was conducted later, which allows us to see the trend in the topic development. According to their research, from the 276 papers selected about the gamification, the overwhelming majority of them was still in the field of education with 46%. The full summary is presented in the Figure 3 below. The next most popular field was health and wellness again with

14%, crowdsourcing was slightly less popular with 9% and social behaviour was mentioned only in 5% of the papers. Notably, new fields have emerged, such as gamification software development, business and management, software engineering and innovation with percentages below 3-4%. The graph's "others" part summarises the fields that are not relevant for the current research, such as governance, safety planning, architecture and more. However, the trend between these two comparative studies is clear: over the period of four years the number of eligible papers grew, as well as the number of the fields in which the research is conducted. (Koivisto and Hamari 2019, p. 196)

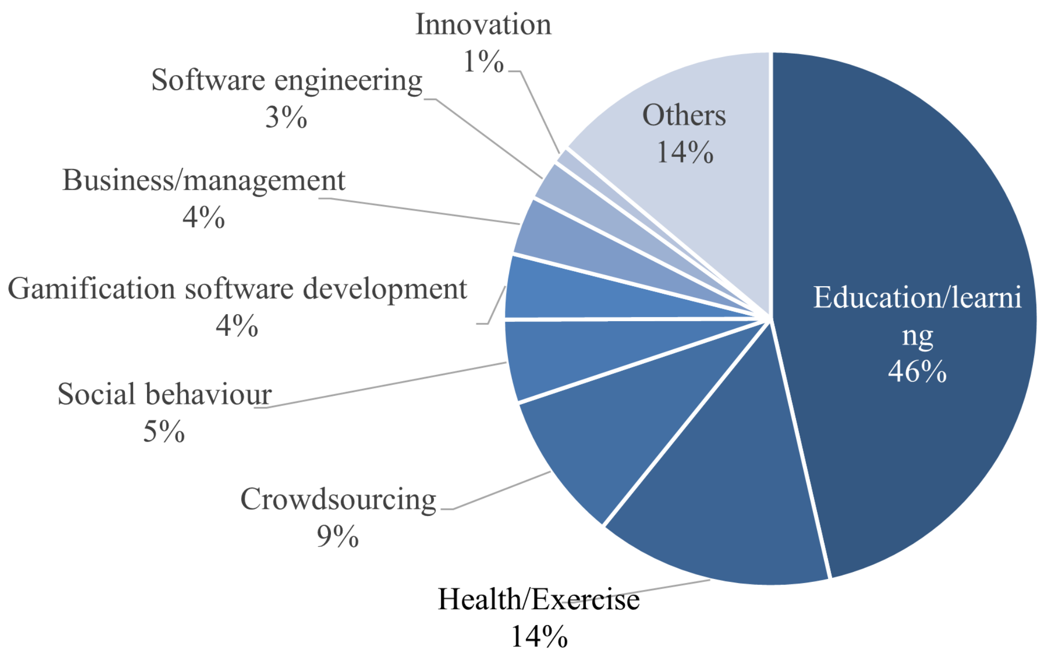

Figure 3. Most researched gamification areas (based on Koivisto and Hamari 2019, p. 196)

Gamification, as outlined in the section 1, is the usage of game elements in non-game applications (Deterding et al. 2011, p. 2). It is quite easy to see why the gamification is used in education and health so widely: these fields require long-term dedication, repetition and are not always seen as fun and engaging by default. Moreover, especially in the case of education, some game elements are already implemented: the students are graded, so an easy way to gamify this would be to turn the grades into experience points. At the same time, the education is also very close to the researchers, as they do not need to implement an overhaul to the existing complex systems. (Seaborn and Fels 2015, p. 28)

Gamification is a complex topic; therefore, it needs to be broken down to smaller pieces.

Werbach and Hunter propose the breakdown presented in the Figure 4 below. Game elements represent smaller components of the game that are used as building blocks, while game-design techniques describe the process of creating the game experience. The non-game context, in turn, stands for the actual end goal of the gamification, be it increased user engagement or improved financial situation. (Werbach and Hunter 2012, pp. 26–30). The following sections explain these concepts in more detail.

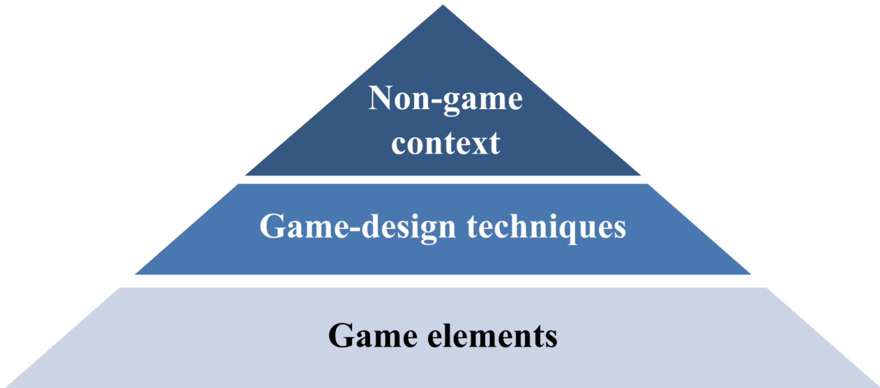

Figure 4. Gamification elements (adapted from (Werbach and Hunter 2012, p. 26))

2.1.1 Game elements

The most commonly used game elements applied in gamification are points, badges and leaderboards (PBLs) (Werbach and Hunter 2012, p. 28; Koivisto and Hamari 2019, p. 199; Seaborn and Fels 2015, p. 27). The research by Seaborn et al. shows that PBLs take the first three places in the studied papers as the gamification element of choice with points comprising 58% of gamification elements, badges – 48% and leaderboards – 35% (Seaborn and Fels 2015, p. 27). The more extended research by Koivisto et al. showed that points were used in 50.5% of the cases, badges in 31% and leaderboards in 30%. Interestingly, Koivisto's research puts challenges and clear goals to the second place among the most used elements with 33% of the cases using it, which shows the shift towards more meaningful gamification in later research. (Koivisto and Hamari 2019, p. 199)

PBLs are game elements, but they are not the only ones in existence. In more broad terms, the game elements are divided into three levels of abstraction from the highest to the lowest: dynamics, mechanics and components. The visual representation of these levels is shown in the Figure 5, with the main idea behind the elements on which level shown. The further paragraphs get into more detailed description of the elements.

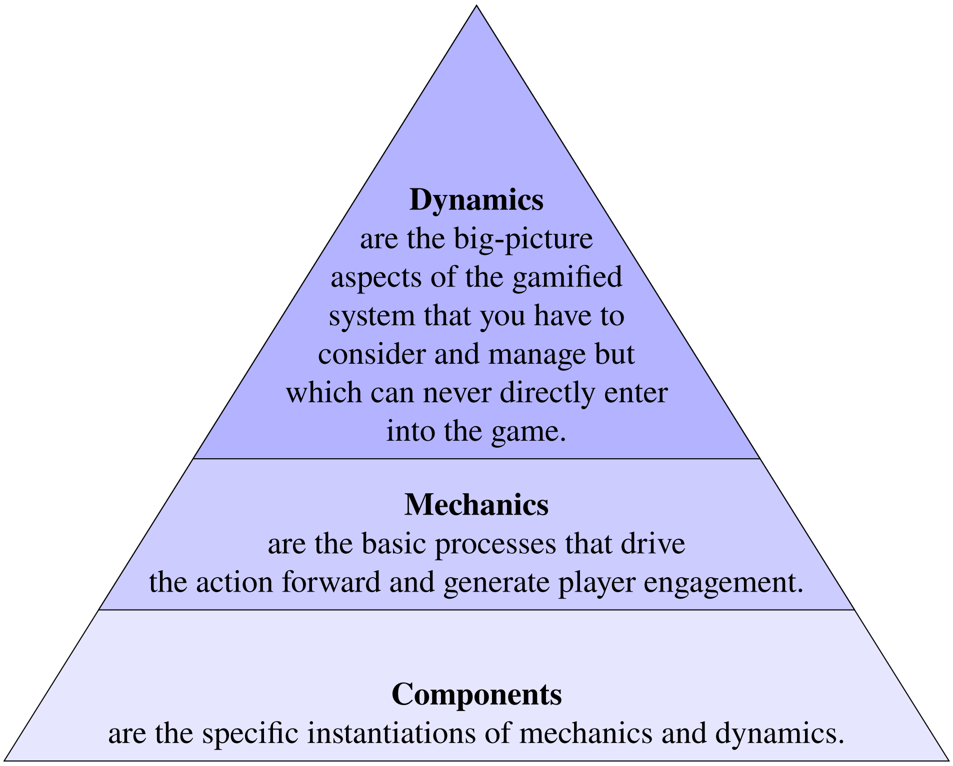

Figure 5. The Game Element Hierarchy (Werbach and Hunter 2012, p. 82)

Dynamics are the game elements of the highest abstraction. These are never visible to the end user and cannot be the direct inputs of the gamified system, however their absence can result in faulty gamification system. The lower level game elements are created in order to support the dynamics and to enforce them. The dynamics include, but are not limited to constraints, emotions, narrative, progression and relationships.

Mechanics describe the more concrete approach to the gamification system, with more tangible elements than on the previous level. Each game mechanic is designed to trigger the bigger game dynamic, while keeping the user involved in the task and moving the state of the gamified system forwards. The most important and widely used mechanics are challenges, chances, competition, cooperation, feedback, resource acquisition, rewards, transactions, turns and win states.

The mechanics are less strict in terms of implementation and some of them can be omitted, however it is recommended to implement them, as they are connecting to the higher level of abstraction and therefore tap into user's motivation. For example, receiving feedback is something that shows the user the sense of progression within the system, and therefore motivates the user to stay.

Components are the lowest level of abstraction among game elements, and they are tied to the mechanics. Components are the most tangible game elements that most of the users are bound to see, however the components alone without the mechanics and dynamics under them do not make successful gamification application. There is a plethora of components, but the most common ones are: achievements, avatars, badges, collections, leaderboards, points, progress bars, social graphs, teams and virtual helpers.

PBLs are, therefore, just a small part in the lowest abstraction level of gamification system, meaning that they do not represent the most important part of the gamification system. (Werbach and Hunter 2012, pp. 77–81). The focus on PBLs in the research and especially implementation in the field of marketing has been denounced as "pointsification" or "pointification". According to the game design researchers, this approach takes the least important part of the game (as shown, the points are the lowest level of abstraction in gamified system) and promotes this as the main goal of the application. (Seaborn and Fels 2015, p. 18) The good practice in gamification system design is to take the correct way down the game elements pyramid shown in the Figure 5 in the begging of the section.

2.1.2 Game-design techniques

Games come in variety of shapes and species and are clearly understood as games, yet there is no clear definition of them. Seaborn et al. present different definitions in their research, for example as non-serious, voluntary, and engaging interactions limited by the rules and structured social behaviour; or requiring unequal end result; or requiring the representation of reality and so on. However, all the definitions refer to the rules, structure, voluntariness, uncertain outcomes, conflict, representation and resolution in one way or another. (Seaborn and Fels 2015, p. 16)

The definition of the game then gives the background to the techniques that can be used to create the game experience which can be used in designing the gamification system. Goethe defines the difference between bad and good game designer, and their design consequently, as the difference in the approach. The "bad" game designer thinks only about the plain game elements, especially components and maybe mechanics at best, while the "good" game designer thinks about the intrinsic motivation of the player first, what feelings the designer wants to generate (the dynamics), and only once the dynamics are clear, the designer moves further to implement mechanics and components that will support the dynamics. (Goethe 2019, pp. 29–30)

Werbach et al. also suggests the importance of making a distinction between the game designer and player to understand the game-design techniques. While for most gamers the main motivation is to win (Bartle suggest four main gamer types: Killers, Achievers, Socialisers, Explorers (Bartle 1996)), so the gamer cares about that goal the most, the game designer's motivation must be to provide the tasks that allow the gamer to achieve the winning feeling. The winning feeling will keep the motivation to continue persistent. In case of the gamification, the tasks are then designed to cover the desired project features and goals. (Werbach and Hunter 2012, pp. 41–43)

2.1.3 Non-game context

Non-game context relates to the actual product the gamification is applied to. The gamification features, despite their importance, are added to the original product, or designed together with the original product. The game elements only promote the original purpose of the project, but should not overtake the importance of the project itself. (Werbach and Hunter 2012, pp. 29–30)

2.2 Gamification objectives

As the games are known for keeping people engaged based on the intrinsic motivation, gamification is usually used in the same sense. However, the final outcomes usually vary depending on the area where the gamification solution is applied.

The most researched area where the gamification is applied is education (Seaborn and Fels 2015, p. 27), (Koivisto and Hamari 2019, p. 196). In education, some of the goals are supporting learning activity, improving existing tutorial system, encouraging participation and increasing student motivation and engagement.

These goals clearly emphasise the idea that gamification is viewed as a tool for increasing motivation and engagement. Other papers reviewed in Seaborn et al.'s study from the fields other than education also overwhelmingly cite motivation and encouragement to complete certain activity as the objective of gamification: e.g. encouraging daily glucose measurement in the health app or encouraging the usage of the recycling bin in the park.(Seaborn and Fels 2015, pp. 23–24)

The usage of gamification in other fields more similar to mechanical simulations and product development is also studied, but on a less theoretical level. One good example is software engineering, where the product development processes are rather similar to the mechanical design and simulations. According to Daniel et al., the most common gamification objectives in software engineering are elicitation of features directly with the stakeholders; improving the quality of the developed code (commenting, following the guidelines, documenting, code review); improvement of testing quality (creating more tests, finding more bugs); increased user feedback collection and improvement in employee motivation. (Daniel et al. 2021, pp. 9–11)

The papers used in Daniel et al.'s review were specifically chosen to be outside of the educational scope, therefore the difference in objectives is quite clear. At the same time, this review is also much newer, meaning that progress has been made in the field of gamification, including more wide range of usage. (Daniel et al. 2021, pp. 9–11)

The gamification objectives outlined in the reviewed research ((Seaborn and Fels 2015), (Daniel et al. 2021), (Koivisto and Hamari 2019)) are rather specific to the education and software engineering fields. With slight modifications, these objectives can be used in setting objectives of the current research, success metrics, as well as benefits and challenges of gamification.

2.2.1 Benefits of gamification

The same way as objectives vary depending on the field where gamification is being implemented, the benefits and challenges vary as well. The most remarkable and applicable results were demonstrated in the fields of management, software engineering, and specifically testing.

Gamification benefits from the management perspective are bottom-up collaboration; culture of innovation; skill identification; easier performance appraisals; receive employee insight and improved relationship within teams. Therefore, management perspective focuses more on employee and productivity development, using the motivation boosting tools of gamification. (Prakash 2015, pp. 103–108)

Software engineering point of view also looks at the more generic organisation culture issues, but also emphasises the specific issues, for example facilitation of requirements prioritization; engagement and motivation to perform activities; improvement of the work performed quality. The first benefit is even more pronounced when the feedback from the stakeholders is required, as the stakeholders might not be that familiar with the topic or sure about the final goal. (Daniel et al. 2021, p. 9)

Software engineering also includes a lot of mundane and repetitive tasks, one of them being software testing. However, Yordanova noticed that gamification can greatly help in the testing process, as the group that had gamification features in their work process found 73% more bugs than the test group. (Yordanova 2019, p. 301)

2.2.2 Gamification challenges

Despite all the benefits, the gamification does not come without its challenges. Software engineering research outlined challenges such as fair assignment of the points while keeping the process enjoyable to the players; finding the elements that would be motivating everyone equally; implementation of the tool itself or the gamified environment; changing the focus of the activity; finding the elements that motivate long term and decreasing creativity.

Most of the challenges outlined here relate to the imperfect human nature and the differences in the gamer/personality types that will interact with the game. While achievers will be motivated long-term by getting more goals to achieve and topping the , explorers will find it difficult to be motivated if the tasks start being repetitive. (Daniel et al. 2021, p. 12)

Gamification process is a complex one and approaches might differ between the companies and researchers. For example, Werbach and Hunter (Werbach and Hunter 2012) propose a six-step process presented in the Figure 6 below, where the first step is defining the objective, followed by delineating desired behaviour, describing the players, developing the activity cycles, making the users engaged and finally deploying the appropriate tools.

As this process suggests, the actual implementation of the gamification tools can only be started when all the preparatory stages are completed. The preparatory stages also help understanding if the gamification is needed for the activity in question in the first place. (Werbach and Hunter 2012, p. 86) The stages shown in the Figure 6 are described in more detail below.

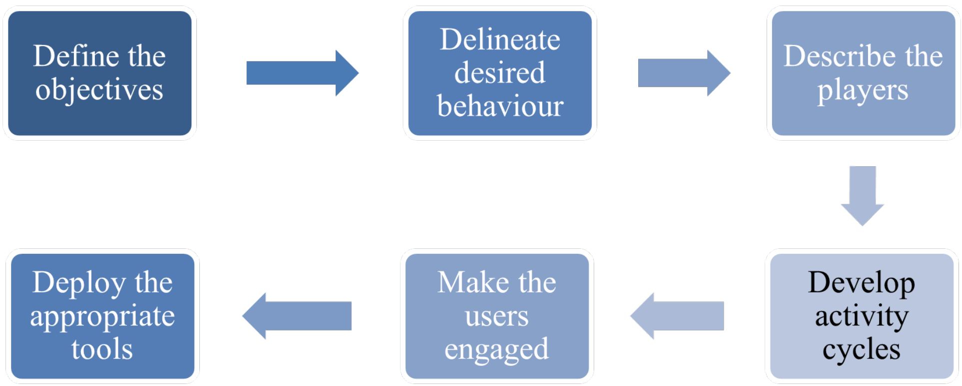

Figure 6. Gamification process (adapted from Werbach and Hunter 2012, p. 86)

2.2.3 Gamification process

The gamification process starts with defining the objectives. Some of the possible objectives were described in the Section 2.2. These goals cannot be processes and must be something achievable and measurable. The goal cannot be defined as "make the user collect the greatest number of points", as this is the process that happens while using the gamification system, and this is not the designer's end goal. The designer should prioritise the goals in case there is too many of them or they are conflicting and come back to them during the whole gamification system design. (Werbach and Hunter 2012, pp. 87–88)

The delineation of the desired behaviour comes next. This is the process of identifying the behaviour the user is supposed to produced when coming into contact with the gamified system, as well as coming up with the measures for assessing the quality of that contact. The desired behaviour are the concrete actions, for example: moving ten tonnes of soil; completing the safety checks; exercise for at least 30 minutes or share the business page on Twitter. The relationship between these behaviours and the goals from the previous step can be indirect, but the behaviours must promote the ultimate goals defined.

After that, the system to assess those behaviours can be defined. The most important and attractive feature of the games is the ability to get feedback on the performance constantly, therefore this should be used quite extensively. Points are the most used metrics for assessing the performance, even if they are not visible to the user directly, as they allow to have easily quantifiable result. However, the points and badges alone should be used with care to avoid demotivating the users. Possible game elements that can be used at this stage were discussed in the Sections 2.1.1 and 2.1.2. “Win states” can be another way of providing feedback, as the feeling of “winning” acts as a strong motivator, however, “winning” comes with inherent problems, e.g. some users are losing and get demotivated or “winning” is the end of the game which also demotivates the user from continuing. Therefore, “win states” should be dynamic and adjusting to the user’s performance to keep being attractive for as long as possible. (Werbach and Hunter 2012, pp. 89–91)

When the objectives are defined and the behaviours are described, it is time to also describe the users. The process of describing the users, or creation of so-called personas, is well-known and used in the fields of marketing and user experience design, and it is not much different for the gamification process. The approach of creating the personas rather than abstract target group has proved effective, as it allows closer connection and understanding the users (Pruitt and Grudin 2003, pp. 2–4).

The description of personas should include general description of the persona; their relationship to the implementer of the gamification system; extrinsic and intrinsic motivation and demotivation of the persona as well as other possible features. It is beneficial to describe as many different personas as possible, especially coming from the different player types discussed earlier (achievers, explorers, socialisers, and killers). A good gamification system will try to serve as many of those player types as possible, tailoring the experiences within the system. (Werbach and Hunter 2012, pp. 91–94)

Devising the activity cycles builds further on the previous steps. The activity cycles define how the progress within the gamified system develops. There are two main activity cycle types: engagement loops and progression stairs. Engagement loop starts when the user does an action based on some motivator, after that gets the feedback, which motivates the user even further and after that the user produces another action, closing the loop. Progression stairs, on the other hand, is a linear process that describes the increasing difficulty of the task. However, as shown in the Figure 7, the process is not exactly linear, but rather exponential with breaks for resting and “boss fights” to elevate the level.

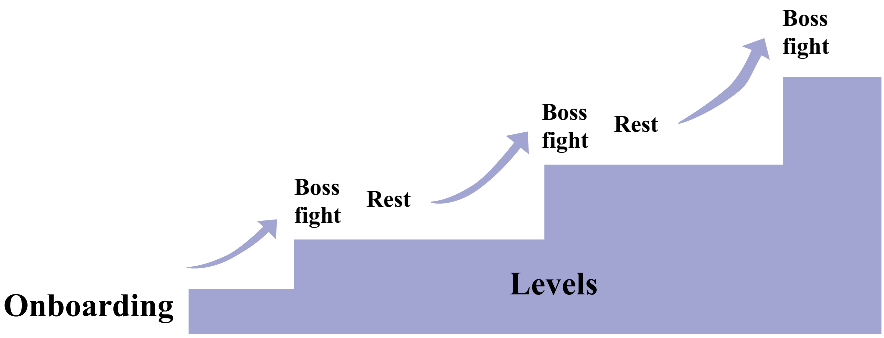

Figure 7. Progression stairs (Werbach and Hunter 2012, p. 97)

The levelling keeps the motivation of the user going: the process of exponential levelling with “boss fights” has proven to be successful in the gaming world. Naturally, the “boss fights” are not applicable for the gamification systems per se, but they can be implemented as tasks with increased difficulty. Despite the linear nature of the progression stairs, the element of randomness should be included in levelling, as the human brain usually prefers the random big rewards more than constant slow progression that might result in the bigger win in the end. (Werbach and Hunter 2012, pp. 94–98)

Measuring the user engagement and fun specifically is a difficult process and cannot be easily quantified. However, the fun is the easiest way of keeping the user motivated, therefore all the gamification systems should be assessed on the perception of “fun”. (Werbach and Hunter 2012, pp. 98–99)

Finally, after all the preparatory stages are completed, the gamification system can be implemented. The actual implementation of the gamification system depends on the non-game context it is built upon, as one of the most important part of the gamified system design is putting it to use to achieve the correct goals. (Werbach and Hunter 2012, pp. 99–102)

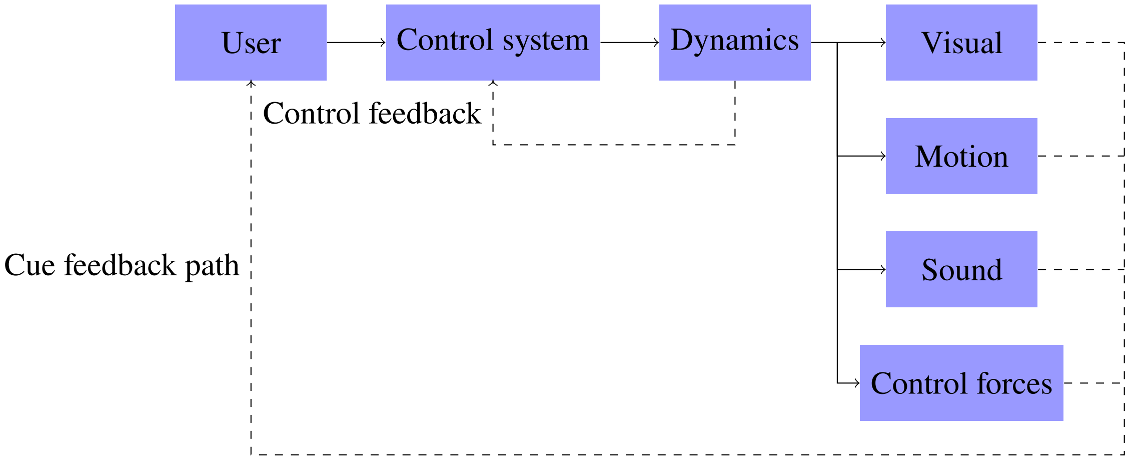

Figure 8. Simulation functional diagram (adapted from Haug and Deyo (1991, p. 5))

2.3 Modelling of multibody dynamics and real-time simulation

Real-time simulation is one the simulation techniques used in engineering. Figure 8 shows that in the case of real-time simulation, the user provides the input to the control system, which in turn changes the system's dynamics, that returns the control feedback to the control system, while changing the different cues that are returned to the user (sound, visual, control forces and motion). The user reacts to these cues and changes the behaviour accordingly, closing the loop. (Haug and Deyo 1991, p. 5)

The simulation method can be called real-time, if the computational process and mathematical model are efficient and precise enough to produce the accurate results in real time period. The modelling process for a mobile vehicle such as an excavator includes multibody, constraints, actuators, hydraulics and contact modelling. (Baharudin 2016, p. 23)

2.3.1 Multibody system dynamics

Dynamic systems in mechanical engineering are usually analysed using the Newton's laws and the acquired equations of motion. In the simplest dynamics modelling, a body is presented as an idealised concept using its density. This way, nonetheless, is not appropriate for modelling of the complicated systems of linked bodies, hence a new method called multibody system dynamics was created.

The name "multibody system" suggests that the term is used to describe a system that is comprised of multiple rigid or deformable components. The motion of these subsystems (components, bodies, substructures), is kinematically constrained by the virtue of various joint types, allowing each subsystem to experience large displacements and rotations. (Shabana 1998, p. 1)

The bodies in multibody system can be either rigid or flexible. Rigid bodies are widely used in real-time simulation for computational efficiency, while flexible bodies can be used to improve analysis accuracy for slender structures. The bodies are connected into a kinematic chain by four main joint types: fixed, translational, rotational, and spherical. A scheme representing the multibody model used for this thesis is presented in the Figure 9.

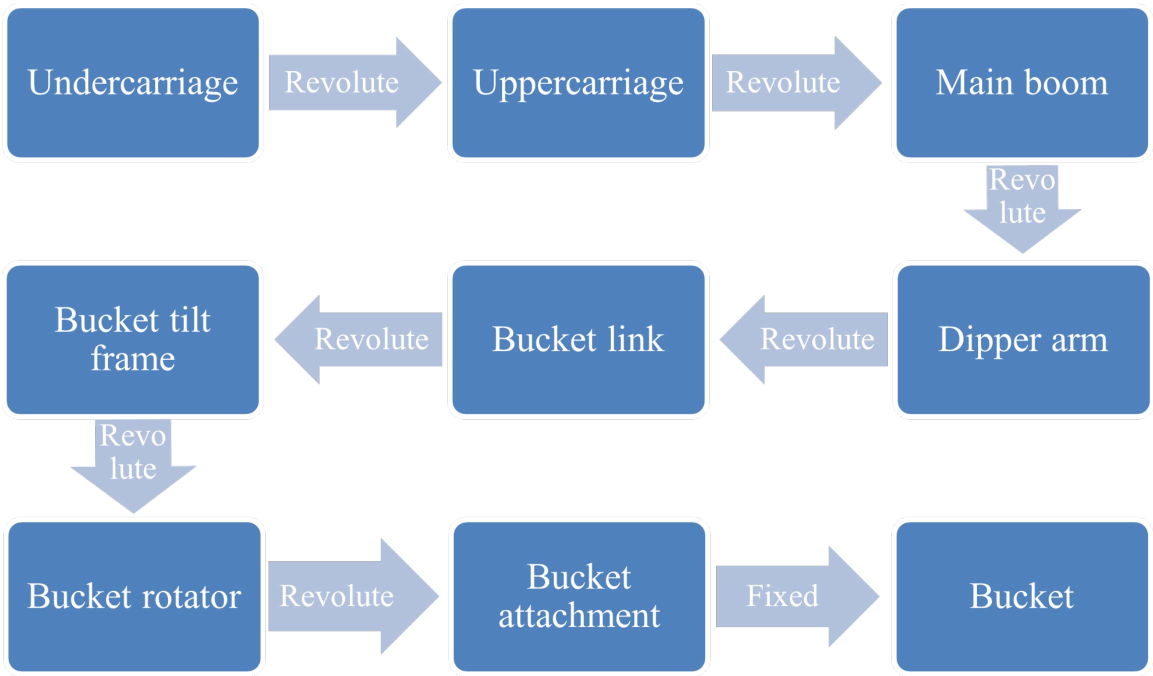

Figure 9. System diagram of excavator

The boxes in the diagram indicate the bodies and the arrows show the joints. The model consists of 9 bodies and 8 joints. This simplified diagram does not take into account the hydraulic actuators (hydraulic cylinders) and their joints.

2.4 Modelling of hydraulics

Hydraulic systems are widely used in mechanical engineering due to their ability to generate large forces using relatively small equipment and often acceptable control frequencies. Still, hydraulics modelling is a rather computationally burdening task, since the performance of all components have to be covered, and specifically fluid compressibility in them. (Pfeiffer 2008, p. 187)

In order to simplify the complex hydraulic components, its individual components are not modelled, but instead are described as single "black boxes": hydraulic volumes. It is presumed that the pressure inside the hydraulic volumes is constant. This method is called lumped fluid theory: it assumes that the modelled system consists of volumes connected by the throttles enabling the flow between them. The volumes, in turn, deal with the fluid compressibility and fluid mass effects to obtain the needed dynamic terms. Part of the hydraulic circuit used in the model for this thesis is presented in the Figure 10 below.

Each of the components in the Figure 10 can be represented with a mathematical model. Volume represents the hose or a pipe connecting two components, and the pressure inside it is assumed to be evenly distributed. When modelling volumes, the size of the hose and its bulk modulus are taken into account. The hydraulic cylinders in this model are double-acting, modelled using the dimensions provided. The model also takes into account the bulk modulus of steel and the losses due to the friction between the cylinder components. The directional flow valve is modelled using semi-empirical approach, meaning that the mathematical model used includes a constant obtained from empirical tests conducted by the equipment manufacturer. This constant is referred to as semi-empirical flow rate coefficient and can be obtained from characteristic curves, provided by the equipment manufacturers. For example, Figure 11 shows the characteristic curve for a 2/2-way directional flow valve manufactured by Poclain Hydraulics Ltd.

These curves are used instead of purely mathematical models, because the relationship shown greatly varies between the equipment manufacturers, hydraulic liquids used, and environment.

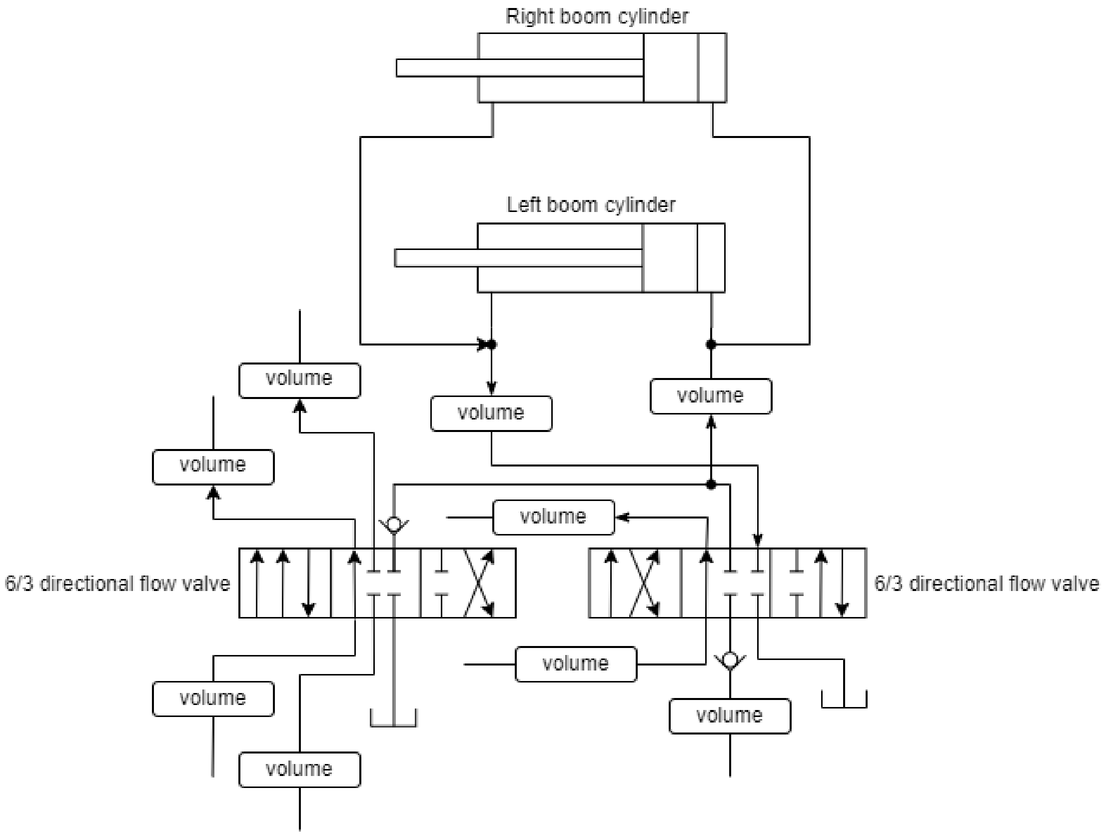

Figure 10. Hydraulic circuit example

The specific valve shown in Figure 11 can operate with flow rates from 0 to 35 l/min and handle pressure difference up to 60 bar, but the behaviour of the valve with the same limits from, for example, Bosch-Rexroth can be different due to the differences in the physical configuration of the valve.

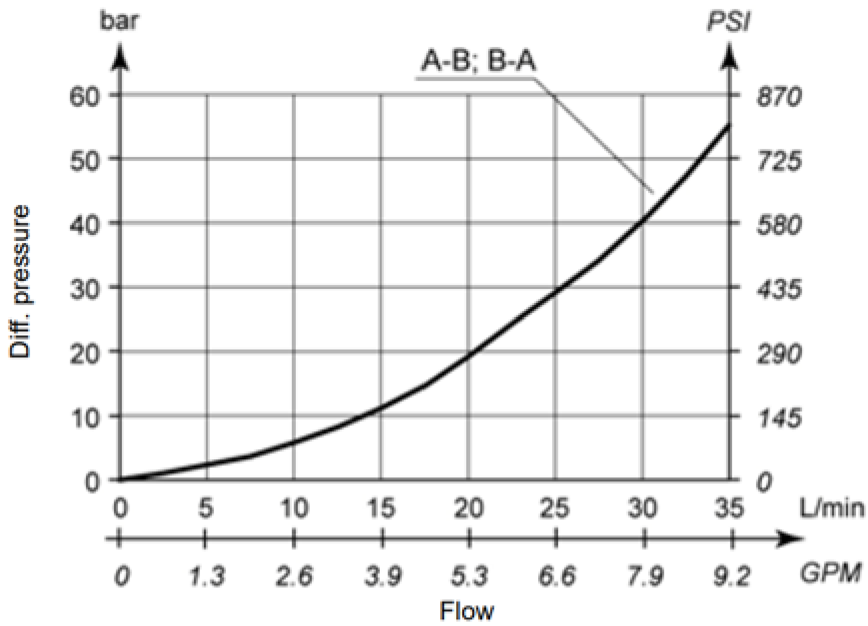

Figure 11. KVC-2/2K: KVC 2/2 way directional valve characteristic curve (Hydraulics 2014)

3 Implementation

This section describes the process of building the gamified and parametrised systems on top of the existing model. Section 3.1 describes the gamification design as a combination of steps described in the Figure 6 and section 2.2. Section 3.2 shows the existing model and how it was parametrised, while section 3.3 combines the preceding sections to show the final gamified product.

3.1 Gamification system design

Gamification system design is usually viewed more as an art than a straight-forward process, however as described in literature review, it can be systemised to the six steps: defining objectives, delineating the behaviour, describing the players, developing the activity cycles, engaging the users, and deploying the appropriate tools. Following this process, it should be possible to design the gamified system that would attract the wide range of users.

3.1.1 Excavator model gamification objectives

The simulator used for this study has different use cases in the research, training, and marketing, therefore the objective defined vary based on the desired use case. Following these use cases three main objectives can be defined: increase the interest of the users in the simulator system; improve the communication between the users and the designers; improve the driving skills of the users, and motivate the users come back to the simulator.

The first objective relates to the research and marketing use cases, as more users engaging with the simulator produces more data for the research group to investigate and evaluate the designed system. At the same time, an attractive simulation system is a useful marketing tool, attracting and keeping attention of potential customers of the system simulated.

Improved communication between the users and the designers is an important tool for the design team, as the end user (machine operator) can provide feedback on the machine before it is physically built, allowing the designers to take this feedback into account on the earliest design stages and therefore decrease the lead times.

Improving the driving skills of the users falls into the training category. This closely ties with the other goals, as the driving skills are likely to improve after the user has driven the simulator a few times, preferably voluntary, and already considers a system interesting enough to use.

Finally, motivating the user to come back to the simulator is a part of both training and research category. When the users come back, they are more likely to improve their skills, while providing even more data for the research.

3.1.2 Behaviour delineation

This step requires coming up with the desired end behaviour of the users. The interviews with the lab personnel and older research papers about the simulator showed that the simulator users use only limited set of parameters, get bored quickly and do not return. Therefore, the desired behaviour can be based on these observations plus objectives that were set for the users previously. The following behaviour can be considered desirable:

- Move 10 tonnes of soil
- Try three different options/difficulties
- Invite others to try the simulator

3.1.3 Describe the players

The user description is the technique widely used in marketing for market analysis and tailoring the products. In the case of gamification, the most distinct feature about the user is the player type. Table 2 below represents four players of different player types with other features specific to the university environment.

The player types shown in the Table 2 follow the player types by Bartle (Bartle 1996), and the possible motivators and demotivators follow the features outlined in his research. Table 2 shows that motivators and demotivators of certain player types are in direct conflict with each other, for example John “the socialiser” values social features of the game, while Conal “the killer” might consider socialising an unnecessary distraction. Therefore, when designing the gamification features, some player types will have to be omitted by design. In the case of this study, the most likely group to be omitted is killers, as the simulator setup does not provide clear multiplayer possibilities which the killers might benefit from.

3.1.4 Develop activity cycles

The current simulator system has the following activity cycle:

1. Choose the machine parameters
2. Start the simulation
3. Achieve the goal
4. Receive the result and assessment

This activity cycle makes use of the engagement loop, as the action from the user is followed by the feedback from the system, such as changes in the collision counters, changes in the transferred material counter. Even the end screen which appears when the simulation is over, creates the motivation for the user to improve on the result further, if this fits the player type of the user. However, this approach does not show clear progression for the user, which affects the motivation of explorer and achiever player types, and does not have any social features, which affect the motivation of the socialisers.

Table 2. Player types

Name	John Doe	Darcie Fowler	Saniya Betts	Conal Thorne
Age	20	23	30	45
Player type	Socialiser	Achiever	Explorer	Killer
Academic background	Second year bachelor's student in business	Second year master's student in technology	First year PhD student in technology	Post-doctoral researcher in technology
Personal background	Advent Twitter user and Instagram-influencer, active in the student organisations and student life, spends a lot of time in university not only for the lectures	Achieves the top grades in most of the courses, completed an internship in heavy machinery maintenance company, spends little time in the university, mainly in the common study areas	Came to university after a successful career in the design office; currently getting used to the university environment and networking, so spending a lot of time in the university; travelling around Finland	A well-known professional in the field, balanced between the working life and academia; focused on achieving the highest status in the current position.
Motivators	Personal connection with the game; ability to interact with other players; ability to share experience with the people outside of game bubble	Clear progress targets; clean user interface; reasonably challenging progression from one level to another to keep out totally novice users	Open world; non-binding scoring system that does not punish spending extra time exploring the surroundings; "easter eggs"	Ability to demonstrate superiority in the trade; ability to cause damage to other players' progress
Demotivators	No connection to general knowledge and broader world; lack of socialising features	Excessive need for interaction with players that does not result into direct benefits; no defined targets; irregular scoring system and logic	Very linear progression that punishes individualism; lack of freely interactable objects; rigid scoring system	No rapid progression; inability to see the effect of the actions on the other players

That is why the new activity cycle includes the levelling possibilities and the social features. The parameter selection is swapped for the difficulty level choice, a tutorial for the novice users is included, while the more difficult levels include extra obstacles and different starting point. The progression metrics in the simulation are rethought; the end screen is updated, and includes a simple verbal feedback system.

3.1.5 Engage the users

This is the most ephemeral quality of the gamified system, as it depends mostly on the user perception. Different player types described in section 3.1.3 consider the fun and engagement differently, therefore the measures for them should be designed differently. The most straight-forward way of assessing the engagement are the user surveys and interviews. The following questions can be asked in those interviews:

1. How excited were you to try out the system?
2. What kept you going through the level?
3. How satisfied were you with your performance?
4. How motivated were you to try another level?
5. How likely would you talk about this experience with your friends?

These questions try to cover all the types of the players that might encounter the gamified system. Questions 2-4 are aimed at all the player types, but question 2 focuses on the motivator types which are player type specific. Question 1 can be applied to all players, but mostly to explorers, while question 5 is mostly useful for socialisers.

3.1.6 Deployment of tools

Based on the sections above, it is possible to identify the tools that might be the most effective in achieving the best engagement. Naturally, it is impossible to implement all available tools into a single gamification project, as besides making system overly complicated, they will conflict each with other.

The focus therefore lies on these aspects:

- Progression stairs
- Continuous feedback
- Spontaneous elements
- Instructions to achieve the best result

Progression stairs can be implemented with levelling, moving from the introduction to the system through increasingly harder challenges to mastery. This will satisfy the needs of achievers, but also explorers, because they would feel the sense of progression, and the socialisers, because they would be able to discuss the new knowledge they received.

Continuous feedback can be implemented in a number of ways, but the most straight-forward options in this case are on-screen meters for e.g., time and distance to the target. The feedback can be expanded to include the final verdict as well, that provides the summary of the whole run in a concise manner that can be shared with other users. This feature caters mostly achievers and explorers, however the socialisers are again involved by including a talking and comparison point.

Spontaneousness is implemented with the way the parametrisation system works. Some of the potential users might not be familiar with the concept of control valve characteristic curves, others might not know how strongly this parameter can impact the system's performance. That is why each run can be unique, bringing the element of randomness to the system. This caters to explorers mostly, and can harm achievers, as they would see the randomness as an obstacle to achieving the best results consistently.

Finally, the instructions to achieve the best result can be implemented by adding the instruction texts for each action, or only for the start of the level. The instructions bring the clarity that is preferred by achievers, but might be viewed as harmful by explorers, as they prefer creative thinking to following the instructions. The socialisers, due to their usually quite shallow interest in the deep mechanisms of the system, would be drawn in by the instructions too, as they provide ease of operation and talking points for the future.

Taking these four elements in mind, the gamification process can be commenced.

3.2 Existing excavator model and hydraulics parametrisation

Gamification is defined as the game elements built on top of the existing system with minimal changes to the given system. Following this idea, this research used an existing simulation model of an excavator, with gamification elements added on top with minimum changes to the model itself. Section 3.2.1 showcases the software utilised, section 3.2.2 gives a brief description of the model and section 3.2.3 talks about the hydraulic circuit parametrisation, the only part of the model that was changed in this research.

3.2.1 Software and hardware used

The software used for this project can be divided into three main categories: simulation, auxiliary and graphical. The simulation software is Mevea Software package, that consists of Mevea Solver, Mevea Modeller and Simulator Launcher. Auxiliary software is everything that was used to create the parametrisation interface, for example Python 3.4 compiler, Atom and Microsoft Visual Studio Code editors. Finally, graphical software was crucial for creating the best possible user experience. The exact names of the software packages and their versions are presented in Table 3.

Table 3. Used software packages

Category	SW package name	Version
Simulation	Mevea Solver	3.0.5
	Mevea Modeller	3.0.5
	Mevea Launcher	1.8.0
Auxiliary	Atom	1.58.0 x64
	Microsoft Visual Studio Code	1.6.23
	Python compiler	3.7.2 32-bit version
	Matplotlib for Python	3.4.0
Graphical	Adobe Illustrator	CC 2018, 22.0.0

Figure 12. Excavator control devices

Some of the parametrisation and gamification features were implemented using Mevea software directly, for example level selection. However, for control valve characteristic curve parametrisation a stand-alone program was created in Python and compiled to executable file, so it was possible to run the program without extra libraries.

The harware used included the Mevea motion platform, as well as physical joysticks and pedals, shown in Figure 12. Through the connection provided by National Instruments (NI) USB-6001 Multifunction I/O device and NI Mevea I/O client, the signals from these control devices were sent to the model.

3.2.2 Model description

The model used in this study was excavator based on Hitachi Zaxis 240G. multibody system dynamics approach was used for the dynamic modelling, while hydraulic system was modelled using lumped fluid theory and semi-empirical methods for certain components, e.g. directional valves. The control system was hardware-in-the-loop (HIL), meaning that the control signals

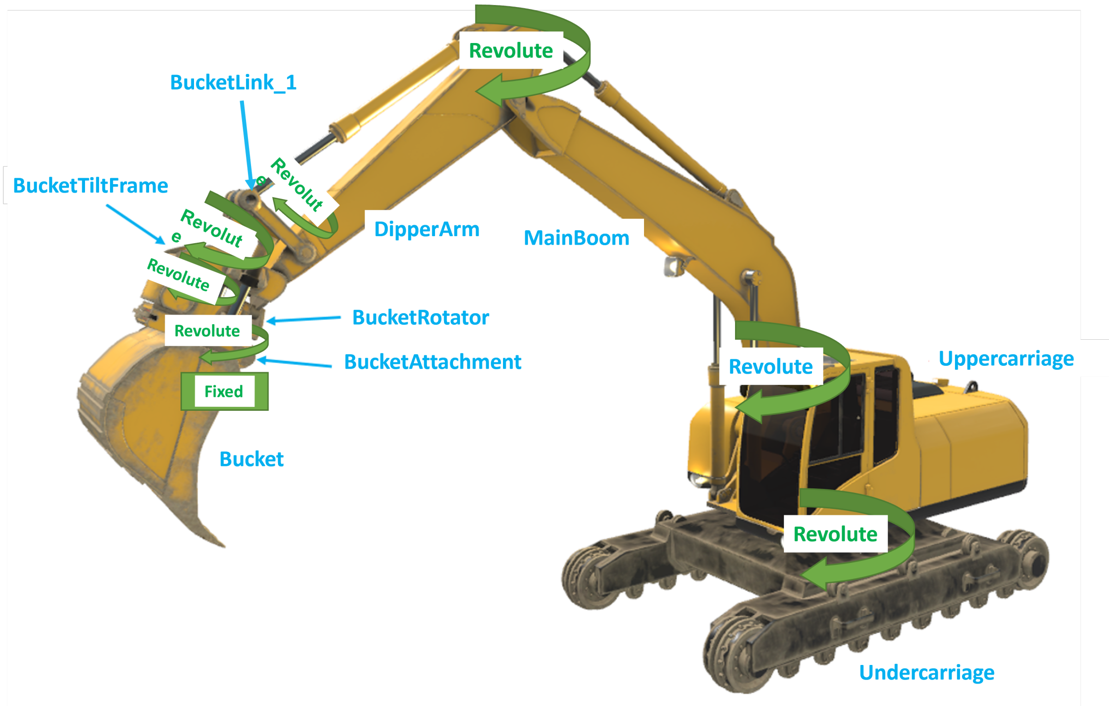

Figure 13. Excavator visualisation with bodies and joints

are obtained from the physical controls: joysticks, buttons and pedals in the simulator.

The models in multibody system dynamics approach are broken down into bodies, which are rigid in this case, and are connected with the constraints. The visualisation of the excavator with bodies and joints is shown in the Figure 13.

This model consists of 9 bodies and 8 joints, therefore it can be modelled in Mevea software as a dynamic system. The model also includes extensive hydraulic system presented in Appendix 1 that consists of 6 cylinders, 9 6/3 directional valves, 13 pressure relieve valves. 3 counterbalance valves, 4 hydraulic motors, 2 pumps and 2 pump controllers. These elements are connected together using 18 hoses, 18 pipes and 30 volumes.The model includes the track component, as this is a tracked excavator. The tracks are modelled as chain of particles in Mevea software with the graphics creating the actual track graphics. Altogether, these elements provide the needed mobility to the excavator.

The models created in Mevea software usually include interfaces for extracting data that can be used for R&D or other purposes. In this model, data sources and outputs are used for extracting the data that is saved to the database for further analysis, and Python scripts are used to generate the feedback in the end of the exercise.

3.2.3 Hydraulic circuit parametrisation

In this research, the parametrisation parameter chosen is the characteristic curve of the directional flow control valves. The characteristic curves depend on the valve and the most common shapes of them, according to valve manufacturer Emerson, are shown in the Figure 14.

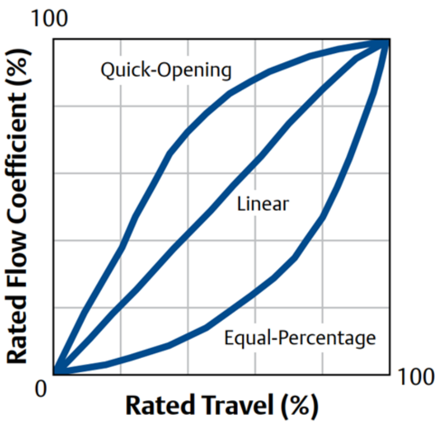

Figure 14. Valve characteristic curve Emerson 2019

As seen from the figure, three most common types of characteristic curves are similar either quadratic function, or linear function, or exponential. This knowledge was used to draft the possible characteristic curves for the valves in the excavator's hydraulic system.

The excavator uses nine 6/3 directional valves, therefore three options for all nine valves were created. An example of the characteristic curves used is shown in the Figure 15.

The horizontal axis in the figures describes the valve's control signal in mA and the vertical axis describes the flow through the valve in l/min. The blue line shows the name of the valve and the original characteristic curve, red line shows the linear approximation of the curve and the brown line shows the possible representation of the curve using natural logarithm. The parameters for the exponential function were chosen so that the function connects the same

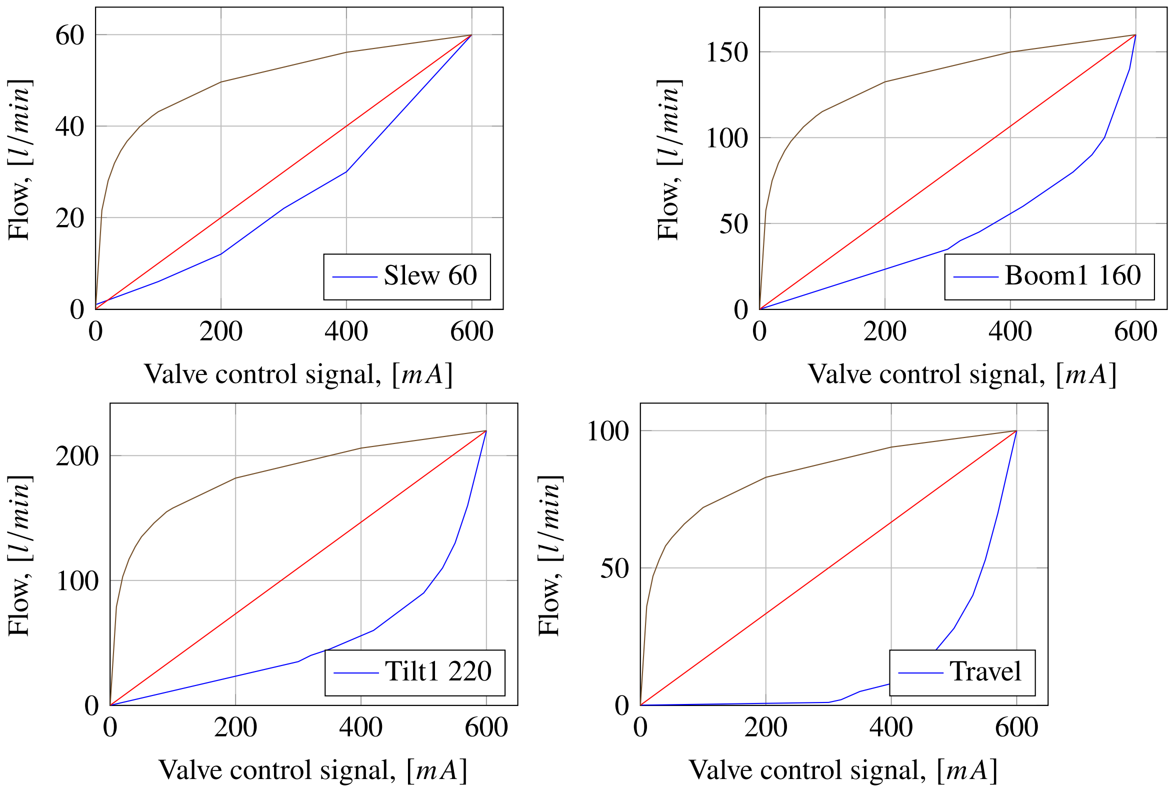

Figure 15. Characteristic curves used in the model

start and end points as the original characteristic curve.

To test the effect of these changes on the model, sample runs with set of each parameters were performed. The input signal fed into the system was kept the same to make the simulation runs comparable. The variable observed, shown in the Figure 16, was the piston speed of the lifting boom cylinder. Blue line shows the response with the original characteristic curve, red and brown show linear and exponential curves respectively.

The horizontal axis shows the simulation time in seconds and the vertical axis shows the piston speed in millimetres per second. With linear characteristic curve the cylinder speed seems to be more steady without visible spikes, while both original and exponential version show visible spikes. With original characteristic curve, that resembles a second order line, the spike comes later and reaches slightly larger value, while with exponential curve the spike comes earlier, but is slightly smaller. There are other visible spikes as well, with the second and the third one being the largest for exponential case, followed by original. All in all, these differences in the cylinder piston speed will affect the overall lifetime of the component and

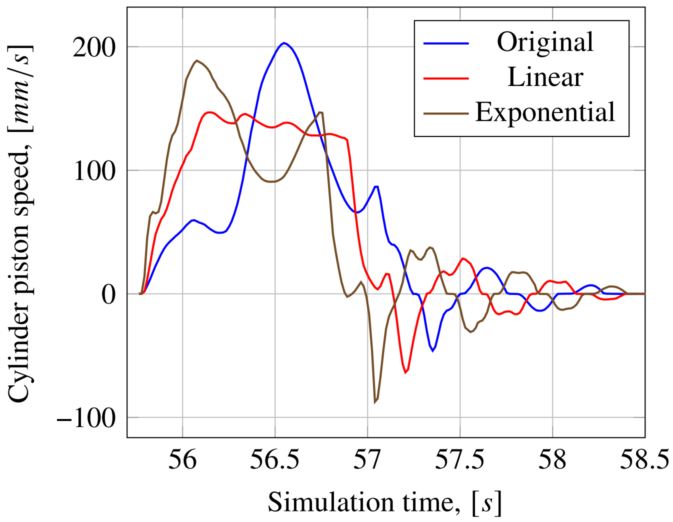

Figure 16. Boom lift cylinder piston speed with three different characteristic curves

the machine. With high variability of the operational speed and significant spikes in it the machine components will wear off faster. More steady operation conditions are desired to prolong the operational life of the machine, therefore, the study of the effect of the valve characteristic curves on the excavator's cylinder pistons speeds is justified.

Mevea software, which is used for modelling in this thesis, does not build the spline directly from the mathematical function, but instead connects the points with given coordinates in linear fashion. The original model had 6-12 points for each spline, which gives rather good approximation, as seen in Figure 15 (blue line is original values). Linear approximation requires only two points, which are simply the minimum and maximum values of the given curves.

Exponential model shown in Figure 15 was built using mathematical equation, however for the modelling only 12 points on each curve were chosen. The points were placed closer to each other in the beginning where exponential function rapidly increases and has the biggest curvature, but once the slope becomes less steep, the points are spaced further apart. It was not possible to keep the intervals between the points exactly the same for all the curves due to difference in maximum x-values, so instead the ratio of those intervals was kept the same. The values were rounded to the nearest integer, except 0.5.

Table 4. Example characteristic curve values

Boom1_PB_160, original		**Boom1_PB_160, linear**		**Boom1_PB_160, exponential**	
Valve control signal, mA	Flow rate, l/min	Valve control signal, mA	Flow rate, l/min	Valve control signal, mA	Flow rate, l/min
0	0	0	0	0	0
300	35	600	160	10	58
320	40	–	–	20	75
350	45	–	–	30	85
420	60	–	–	40	92
460	70	–	–	50	97
500	80	–	–	70	106
530	90	–	–	90	112.5
550	100	–	–	100	115
570	120	–	–	200	132.5
590	140	–	–	400	150
600	160	–	–	600	160

Keeping these rules in mind, the values presented in Table 4 were chosen.

However, to further parametrise the model and represent the full possible range of values that characteristic curves might get, sample values from Table 4 were not enough. Instead, these values were used to create a sample of the infinite number of curves that are enclosed in the space created by the original and exponential curve.

To simplify the modelling and keeping in mind that Mevea Solver deals with single points rather than mathematical functions, the following mathematical model for determining those points can be derived:

$$x_{new} = x_{orig} + \frac{\frac{y_{orig}}{y_{lin}/x_{lin}} - x_{orig}}{n} \cdot i \tag{1}$$

where x_{orig} is the value of x in the original (exponential or second-order) curve, y_{orig} is the y-value in the same curve, x_{lin} and y_{lin} are the maximum x and y values of the linear model, n is the number of curves that is created in the space between the exponential or second-order curve and the linear curve, and i is the number of the curve from 0 (means the same as original

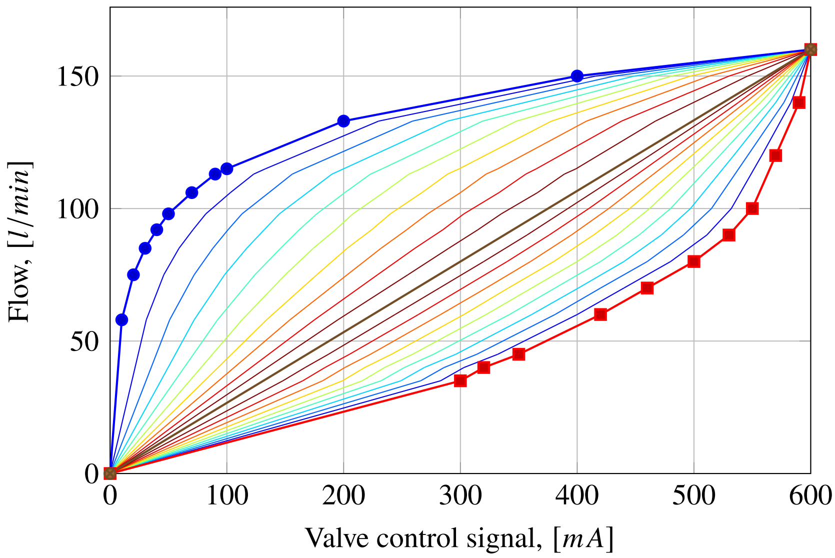

Figure 17. Possible characteristic curves

exponential/second-order) to n (the same as linear). y-value for the new curve is kept the same as for the original exponential or second-order curve. The example of curves produced by this formula is shown in Figure 17, where $n = 10$ and the dotted curves represent the original values for second-order, linear and exponential approximations.

The model can be easily adjusted to handle the desired number of curves within the boundaries provided by the functions. This model tends to follow these rules: bigger n gives more possibility for fine-tuning the shape of the resulting curves; i approaching 0 gives a result closer to the original exponential or second-order equation, while i approaching n results in more linear curve.

3.3 Operator user interface and interaction design development

As noticed in the previous research about the simulator (Islam 2017, p. 44), the users tend to always select the same parameters, for example the biggest possible bucket and the largest available cylinder, but this study was aimed at challenging this tendency using gamification techniques.

Firstly, levelling was implemented. The ideal model for levelling is presented in Figure 7, however in the case of this study the “boss fights”, the stage of increased difficulty before progressing further, was implemented indirectly through increased level difficulty, and the levels presented in Table 5 were introduced. The table summarises the features of each level.

Table 5. Levels introduced to excavator simulation

Level	**Description**
Tutorial	Teaching the user basic excavator controls
Level 1	Loading 1tn of soil into the hopper located next to the excavator
Level 2	Loading 3tn of soil into the hopper located next to the excavator
Level 3	Driving to the hopper from the edge of the site and loading 3tn of soil into the hopper

The progression in the levels is clear: first the user gets to know how to use the excavator, then loads a small amount of soil into the hopper, then larger, and finally the user has to drive to the loading location themselves. This way, the novice users can feel comfortable about their actions, as well as see their progression from completely unknown machine to confident user; at the same time experienced user will not get bored by loading soil to hopper from just one location. The level selection is straightforward and is presented in Figure 18.

Figure 18. Level selection screen

The next step the user undertook was parametrisation. The model presented in Equation 1 and Figure 17 gives a great versatility of possible valve variations, however all of them cannot be used at the same time. To limit the options in order not to overwhelm the user, the simulator prompts to the selection of the curve only once, and after that the similar shape of the curve (*i*-value) is used for all 9 valves in the model. This user interface was created using Python with Matplotlib library, which provides the plotting tools similar to Matlab. The screenshot of the final user interface is shown in the top part of Figure 19.

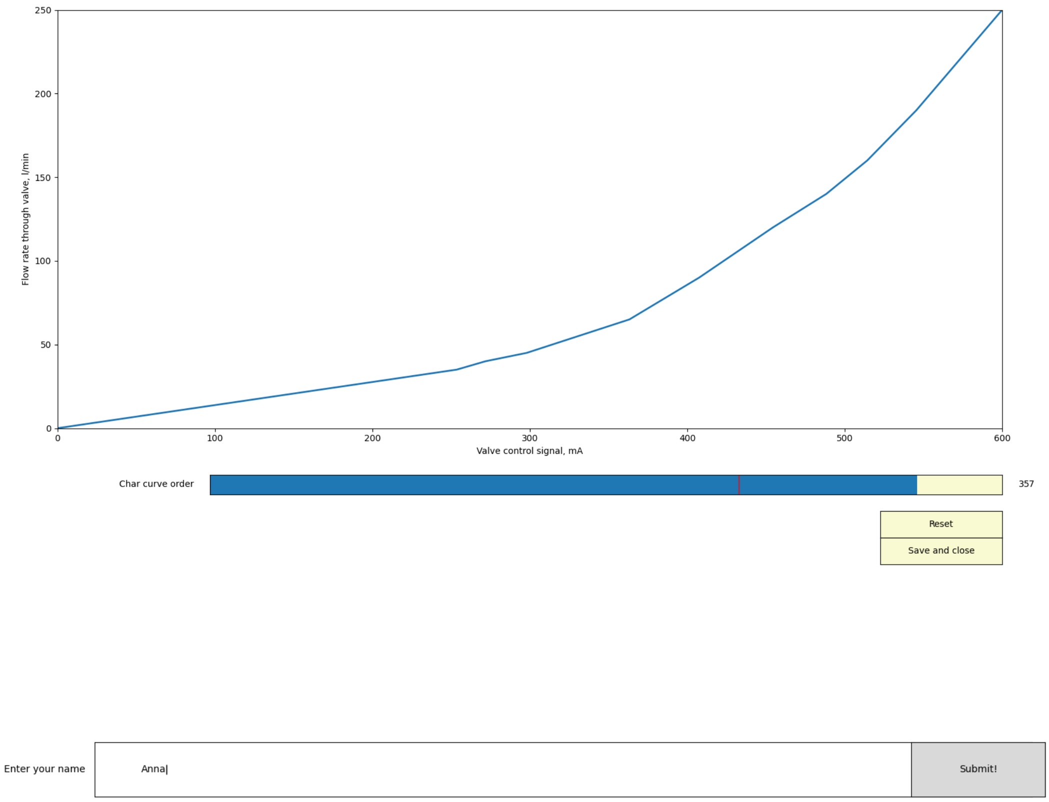

Figure 19. Characteristic curve parametrisation and name request windows in the simulator

The user can move the bar representing i-value to affect the shape of the characteristic curve. After choosing the desired shape, the user can save the result and close the window, which leads to simulation start. Clicking "Reset" button returns the original randomly generated curve. To ensure that there was versatility to the parameter selection, the curves were randomised for each run, so even if the user did not move the slider by themselves, the characteristic curve would be different.

Next, the user was prompted to enter the name to keep track of the results for analysing the performance. No restrictions or requirements on the names were imposed and the interface was kept as minimalistic as possible, as seen in the bottom part of Figure 19. The interface was implemented with built-in Matplotlib tools.

The information about the starting time of the run, parameter curve selection and the username is saved in simple text format for further analysis. After the selection of the level and parameters are done, the simulation starts. The further gamification features were implemented in the simulation window directly. The biggest addition were the on-screen guides to keep the motivation of the user and to provide instructions when needed.

To make sure that the user is indeed familiar with the task at hand, start screens with the summary of the level were included. An example of start screen is shown in Figure 20.

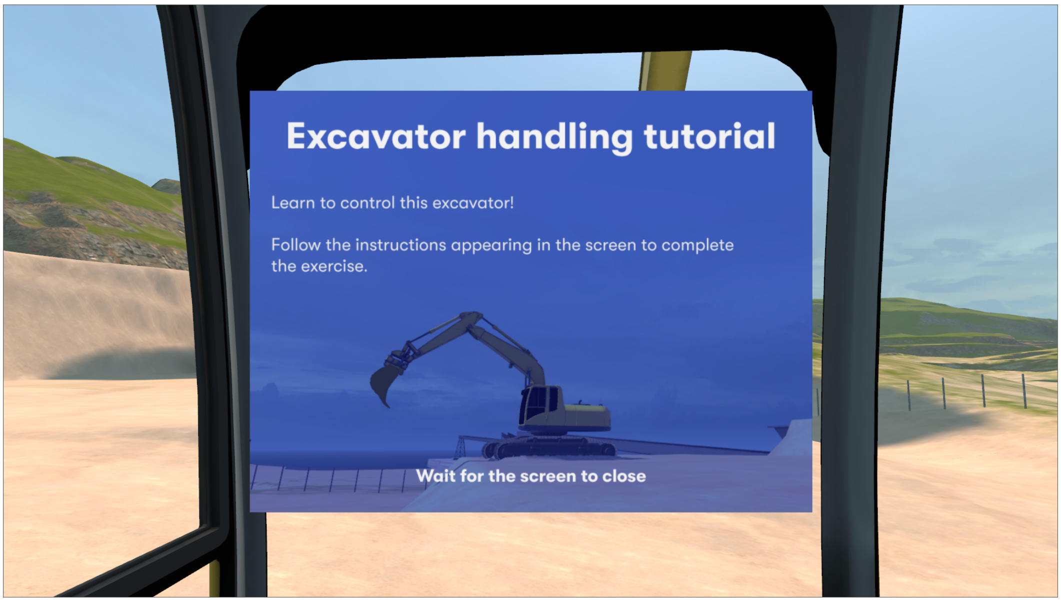

Figure 20. Example of start screen

The start screen also provided a hint on what would be the performance metrics, however it did not specify them directly, leaving space for interpretation and curiosity in the user's mind.

Tutorial level included step-by-step instructions for each movement at the bottom of the screen, as shown in Figure 21. The instructions were specific for this model of the excavator and control system; however, they were in line with the commonly used excavator control systems. The instructions were made with large font and over contrast background to simplify the reading.

Figure 21. Tutorial level view

The on-screen instructions for each step are tutorial-only feature, as for more experienced user they will be unnecessary and demotivating. However, higher levels include other types of useful instructions, for example timer and progress bar. The progress bar used is shown in Figure 22, and it indicated how far the user was from the goal, $1t$ or $5t$ of soil transferred, depending on the level difficulty.

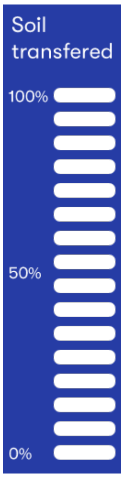

Figure 22. Progress bar

The levels ended when the specified goal was reached. In case of tutorial, the requirement was performing all the actions according to the instructions, while for the rest of the levels that was soil transfer goal. Upon completion, the user was shown the end screen presented in Figure 23. The end screen provided the definite conclusion for the level, and at the same time the metrics that would encourage user's future improvement.

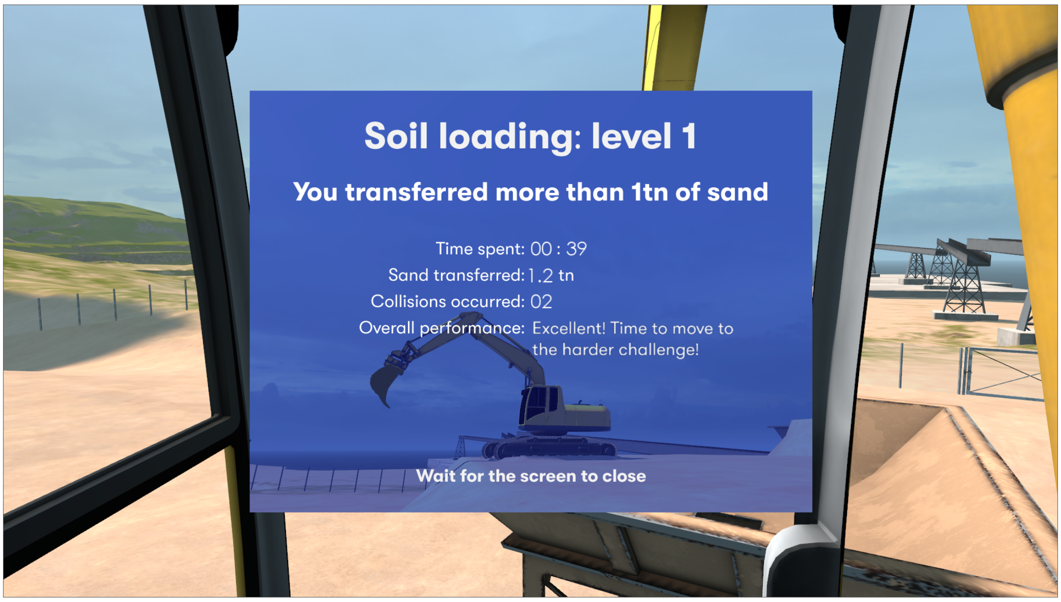

Figure 23. Level 1 end screen

The first three metrics were numeric and were presented as is, not given a specific score. This was done to avoid the trap of using points without clear need for them, which was shown demotivating in some cases (Seaborn and Fels 2015, p. 19). However, "Overall performance" gave written feedback, which according to earlier research, could be more important than naked numeric value. The feedback was using pre-written "canned" texts, which are shown based on the hidden scoring system. The scoring was based on the three metrics shown in the end screen, but it could be expanded to include even more.

The scoring for all the levels, except the tutorial, relied on the derived formula:

$$S_t = 10dp_{\%} + a - r \tag{2}$$

where d is level difficulty, $p_{\%}$ is the percentage of expected productivity, a is awards and r is reductions. Difficulty d was chosen based on the assumption that the levels are linearly more difficult, therefore Level 1 had difficulty 1, Level 2 – 2 and Level 3 – 3. General productivity is measured in kg/s, using the values immediately available in Mevea Solver, and it did not need conversion, as only the percentage representation of this value is of interest. The 100%

productivity was established by running five test runs and taking the average productivity of those.

Awards a consist of two measures: how little the envelop where the excavator works is and how little the excavator tracks are moved when loading the hopper. The envelop is measured by the following formula:

$$s = yaw_{max} - yaw_{min} \tag{3}$$

where yaw_{max} is the largest angle of rotation around y-axis of the upper carriage relative to undercarriage and yaw_{min} is the smallest angle respectively, values given in degrees. The envelop value is then converted to percentages, where 100% represents no rotational movement of upper carriage relative to the under carriage, and 0% at least one full rotation about y-axis.

For the track movements, the awards were calculated by taking the percentage of the total time the tracks inputs were inactive. In this case, 100% meant the tracks inputs were steady during the exercise, while 0% meant that the tracks were constantly moving. Level 3 took into account only the track movements when the excavator started loading the hopper.

Reductions r were based on two metrics: spillage and collisions with environment objects. Spillage deductions were calculated as the raw spillage value in kg multiplied by 0.01, as the spillage alone can result in values over 100, which might not be acceptable in this case. Collision deductions, however, were weighted based on their impact on the model. Mevea software allows categorising the collisions in three groups: minor, serious and critical based on the velocity of the collision. Therefore, the minor collisions received multiplier of 1, serious: 2 and critical: 5. The collisions with hopper had additional multiplier 2.5. The final deduction for collisions is a sum of the collisions multiplied by their respective weight.

To visualise the possible outcomes and evaluate the viability of the scoring system, the Table 6 shown can be created. Based on the sample scores the different feedback messages would

Table 6. Sample scores

	Player 1	**Player 2**	**Player 3**
Difficulty, #	1	2	3
Productivity, %	98	80	64
Envelop, %	90	83	70
Movement, %	100	100	75
Spillage, kg	20	76	110
Minor collisions with hopper, #	3	3	6
Serious collisions with hopper, #	2	3	4
Critical collisions with hopper, #	2	4	4
Minor collisions with ground, #	1	2	2
Serious collisions with ground, #	0	2	2
Critical collisions with ground, #	0	0	0
Productivity adjusted	980	1600	1920
Awards	190	183	145
Deductions	63.5	154.5	201
Total score	**1106.5**	**1628.5**	**1864**

be assigned. The table shows that even nearly perfect run in Level 1 might not be enough achieve the best score, which should motivate the users to try another time. The feedback generated was dependent on the level and the points received. The summary of the feedback messages is presented in Table 7.

The feedback messages were presented to the user instead of the points to avoid the trap of providing bare scoring that proved to have less motivational power than worded feedback. After closing the simulation, the user was returned to the level selection screen, to encourage more runs. The user performance and parameters describing the behaviour of the system were stored for further analysis. The system did not store any personal user information, such as name or experience with controlling the machine.

Table 7. Feedback messages

Level	**Total points**	**Message**
Level 1	< 400	You can do better! Go back to the tutorial to brush up your knowledge or try harder next time.
	400 - 799	Good! Try again to improve your result and move on to the next level!
	> 800	Excellent! Time to move to the harder challenge!
Level 2	< 700	You can do better! Go back to level 1 to brush up your knowledge or try harder next time.
	700 – 1199	Good! Try again to improve your result and move on to the next level!
	> 1200	Excellent! Time to move to the harder challenge!
Level 3	< 900	You can do better! Go back to level 2 to brush up your knowledge or try harder next time.
	900 – 1499	Good! Try again to improve your result and move on to the next level!
	> 1500	You did amazing! Can you improve your performance even more?

4 Results and discussion

After the model with parametrisation and gamification, as described in the sections before, was modelled, it was deployed to the simulator located in the Laboratory of Intelligent Machines of LUT University. The testing was conducted on two separate days with two different groups of people. During the testing, the data regarding the user performance and parameter selection was collected automatically. After completing all the levels, users were prompted to complete a short user experience survey, presented in detail in Appendix 2. The following sections will discuss the results of these test days and possible improvements in the future.

4.1 User involvement

One of the main reasons to implement a gamified system is to increase the user's engagement with the system in order to collect more data usable for R&D purposes. The effectiveness of implemented gamification methods was assessed with the user experience survey. The user experience survey was designed according to the framework outlined in section 3.1.5, and the mandatory questions and answers are presented in Appendix 2.

16 people participated in the survey, the quantitative results of which are summarised in Table 8. The users could rate each option on the scale from 1 to 5, where 1 means "no interest/excitement" and 5 means "extremely excited/motivated". The users were also allowed to leave open comments to each questions, which are discussed in the text as well. The survey was anonymous and all simulator users completed it.

In general, the simulator created positive emotions for the users, with all the questions receiving an average score over 4.0 (at least rather excited/motivated by the simulator). The users pointed different motivators for continuing with the exercises, with five of them talking about curiosity and learning experiences; three pointed out the competitiveness aspect; one – the usage of tutorial for getting to know the operations and another one the social aspect of

Table 8. User experience survey summary

	How excited were you to try the simulator?	How satisfied were you with your performance?	How motivated were you to try another level?	How likely would you recommend trying out this simulator to your friends?
Average	4.375	4.1875	4.3125	4.4375
Median	4.5	4	5	5
Minimum	2	2	1	3
Maximum	5	5	5	5

getting motivation from fellow users; the realism of the simulator was pointed out as well. All in all, 11 out of 16 users responded directly to the game elements implemented. Three more users noted "nothing in particular" that motivated them, but they talked about game elements in the further comments. This shows that game elements can indeed help the user engagement and retention.

In further open comments, the users pointed out the usefulness of the tutorial level and how the progression of the levels helped them stay motivated. Only one user out of 16 has driven the simulator and another one has driven the real excavator before, therefore the tutorial was highly appreciated in this group. However, the tutorial level might not be necessary for more experienced users, so the usage of the tutorial levels should be assess on case-by-case basis.

Despite all the positive feedback, one user felt rather negative about the simulator experience, pointing out that testing was more like a chore, and another user felt less negative, but still was more motivated by peer pressure than game elements. This suggests that even the gamified simulator might not provide engaging enough experience, especially to the users who have tried the simulator before.

Users also suggested possible ways of improving the simulator experience, such as highlighting the difference between levels 1 and 2. It was pointed out that these two levels felt very similar and therefore monotonous, so a more defined progression, such as moving the excavator to a new location, is needed. Another user proposed an idea for a new on-screen meter that would tell the amount of soil in the bucket currently, as it was rather difficult for them to judge how full the bucket was getting and how much it contributed to the goal.

All in all, the gamification created interesting environment for the users, and encouraged them to discuss the simulator and the possible ways of developing it their skills further. The users also felt encouraged to talk about their experience with their connections to increase the outreach of the project.

4.2 User performance

The most recognisable feature of the gamified system are points and leaderboards. In this implementation, the users were not given the points directly, but instead were given verbal feedback based on the conversion system presented in the Table 7. This was done to avoid the problem of "pointsification" and increase the user's motivation for improving even more. However, the points were still collected in the background, together with other user performance data: position of the bucket in relation to the undercarriage; total fuel consumption; total time spent on completing the exercise. Data for tutorial level was not analysed, as the main goal of that level is getting to know the system in general, instead of focusing on the performance quality. The performance was also affected by the hydraulic parametrisation, but its influence is discussed more in the following section.

Excluding the tutorial level, 16 users produced 45 runs of the model under three levels of difficulty. 15 users out of 16 tried level 1, 13 – level 2 and all 16 – level 3 with one user engaging with it twice. The summary of the points received by each user is presented in the Table 9 alongside the user's productivity in tonnes per hour (t/h). The best results for each level are highlighted in green and the worst in red based on the statistics presented in the bottom of the table.

The user's progress is clearly visible by comparing the results of levels 1 and 2. All but one user improved both their point score and productivity from level 1 to level 2, with user 12 achieving the largest improvement in points (55% better) and user 11 in productivity (66.5%). On average, the users' performance got better by 35% in points and productivity. This shows

Table 9. User performance summary

User	Level 1		Level 2		Level 3	
	Points	Productivity [t/h]	Points	Productivity [t/h]	Points	Productivity [t/h]
1	236.961	20.081	–	–	356.677	19.312
2	331.409	27.195	435.994	33.508	203.786	10.243
3	–	–	480.154	35.940	315.926	19.154
4	524.328	36.717	637.078	45.642	135.962	9.791
5	400.324	26.683	–	–	152.219	10.917
6	172.185	16.671	301.619	23.181	180.922	11.495
7	504.617	38.740	685.692	50.134	295.948	17.030
8	501.529	33.473	590.088	38.630	357.640	21.299
9	320.411	26.511	536.344	41.631	329.165	18.323
10	552.102	39.208	–	–	203.770	13.895
11	268.328	20.627	359.544	61.723	192.833	14.999
12	257.827	20.907	573.725	46.388	340.981	21.575
13	367.004	25.639	234.748	19.325	197.990	16.199
14	363.629	30.277	574.272	45.358	502.656	35.643
15	421.551	35.350	794.475	62.880	409.023	26.642
16	368.232	27.223	809.483	62.667	651.199	41.524
Average	372.695	28.353	539.478	43.616	298.487	19.944
Median	367.004	27.195	573.725	45.358	295.948	18.323
Maximum	552.102	39.208	809.483	62.880	651.199	41.524
Minimum	172.185	16.671	234.748	19.325	135.962	9.791

that the users' learning is progressing rapidly.

However, the results of the level 3 show that the users' learning only progressed for the basic soil loading operation and not for the more complex handling of the excavator. Level 3 required user to rotate the excavator using non-trivial technique and drive the excavator to the soil transfer location, therefore the productivity of digging has decreased, as well as its precision, which in turn affected the total score. Six users managed to improve their total score over level 1 with only three of them improving the productivity as well. No users improved their scores compared to level 2, which shows that the step between levels 2 and 3 might be too large. As mentioned in the previous section, this can be addressed by making level 2 more complicated.

The points received by the user, among other things, depended on how compact they could keep the operation envelop. This is important for ensuring the most efficient fuel consumption, as well as safe operation without unnecessary collisions. The ability to keep the bucket within the minimum envelop around the excavator can be used to study how the user has progressed in learning the controls and using them precisely. The Figure 24 shows the paths of the excavator's bucket relative to its undercarriage for the user 6, who had the worst performance in the level 1. The dashed blue line shows the bucket path in level 1, with thick red and thick brown showing levels 2 and 3 respectively. The light grey circle shows the position of the undercarriage.

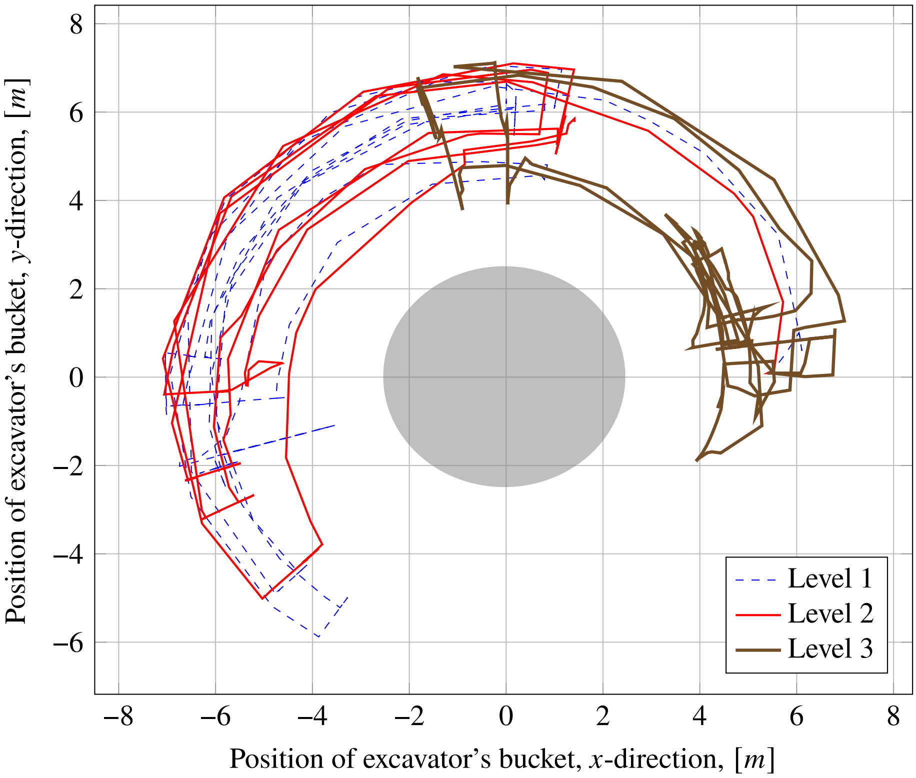

Figure 24. User 6 movements of the excavator's bucket relative to the undercarriage in different levels

The figure shows that user 6 moved the bucket a lot in the level 1, but managed to become more precise in level 2, and in level 3 they were keeping the bucket in a half of the space used before. Due to the improved bucket positioning, user 6 managed to marginally improve their scores from level 1 to level 3, despite losing 45% of level 1's productivity. The productivity loss is attributed to the level 3 productivity calculation including the time required to move to the new position, and not pure digging time. However, the progress is still visible because of the scoring system.

Despite scoring system being generally useful in order to assess and compare user's perfor-

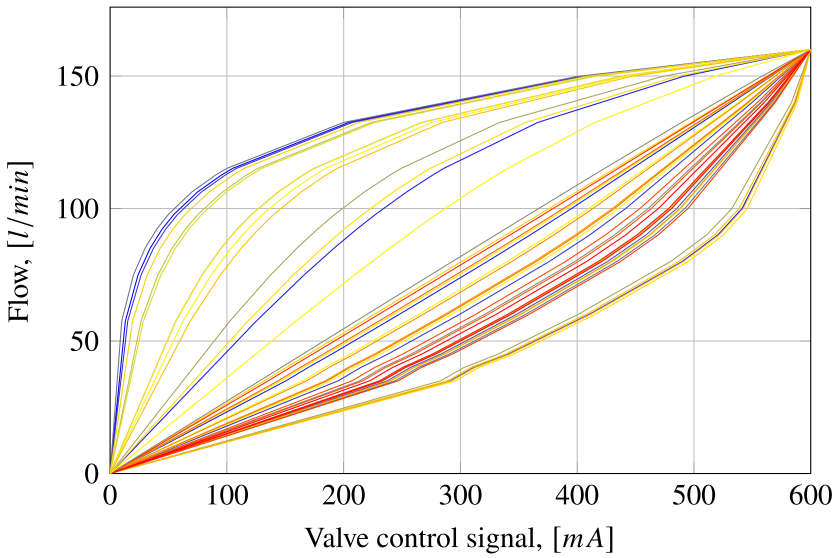

Figure 25. Characteristic curves used in tests

mance, it is worth noting that it requires adjustment. With the limits outlined in the Table 7, no user managed to get "good" score in level 3, only two and six user got "good" score in levels 2 and 1 respectively. This can become an issue going forward with the system, as the users might feel cheated by the system and lose the motivation due to the lack of visible progress.

4.3 Influence of parametrisation on user's performance

Before launching the simulation, the users were given an option to adjust the characteristic curves of the hydraulic valves used in the model. However, the option was not mandatory, and to improve the data collection, a random curve was suggested every time the new simulation started. The users were not given any positive feedback for modifying the pre-defined option. The compilation of all the curves used in the tests is shown in the Figure 25. Each line represents the shape of the single curve chosen for the run. Due to the implementation used (random uniform number generator in Python) the results are rather evenly distributed even with only 45 runs presented out of 400 possibilities.

Due to such randomisation it is difficult to find the comparable examples of the parametrisation in the user runs. Usually the same user received quite wide distribution of curves, and with only three runs from each user available, it is difficult to make reliable connections. However, it was still possible to find a few runs with relatively similar curves by the same user, as shown in the Figure 26. Level 1 curve is indicated in blue, level 2 in red and level 3 in brown.

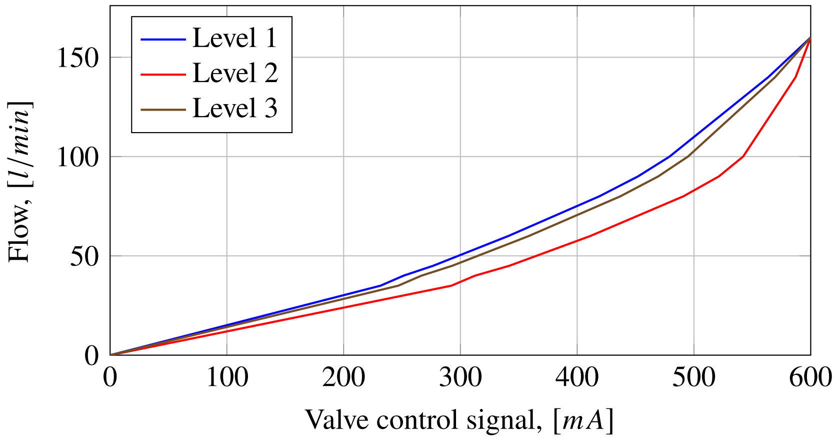

Figure 26. Characteristic curves used by user 2

These curves, especially the one for level 2, is similar to the original second-order option, therefore is the most similar to the real life option. The corresponding bucket position for this user on levels 1-3 is presented in the Figure 27. Blue line shows the path during level 1, red and dashed brown for levels 2 and 3 respectively.

It is clear that the blue line seems to be around smaller area than the red or the dashed ones. This can mean that it is easier to keep the bucket within the desired area due to the more linear response of the hydraulic actuators. However, the red line showing level 2 is located inside the area of the level 3 line, meaning that even though the behaviour of the valves is less linear in the last case, it is still easier to keep the bucket under control. Therefore, the results are not conclusive and more investigation is needed with bigger amount of participants or more streamlined parametrisation.

4.4 Gamification and obtained R&D data

The user experience survey showed that the users feel rather engaged with the simulator and are motivated to use it again. This means that more data for different purposes, including R&D can be collected in the background. However, if additional R&D features such as parametrisation of components are added, they are not always used as intended. The tests

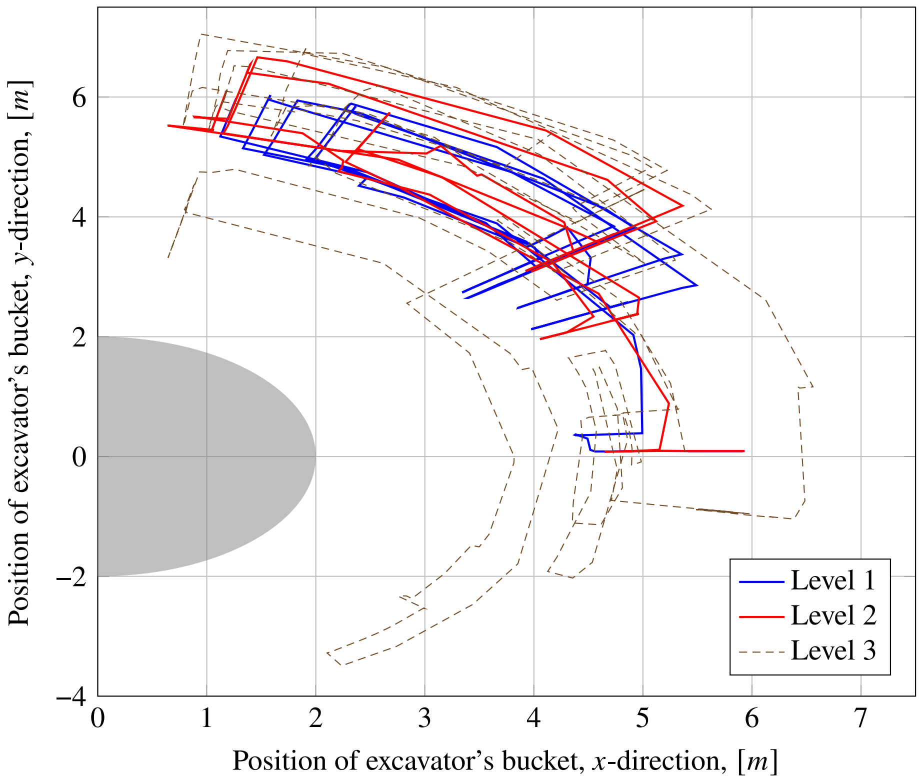

Figure 27. User 2 movements of the excavator's bucket relative to the undercarriage in different levels

showed that users did not express interest in changing the parametrisation from the randomly generated number, therefore it is difficult to approach data collection systematically.

At the same time, the data that is collected, should be chosen carefully. Mevea software allows recording of various types of parameters, however they must be defined before the simulations are run, to be saved to the database for the later analysis. In the case of this research, it might have been useful to record the input data and direct response of hydraulic cylinders to it, instead of only remotely associated bucket position.

5 Conclusions and future outlook

The presented research focused on creation of a gamified version of the excavator simulator with the hydraulic parametrisation. As the gamification is generally built upon an existing system, the simulator in the Laboratory of Intelligent Machines of LUT University was used to develop and test the solution. A program for changing hydraulic valves characteristic curves was developed, alongside the gamification solution. Gamification done to the simulator included the addition of levels: one tutorial with explanation of the excavator usage procedure, and three progressively more complicated levels, as well as on screen meters during the simulation and end screens with feedback. In the background, the data about the simulator usage was collected and analysed to make connections between the selected hydraulic parameters and the operator's performance.

As a part of creating this solution, a review of gamification methods was performed. This review aimed at describing the streamlined way of creating a gamified system, that can be implemented to other systems in the future. The implementation of the gamification system for the thesis followed the guidelines discovered during the review. The systematic approach to implementing gamification helped avoiding confusion and common traps of gamification systems.

The developed system was tested with the group of LUT University students, and the survey was conducted to estimate the impact of the gamified system on the user's motivation. The metrics discovered using the literature review were used, and they showed that majority of users reacted positively to the gamified system and were motivated to continue using it. However, there were dissatisfied users as well, showing that single gamification solution cannot be a silver bullet to all the motivation and engagement problems.

The parametrisation of hydraulic parameters was done with Python program that launched every time the simulation started. The parameter selection was randomised at every start to avoid getting the same results all the time. The users generally did not seem interested in fiddling with this parameter and left the choice to the machine. Due to the randomness of this process, comparing the impact of the parametrisation on the operator's performance was challenging, but meaningful conclusions can be done.

The data generated by the users during the simulation runs was saved into the local database that was later extracted and analysed. The data collected was sufficient for the purposes of this research, however, the more thorough analysis for R&D purposes will need more careful parameter selection. This also increases the difficulty of extraction and data analysis.

In the end, all the research questions posed in the beginning of the research were answered. This research proved that a gamified system on the basis of a real-time mechanical simulation is possible and it can be engaging to the users, at the same time providing valuable information for further development and improvement of the machines. However, some development topics were left behind and will need further investigation in the future.

5.1 Development proposals

This section presents a brief overview of the possible improvements to the simulator and the gamified system development.

Firstly, as the gamification is a deeply software development process in nature, that is why more software development practices should be implemented. Pre-deployment testing was clearly lacking in this project, as there were issues still appearing during the simulation runs conducted for this research. With more thorough testing procedure, more bugs would have been eliminated, and the scoring system would have been developed to better fit the skill level of the wider audience. As section 4.2 points out, only very few users managed to get positive feedback due to overly high scoring limits. This preliminary testing can also point out potential improvement points, such as more distinct and encouraging leveling.

User progression tracking was not implemented, even though this is a very powerful gamification and motivation tool. The user was given only feedback about the present run with no comparison points to own previous runs or runs of other users. In the future, this system can include proper user management system, where the user can keep track of own and other's progress.

There still is a lot of gamification components that can be added to the system, but were not added at this point. This includes badges for various achievements that can motivate more explorer gamer types (e.g., "Traveller" for reaching the edge of the usable environment). The instructions and the on-screen indicators can still be improved.

The parametrisation system can be improved by making it more predictable. In the future, instead of relying on user actions or random number generator, the researcher can feed the interesting data into the program without user interference. At the same time, something can be done in order to make the parametrisation more engaging and interesting to an average user, for example adding a badge or additional scores for modifying the hydraulic parameters.

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Appendix 1.

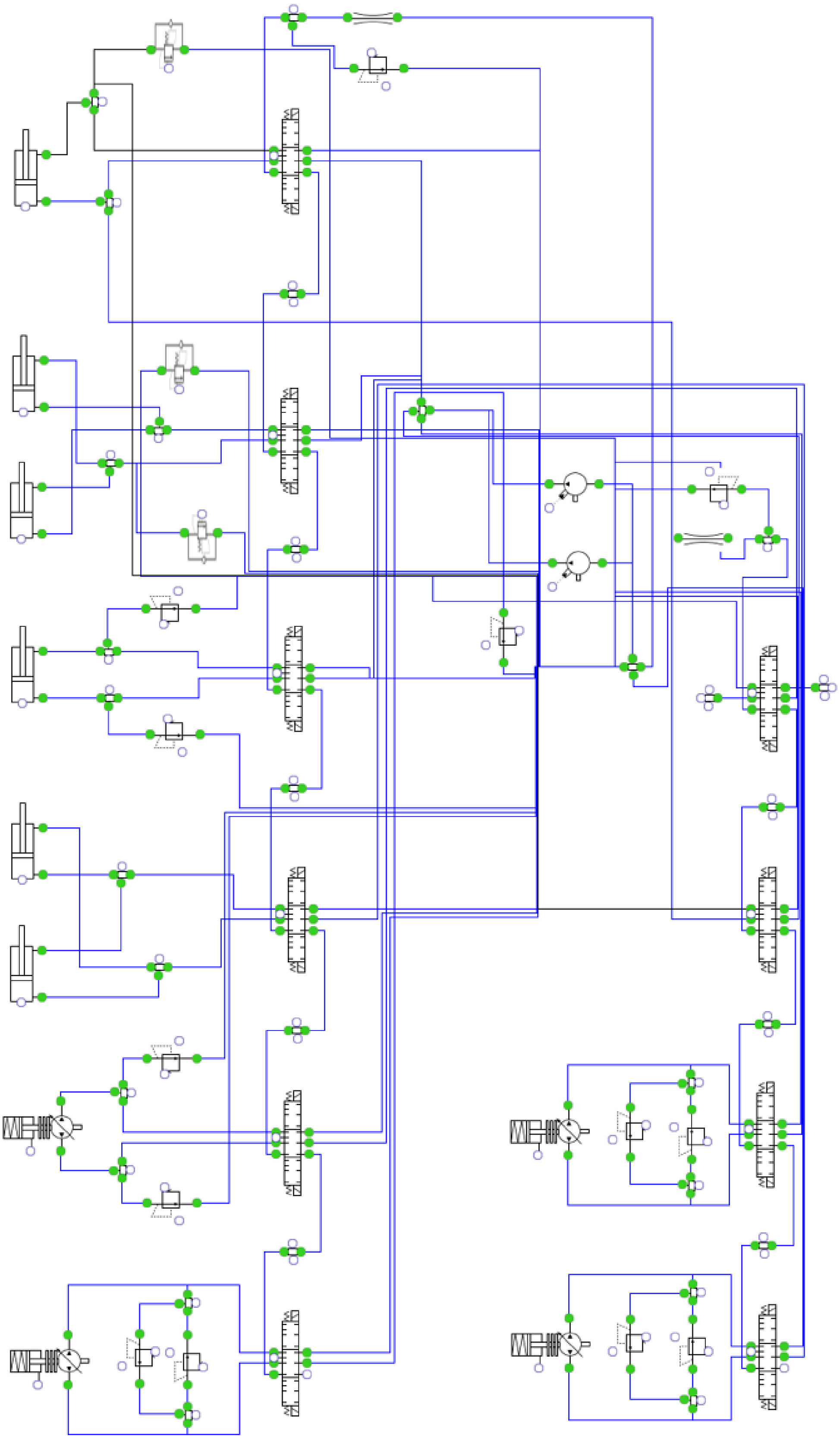

Figure A1.1. Full hydraulic circuit of excavator

Table A2.1. User experience survey

How excited were you to try the simulator?	What kept you going through the level?	How satisfied were you with your performance?	How motivated were you to try another level?	How likely would you recommend trying out this simulator to your friends?
5	It was very similar to reality so it was easy to control.	5	5	5
4	Nothing in particular	4	4	5
4	Just the process.	5	5	5
5	Drive	5	5	5
5	Encouraging comments from bystanders.	4	3	3
4	Motivation to learn	5	5	5
5	Feeling of getting the hang of it	5	5	5
4	Wanted to beat it i guess	4	4	5
5	Eagerness to learn the controls and feel a sense of accomplishment after completing the task. Finding and testing out the optimal way of lifting the substance from the ground and avoiding excess spillage.	4	4	4
5	Nice instructions	5	5	5
4	Learning the controls so that they are in the muscle memory	4	5	3
2	Because I had to	4	1	3
4	Just wondering how the challenges would be in every levels	3	4	4
4	Immense peer pressure	4	4	4
5	Urge to dig and excel in operating excavation	4	5	5
5	I was curious to see how I will do	2	5	5