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Leveraging Visual Gamification to Enhance Undergraduate Education of Geological Modelling

Bachelor's Project Computing Science

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Abstract

Undergraduate geology students are often ill-prepared to apply mathematical principles in modelling reservoir structures. Several visualisation tools exist to help students grasp modelling techniques more effectively.

This thesis outlines the development of a geological modelling visualisation tool, capable of B-spline interpolation and Sequential Indicator Simulation (SIS), enhanced by incorporating gamification elements (namely 'Missions' and 'Badges'), with the aim of making interaction with the tool more engaging. In doing so, an improvement in the rates at which undergraduate geology students learn the mathematical principles used in geomodelling is expected.

Acknowledgements

I would like to thank my supervisors for giving me the opportunity to work on this interesting, and most importantly fun project, which made it feel more like my own personal project rather than a task given to me. Their help and support, both practical and mental, were crucial for me to complete the project successfully.

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1 Introduction and Motivation

Learning how to apply and understand mathematical principles in geomodelling can be a challenging endeavour. To facilitate the visualisation of physical structures in three-dimensional space, several computer applications that leverage modern computer graphics have been developed. The primary educational benefit of these tools is their interactive nature.

Gamification, an educational theory, suggests that incorporating game design elements into education can enhance engagement and, thus, improve the rate of learning among students. There are numerous examples of gamification being successfully applied in fields outside geology, such as mathematics [11], demonstrating positive impacts.

This project entails the integration of 'Missions' and 'Badges', two gamification elements, into a fit-for-purpose interactive visualisation tool for geological modelling developed as part of the Bachelor's thesis. The tool is capable of performing two prominent geomodelling techniques: B-spline interpolation and Sequential Indicator Simulation; these methods will be used to illustrate mathematical geomodelling concepts. The initiative is aimed at enhancing user engagement and analytical capabilities within the visualisation environment. These gamification elements are described in the game attribute taxonomy developed by Bedwell et al. [1], which will guide the development of the gamification features.

Recently, gamification has become a popular research area. Although it is being applied in many fields, there is a notable gap in combining visualisation tools for geological modelling with gamification. The project aims to bridge this gap and explore its effects, with the objective of creating an educational tool beneficial for undergraduate geology students' learning geomodelling.

These students, often not well-prepared by their curriculum, might require additional engagement to learn the involved mathematical principles. Additionally, current geomodelling applications are made for production modelling rather than learning, and they present themselves with complex user interfaces, which makes them difficult for undergraduate students. This project will also increase awareness in this research area, encouraging future investigations into which specific gamification elements are beneficial in this context.

2 Contribution

The project fits into the area of scientific visualisation and computer-aided education, and it identifies the combined effectiveness of a geomodelling visualisation tool with a gamified approach on the learning process of undergraduate geology students. After developing the tool, it is tested to assess its impact on learning, from which conclusions on the tool's effectiveness have been drawn. Thus, we are answering the research question: *"How does the integration of computer visualisation and gamification elements, such as 'Missions' and 'Badges', influence undergraduate geology students' understanding of geological modelling and associated mathematical principles?"*. Successfully answering the research question will lead to the following contributions:

- An intuitive visualisation tool for modelling to be used by undergraduate geology students.

- A novel visualisation tool for modelling that distinguishes itself from existing counterparts by implementing gamification elements.

To answer the research question, it can be subdivided into smaller sub-questions.

- “What percentage increase in retention of mathematical principles used in geological modelling is observed among students after interacting with ‘Missions’ and ‘Badges’?”
- “How do users describe their experience with the integration of game elements in terms of ease of use and engagement? What percentage of users report a positive impact on their experience compared to an equivalent tool without game elements?”

The first step is to go over the background knowledge and a review of the existing literature on both educational modelling visualisation tools and gamification in Section 3 (Related work). In Section 4, the methodology including all aspects of the project is thoroughly described. Finally, the results and discussion are laid out in sections 6 and 7.

3 Related work

3.1 Background

To fully comprehend the sections that follow, important literature and theory need to be covered, both in the field of geomodelling and in gamification.

3.1.1 Geomodelling

Geological characterisation and assessment of subsurface properties, such as porosity distribution and rock composition homogeneity, are pivotal aspects of geomodelling porous reservoir media. Understanding these characteristics allows for accurate prediction of fluid flow behaviour and reservoir performance, crucial for industries such as oil and gas exploration and production [13]. Although there are various geomodelling techniques to choose from, this project concentrates on two specific methodologies.

The first technique, B-spline interpolation, falls under the category of property modelling methods, primarily concerned with estimating continuous variables within the subsurface. Employing a pixel-based approach, this method generates smooth and continuous representations of geological properties by interpolating irregularly-spaced data points. The interpolation process involves computing a linear combination of piecewise polynomial functions known as 'basis functions'. These functions are defined over intervals called 'knot spans', where they exhibit nonzero values, thereby influencing the properties of the surface within the respective span. The 'knot vector' encapsulates the arrangement of these spans. Through an iterative optimisation process, typically involving least squares optimisation techniques, the coefficients of the basis functions, referred to as 'control points', are adjusted to optimise the alignment of the interpolation with the input data.

In contrast, the second technique, Sequential Indicator Simulation (SIS), belongs to the domain of Gaussian Classification methods and also operates on a pixel-based framework. Unlike B-spline interpolation, SIS is classified as an indicator modelling technique, primarily focused on simulating categorical attributes of the subsurface. It builds upon the principles of indicator kriging, integrating heterogeneity through stochastic methods [13]. SIS produces multiple iterations of simulations, striking a balance between deterministic local conditioning and indicator kriging, while incorporating stochastic random draws. This ensures that randomness is introduced into the simulation process while preserving the spatial continuity observed in the input data.

3.1.2 Gamification

"Educational gamification aims to enhance learners' motivation and engagement by integrating game design elements into educational settings" [5].

Research activity in this domain has surged over the past decade [14], and its highly theoretical nature and difficult-to-assess effects have led to lots of research where gamification is talked about in unstandardised terminology. An example is the unclear distinction between serious games and gamification, where the lack of theoretical work is a significant oversight that hampers progress in both fields [10]. To bridge this gap, Landers published a paper to lay down a framework for gamified learning, and its distinction from serious games [10]. This project follows the theoretical framework of gamification by Landers, to adhere to the proposed standard.

The paper builds upon the game attributes formally described in the Bedwell taxonomy [1], and proposes that research in the field of gamification must delineate the game attributes extracted by game elements. Game elements are defined as features or mechanics that are common in games [4], such as 'Missions', 'Badges', 'Leaderboards'. Game attributes refer to broader characteristics that define the setup and functionality of the game environment, such as immersion, narrative, or interactivity. Note that each game element targets one or more game attributes, and may extract game attributes to varying degrees, for example, the 'Missions' game element targets the 'progress' and 'rules/goal' game attributes, however depending on the implementation, they may extract 'progress' to a higher degree, while 'rules/goal' attribute might be more subtle.

In his paper, Landers makes a precise distinction between 'serious games' and 'gamified learning': "In serious games, all of these (game) attributes are present, but vary in degree. In gamified learning, specific game attributes are targeted, extracted, and adapted to non-game contexts". Studies follow the theory that serious games affect learning directly, with approaches such as the research-and-practice model [6] showing that the instructional content is causing the learning, and that the game is acting as the instructor [10]. Gamified learning, on the other hand, does not try to cause learning directly, but instead induces certain behaviours and or attitudes, intending to have the attitudinal change enhance the already existing instructional content. The instructional content must be already sufficiently well-suited for education because the enhancement made by gamified learning can only improve the content if it is good. If the content is not adequate, then gamified learning will only change the learner's attitude towards learning material that is not going to help them.

3.2 State of the Art

The practice of modelling itself serves as an effective pedagogical tool for understanding mathematical concepts [2]. Moreover, a plethora of visualisation tools exist to facilitate comprehension. These tools encompass Augmented Reality (AR)-based, virtual reality (VR)-based, and mixed reality (MR) tools [15, 7, 8], all sharing a common 3D visualisation aspect, although interacted in varying manners. However, what is often lacking in these educational tools in geology is a ‘gamified’ approach to learning.

The seminal framework for gamified learning, as discussed by Landers, forms the cornerstone of gamified learning approaches [10]. Several game design elements of the aforementioned approach, such as ‘quests’, ‘badges’, ‘points’, and ‘leaderboards’ have been systematically detailed in the game attribute taxonomy developed by Bedwell et al. [1]. Notably, research activity in this domain has surged over the past decade [14]; thus gamification has found utility as a teaching methodology in university-level education across different disciplines. For instance, research focusing on the education of mathematics to students with a liberal arts background, especially those who might not possess a strong foundational knowledge of mathematics, highlighted the significant advantages of employing gamification strategies in their education [11]. Similarly, in Computer Science, a study applied gamified learning to UML modelling coursework [9]. Here, diverse reward systems were employed to augment teaching methodologies.

3.3 Research Gap

In the field of undergraduate Geology education, current curricula inadequately prepare students to apply mathematical principles in geomodelling. While there are several pedagogical visualisation tools, they are only casually employed in current geomodelling didactics due to their sheer complexity. The insufficient use of engaging, visual tools in geomodelling education represents a major difficulty for closing maths-literacy gaps for geology students.
Our project bridges this gap by introducing a simple, easy-to-use, gamified visual tool for geomodelling education. Because it is specifically designed for learners, it hides the complexity of established geomodelling packages, making the learning process of the practical application of mathematical concepts in geomodelling more engaging and cognitively accessible. This project consists of an exploratory toolbox that integrates visualisation techniques with two elements of gamification, namely ‘Missions’ and ‘Badges’, to create an immersive and effective learning environment.

4 Methodology

4.1 Experiment Setup

The experiment for this bachelor's project is done through a user study. The ideal participants for the study are undergraduate geology students, and it seeks to measure:

- Whether there is a positive impact on experience compared to an equivalent tool without game elements
- Retention improvement
- Engagement

Retention is defined as the ability to recall information, and engagement refers to a learner's active involvement in a learning activity.
The user study has a thirty-minute time limit and is split into two tests. The first test is an interactive application demo, during which the participants are guided through a step-by-step guide to install a demo version of the application. The test consists of an initial tutorial on the application interface, then a short lesson followed by a practical exercise and a theoretical exercise. During the application demo, in order to assess engagement, the users are asked to stop mid-way through the demo if they ever stop feeling engaged with the application.
The theoretical exercise is designed such that part of the questions are about material covered only theoretically during the lesson, and the other part is about the material taught interactively with the modelling tool. This gives insight into if the interactive nature of the tool improved retention.
The number of badges obtained by the participants will be recorded. The lesson and exercise together contain several badges; however, the badges used in the user study are not the same ones as in the final application. The user study makes use of fewer badges than the final application, and they have different meanings and requirements compared to the final badges. This was done because (as explained in the badge design section later on) badges represent milestones and achievements in the learning journey of the users, but the user study's short duration means that the users would not be able to achieve badges, and the user study would not collect any results about them.

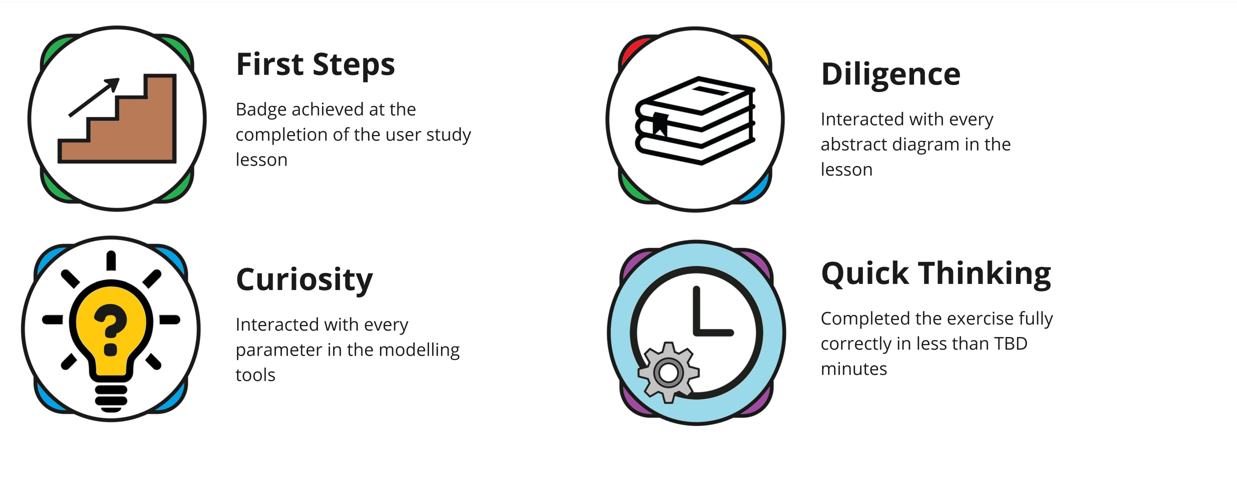

Figure 1: User study badges

The second test is a qualitative survey hosted on Google forms, where participants will be asked to answer multiple-choice and open questions about the ease of use of the application, whether they felt a positive impact on their experience from the gamification elements, or if they felt intrusive. The amount of badges obtained and exercise score will be taken into account to evaluate the responses.

4.1.1 Hypotheses

In the hypotheses, I refer to 'Missions' and 'Badges' solely as gamification elements, for the sake of brevity.

Retention of Mathematical Principles
Null Hypothesis (H0): The integration of gamification elements and visualisation in geomodelling tools does not increase the retention of mathematical principles.
Alternative Hypothesis (H1): The integration of gamification elements and visualisation in geomodelling tools increases the retention of mathematical principles.

Impact of Gamification on Usability
Null Hypothesis (H0): The integration of gamification elements and visualisation increases the usability of geological modelling tools for undergraduate geology students.
Alternative Hypothesis (H1): The integration of gamification elements decreases the usability of geomodelling tools for undergraduate geology students.

Enhancement of User Experience through Gamification
Null Hypothesis (H0): The integration of gamification elements does not enhance the user experience of geological modelling tools for undergraduate geology students.
Alternative Hypothesis (H1): The integration of gamification elements enhances the user experience of geological modelling tools for undergraduate geology students.

4.1.2 Structuring the Hypotheses for Analysis

Retention of Mathematical Principles
Measurement Approach: the scores of questions on material covered theoretically are compared to the scores of questions on material taught interactively with the modelling tool. Additionally, the number of badges achieved by each participant is weighed in.

Analysis Strategy: determine if there is statistical insignificance in scores between theoretical and interactive questions.

Impact of Gamification on Usability
Measurement Approach: responses from the qualitative survey regarding the usability of the application are to be analysed.

Analysis Strategy: verify that gamification elements do not complicate the use of the tool.

Enhancement of User Experience Through Gamification
Measurement Approach: feedback from the survey on the participant' overall experience is examined. Moreover, the number of badges obtained and how this correlates with their experience is checked.

Analysis Strategy: check if there is no significant correlation between the presence of gamification elements (badges earned) and higher levels of reported user satisfaction and engagement.

4.2 Data

The data required and used for this project solely revolve around feeding input data to the modelling algorithms.

4.2.1 Property modelling

The 2D and 3D B-spline interpolation are both property modelling algorithms, and they require discrete numerical samples of geological properties of rock such as porosity and permeability. They are designed to reconstruct subsurface properties or rock compositions using hard conditioning data, which come from well logs. Well logs are records of petrophysical properties measured along the predominantly vertical trajectory of drilling points. We make use of pseudo-well logs, which are derived from sources other than actual drill sites. These pseudo-well logs are generated by sampling pre-constructed models through GemPy [1]. The sampling is performed at laterally irregular positions along straight-vertical paths. The extracted petrophysical properties, as shown in Figure 2. The datasets are in the form of CSV files, with contiguous entries for each well observation.

#	x	y	z	indicator	geoformation	porosity
70	731515.8587	1923146.086	-1800	7	basement	0
70	731515.8587	1923146.086	-1511.111084	7	basement	0
70	731515.8587	1923146.086	-1222.222168	7	basement	0
70	731515.8587	1923146.086	-933.333313	5.000013921	TRIAS	0.1533366825
70	731515.8587	1923146.086	-644.444458	4	LIAS	0.2255410397
70	731515.8587	1923146.086	-355.555542	4	LIAS	0.2386571064
70	731515.8587	1923146.086	-66.66666412	4	LIAS	0.2174713382
70	731515.8587	1923146.086	222.222229	4	LIAS	0.23342832
56	737512.2226	1920690.452	-1800	7	basement	0
56	737512.2226	1920690.452	-1511.111084	7	basement	0
56	737512.2226	1920690.452	-1222.222168	7	basement	0
56	737512.2226	1920690.452	-933.333313	7	basement	0
56	737512.2226	1920690.452	-644.444458	7	basement	0
56	737512.2226	1920690.452	-355.555542	7	basement	0
56	737512.2226	1920690.452	-66.66666412	4	LIAS	0.2236645547
56	737512.2226	1920690.452	222.222229	4	LIAS	0.2215688862
56	737512.2226	1920690.452	511.1111145	4	LIAS	0.2179118073
24	731695.733	1919797.895	-1800	7	basement	0
24	731695.733	1919797.895	-1511.111084	7	basement	0
24	731695.733	1919797.895	-1222.222168	7	basement	0
24	731695.733	1919797.895	-933.333313	7	basement	0
24	731695.733	1919797.895	-644.444458	7	basement	0
24	731695.733	1919797.895	-355.555542	7	basement	0
24	731695.733	1919797.895	-66.66666412	4	LIAS	0.2216623266
24	731695.733	1919797.895	222.222229	4	LIAS	0.2149188375
24	731695.733	1919797.895	511.1111145	4	LIAS	0.2168031198
34	734638.9895	1917534.983	-1800	7	basement	0
34	734638.9895	1917534.983	-1511.111084	7	basement	0

Figure 2: CSV Well-log dataset

[1] Gempy : https://www.gempy.org

Pre-processing the data for B-spline interpolation was straightforward for both the 2D and the 3D algorithms. The datasets have three-dimensional positional coordinates and associated porosity values, along with other fields. In the case of 2D B-spline interpolation the data frames had to be split into several data frames of wells at the same depth, with at least sixteen samples to meet the requirement :
$(kx + 1) \times (ky + 1) \mid k = 3$ (default). kx and ky being the degrees of the B-splines [3]. Extracting samples at different depth levels and removing the third dimension (z) is done so that the data can be laid out on a two-dimensional grid (first step of 2D B-spline interpolation). On the other hand, 3D B-spline interpolation, as the name suggests, does not require the aforementioned pre-processing step, but instead, the datasets are split into data frames with at most eight hundred samples, being the most the algorithm can handle due to runtime constraints.

4.2.2 Facies

Sequential indicator simulation (SIS) is a geostatistical method used in facies modelling to predict the spatial distribution of different rock types within a reservoir. The same well log data used for B-spline interpolation is also used for SIS. In this case, the fields of interest are indicator values: categorical variables representing the facies type of the sample. Other than some field names of the datasets having to be modified, no pre-processing of the data was required for SIS.

4.3 Approach

First prior to discussing the implementation of the application, it is important to describe how the system is designed and the reasons for the decisions that constitute it. Since the application is heavily centred around domain knowledge in both gamification and geology, the reasoning behind decisions is quite specific.
This section gives an overall description of the system, followed by an in-depth description of the gamification component of the system.

4.3.1 General System Design

The system is divided into illustrated lessons and exercises, which are distributed into one of multiple categories according to the geological concept they teach or assess. This categorisation of lessons and exercises will be further discussed in the gamification design section; however, in terms of design, it is important to note each category corresponds to a single geomodelling technique and a single geomodelling concept. The **lessons** and **exercises** within the categories are ordered sequentially, meaning that to be eligible to access a lesson or exercise, all the previous lessons and exercises need to be completed.

Lessons
The lessons are a blend of traditional explanation and visualisation of a modelling technique through fit-for-purpose abstract visual models. The user is guided through theoretical geology concepts in the form of illustrated text, images and hyperlinks that are interwoven in the

educational content, which (when pressed) display an interactive plot. The plot highlights a specific theoretical concept through modifying parameters, data, configurations of the modelling algorithms, and the visualisation of their effects. The practice of modelling itself serves as an effective pedagogical tool for understanding mathematical concepts [2], and in my opinion, model interaction coupled with visualisation carries intrinsic educational value, because it allows a learner to confirm or correct their own mental visualisation. For example, given a lesson with the objective of teaching the effects of changing the smoothing factor of the B-spline in B-spline interpolation, would be followed by the user being instructed to interact with an abstract model highlighting the effects of changing the smoothing factor of a B-spline with a slider.

Exercises
On the other hand, exercises will be presented as an integrated environment of three types of questions:

- Plain multiple-choice questions
- Multiple-choice questions with model inspection
- Fully practical modelling questions

The multiple-choice questions serve as theoretical evaluations of the material covered, while the fully practical modelling questions are wholly practical tasks where the user is asked to interact with the model's parameters and configuration in order to induce a characteristic requested by the exercise. The user has a button to easily confirm the model configuration when they believe it satisfies the requirements of the exercise. The final configuration chosen by the user is evaluated by the application, based on per-exercise conditions on the model (i.e. value range checks). The multiple-choice question with model inspection falls right in between: just like in the fully practical questions, a button to launch a geomodel will be present, but instead of configuring the model and submitting it, the question will still be answered like a plain multiple-choice question. This form of question is used for model inspection and result interpretation rather than model configuration.
In order for the application to present the educational content in a comprehensible manner, it is necessary to keep complexity in other areas at a minimum. That is why, the application is bundled with a simple text and image-based tutorial, aimed at getting the user accustomed to and comfortable with the user interface of the application and the modelling windows, so that the learning process is not slowed down by the novelty of the system.

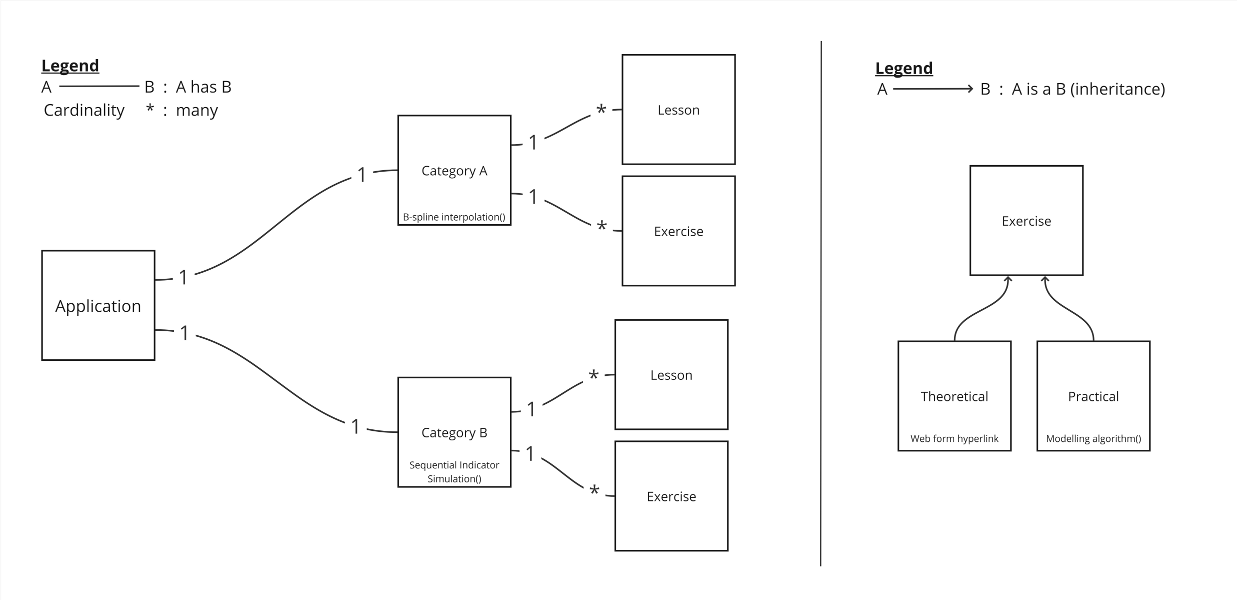

Figure 3: Conceptual system design diagram

4.3.2 Gamification Design

The remainder of this section is described according to Landers' framework [10] so as to keep standardised terminology. Furthermore, users will be referred to as students.
For this project, to pursue the endeavour of 'gamifying' a geomodelling tool, two 'gamification elements' are implemented, namely 'missions' and 'badges'.
The general system design is closely related to the gamification design: categories are instances of the 'missions' game element. By extension, missions contain a sequential series of lessons and exercises. Conceptually the missions are paths of lessons and exercises for the students to complete, in order for them to learn a major geomodelling concept. They are meant to give the students a direction to follow and a milestone to pursue. Thus this game element extracts the 'progress' game attribute

The missions will be:

- B-spline interpolation and Porosity
- Heterogeneity in Sequential Indicator Simulation

The student will be able to progress through both missions at the same time; however, the order of the lessons and exercises within them still needs to be respected. The student progress through the missions will be kept track of with a progress bar, where the 'goal of the game' is fully completing the mission.
The second gamification element that is implemented are 'badges'. Badges are virtual achievements, which in this case are meant to give recognition of one's achievements in their learning process. In this system, badges with different names will be awarded at specific milestones of the mission; for example, at the end of a mission, the 'mastery badge' of the geomodelling concept taught within the mission will be awarded.

Badges extract the 'rules/goals' attribute more strongly than missions do; in fact, badges are meant to supplement the 'progress' attribute of missions with the 'rules/goals' attribute. This ensures that students have a clear direction to follow and a specific goal to achieve.

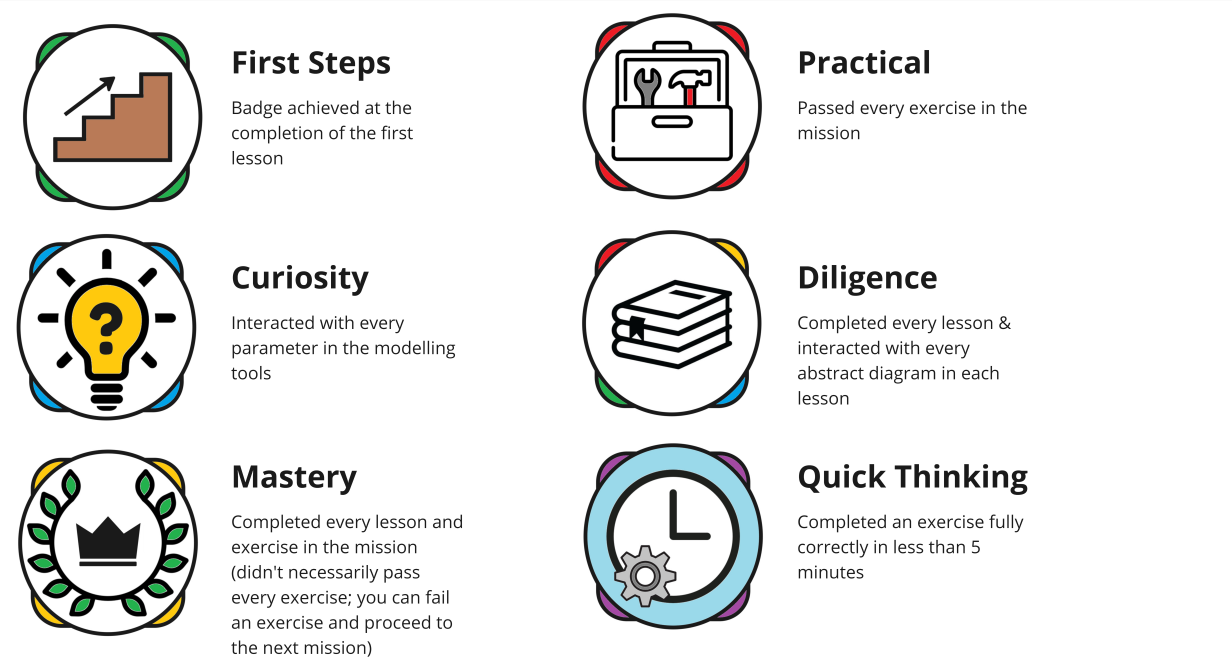

Figure 4: Final application Badges

Additionally, the geomodelling visualisation portion of the application extracts the 'control' game attribute by allowing the student to interact closely with the system, and the system changing the model based on the user inputs. Finally, exercises target the 'assessment' game attribute, providing the students with a way to measure their achievements within the game.

4.3.3 GUI Design

Missions

Missions are the first game element that the user interacts with when launching the application. The user is presented with the list of missions in the form of large horizontally arranged buttons.

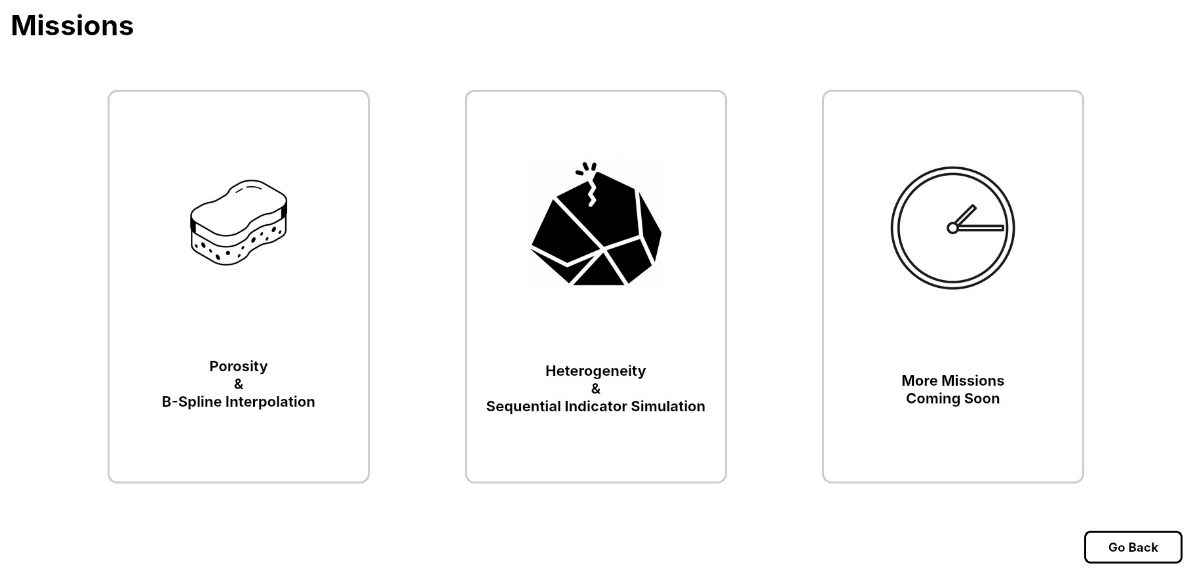

Figure 5: Mission list screen

When the user presses on a mission button, the mission screen is presented. On this screen, the game element is on display. The key graphical elements relevant to the mission are:

- Item list
- Mission progress bar

The item list consists of a sequential horizontal list of buttons, where each button is either a lesson or an exercise. An item can either be 'locked' or 'unlocked', which can be seen by the item icon being greyed out or coloured.

The mission progress bar fills up the more items are completed. At each item completion the progress bar is incremented which 'unlocks' the next item.

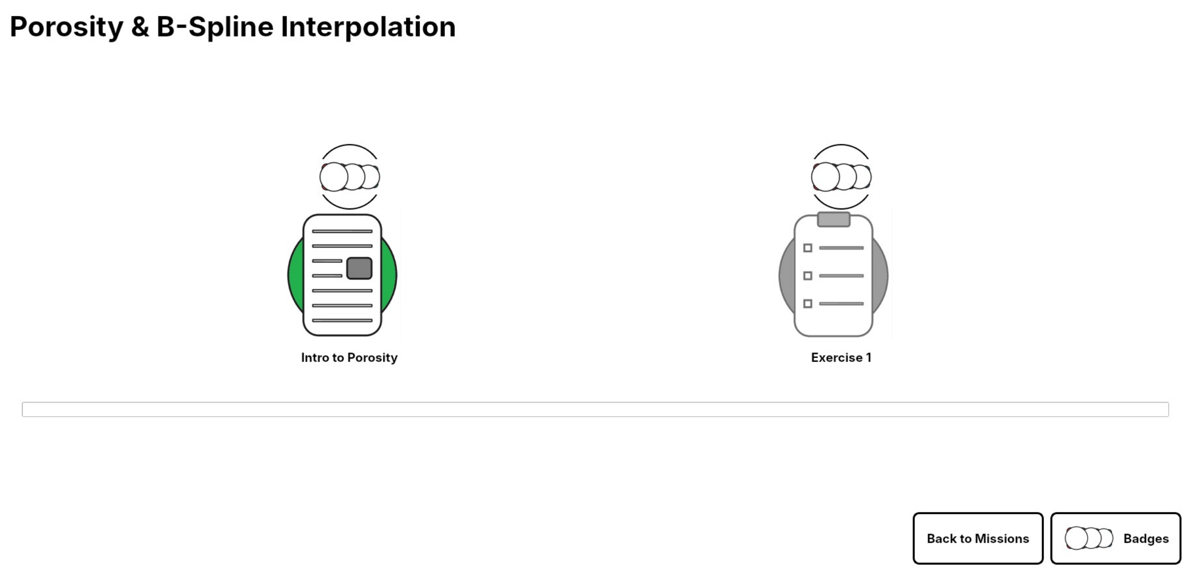

Figure 6: Mission screen

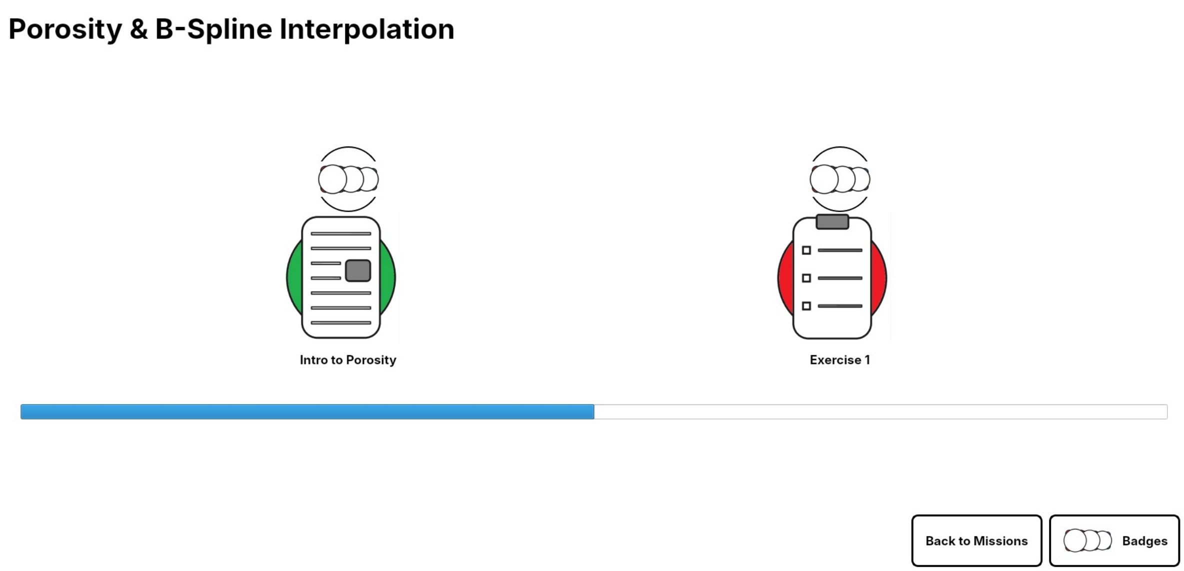

Figure 7: Mission screen, unlocked

Badges

Badges appear in the mission screen directly on top of the items that can potentially grant the student a badge. If an item can grant a single badge then the icon of the badge appears, whereas if an item can grant multiple badges then the 'badge list icon' appears. It acts as a button that can be pressed to open a 'scrollable' hovering section containing all the achievable badges in the item.
The badge icons on top of the items, whether it is a single badge or multiple, can be 'achieved' or 'not achieved'. The icons are coloured or greyed out accordingly, similar to the item icons. If an item is 'unlocked', the badges above it can be obtained, and trivially badges that appear above an item, which have not been 'unlocked' will also appear as 'not achieved' and cannot be achieved until the item is 'unlocked'.

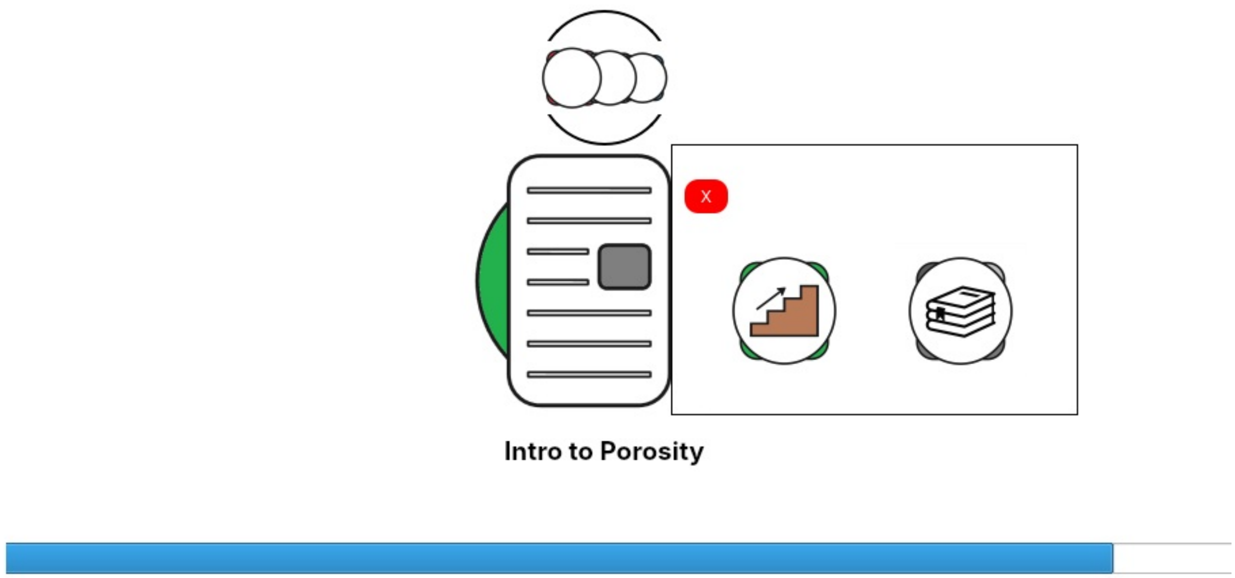

Figure 8: Multiple badges in a single item

In the bottom right corner of the mission screen, there is a button which takes the user to the badge list screen where an overview of all the badges in the mission is given, along with the badge name and description.

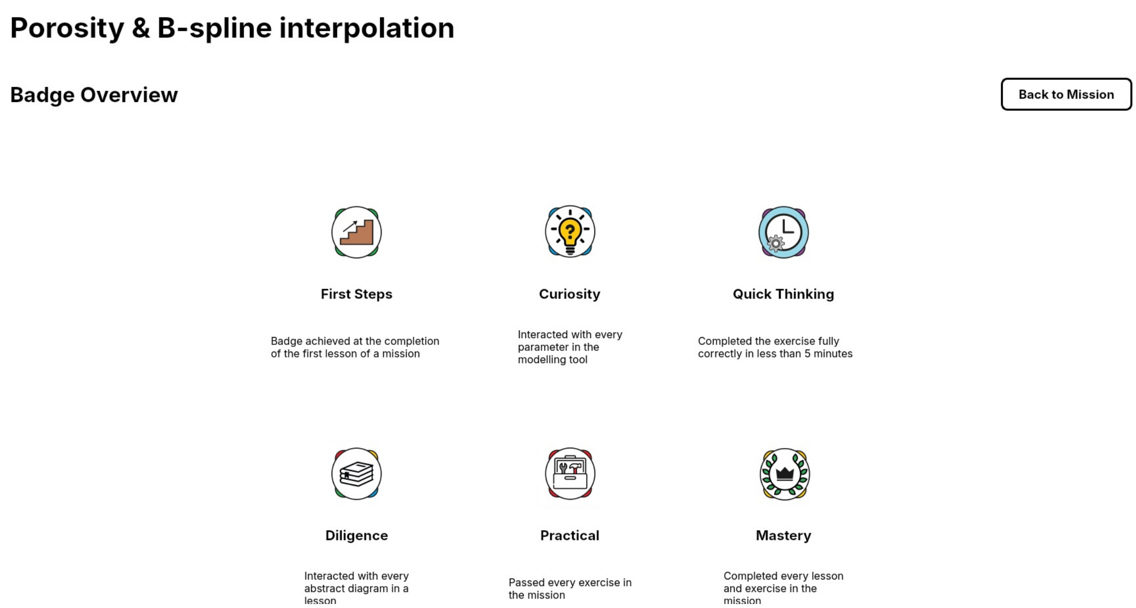

Figure 9: Badge List Screen

Lessons

The lesson screen is shown when the user presses on a lesson item in the mission screen. It is laid in two sections:

- Left-hand side - learning material
- Right-hand side - abstract models

The LHS contains the learning material which is comprised of text (headings, subheadings, body), illustrative images, LaTeX formulas, and hyperlinks.
Each lesson has a markdown file which contains all the aforementioned content. The application pulls the markdown from the file and converts it to HTML (using `markdown2` module) which is then rendered on the LHS. The LaTeX formulas in the markdown file are converted into temporary image files (automatically handled by Python's `tempfile` module). The hyperlinks, when clicked, can either lead to a URL or to an abstract diagram, which is then displayed on the RHS of the screen.

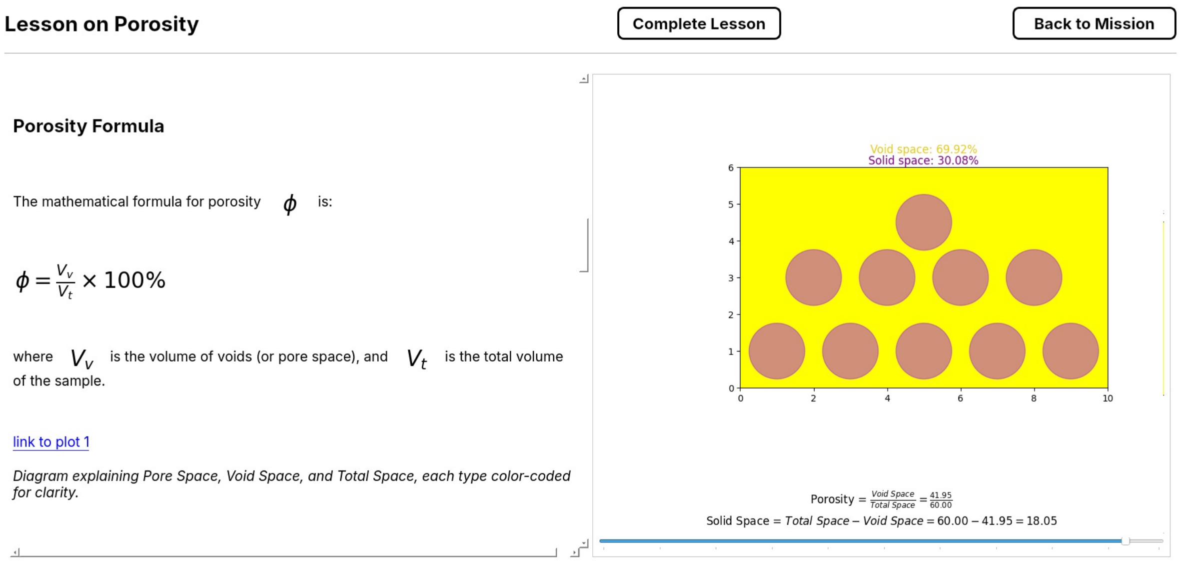

Figure 10: Abstract diagram

Finally, in the top bar above the LHS and RHS sections, the user can press the 'complete lesson button' at their own will, which then leads to the lesson completion screen where, notably, a list of the badges achieved within the lesson are displayed.

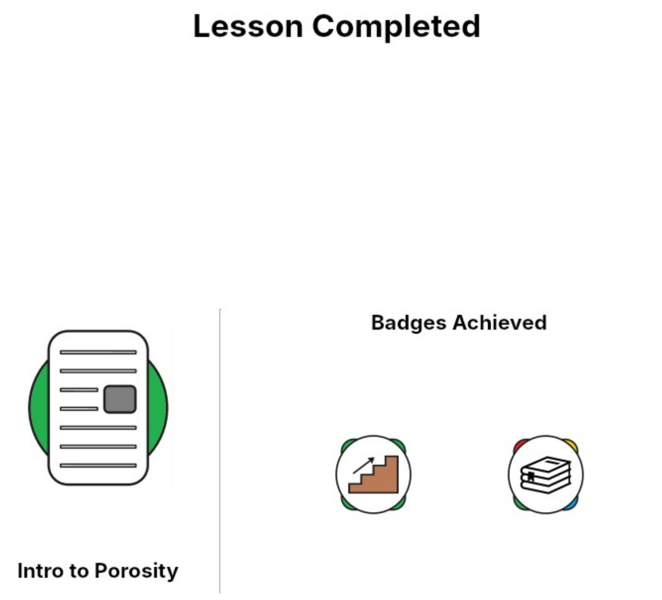

Figure 11: Lesson completed screen

Exercises

The exercise screen is accessed the same way as the lesson screen. It displays a simple screen of questions. The question titles, question descriptions, answer choices, model launching buttons, and images, are all extracted from .txt files of each exercise through text parsing functions.

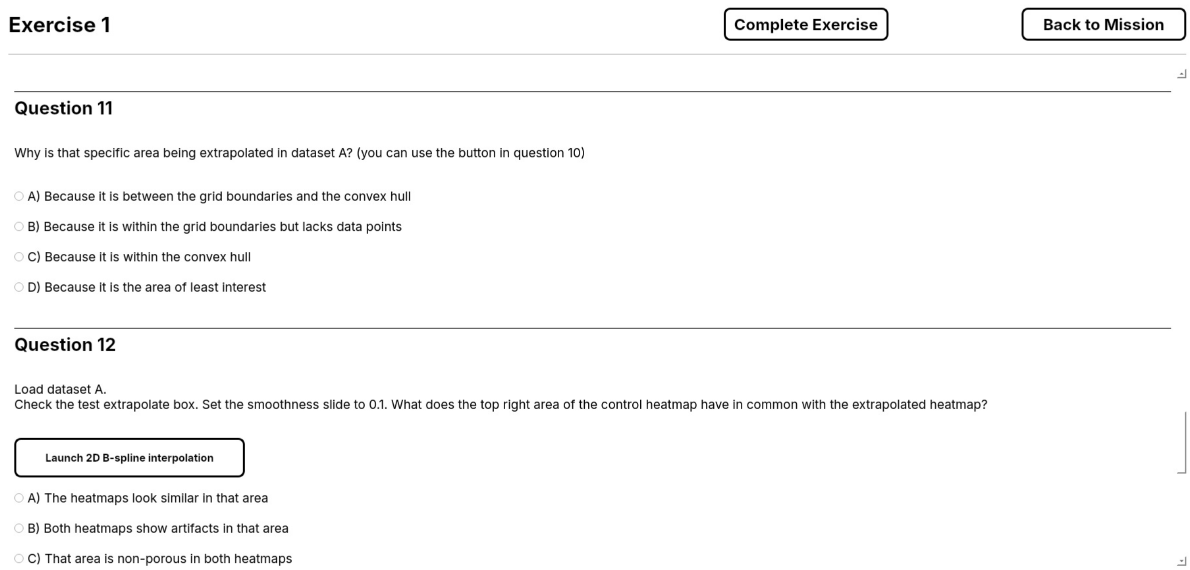

Figure 12: Exercise screen

Finally, just like in the lesson screen, the top bar contains the complete exercise button, which takes the user to a screen displaying the badges achieved in the exercise and the exercise score.

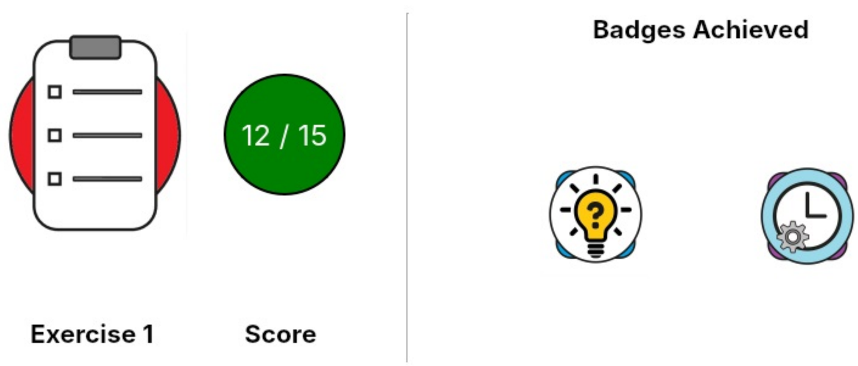

Figure 13: Exercise completed screen

4.3.4 2D B-spline Interpolation

The process for the 2D B-spline interpolation model, with an appropriate input CSV file as described in the data section, has the following stages:

- Create grid
- Spline fitting
- Visualisation

The grid is a two-dimensional `meshgrid` from `numpy`, made given a range and resolution for the x and y coordinates. A spline is initialised by passing the arrays of x, y, and *property* (where property is what is being interpolated) to the `scipy` function `SmoothBivariateSpline`, which returns a spline object. A value for the smoothing factor s is also required. Finally, the spline is evaluated on the grid. Once the interpolation is complete, the result is displayed with a heat-map using `pcolormesh` imported from the `matplotlib` library.

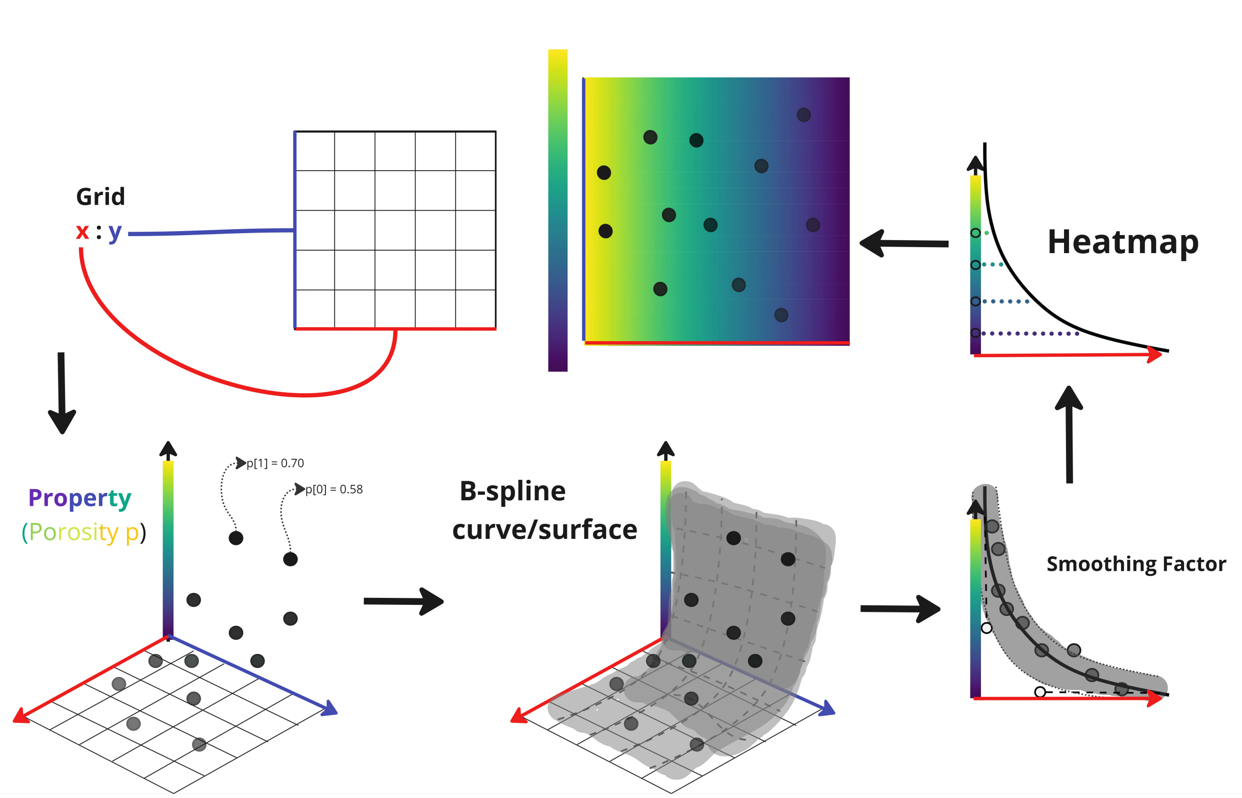

Figure 14: Visual depiction of 2D B-spline interpolation

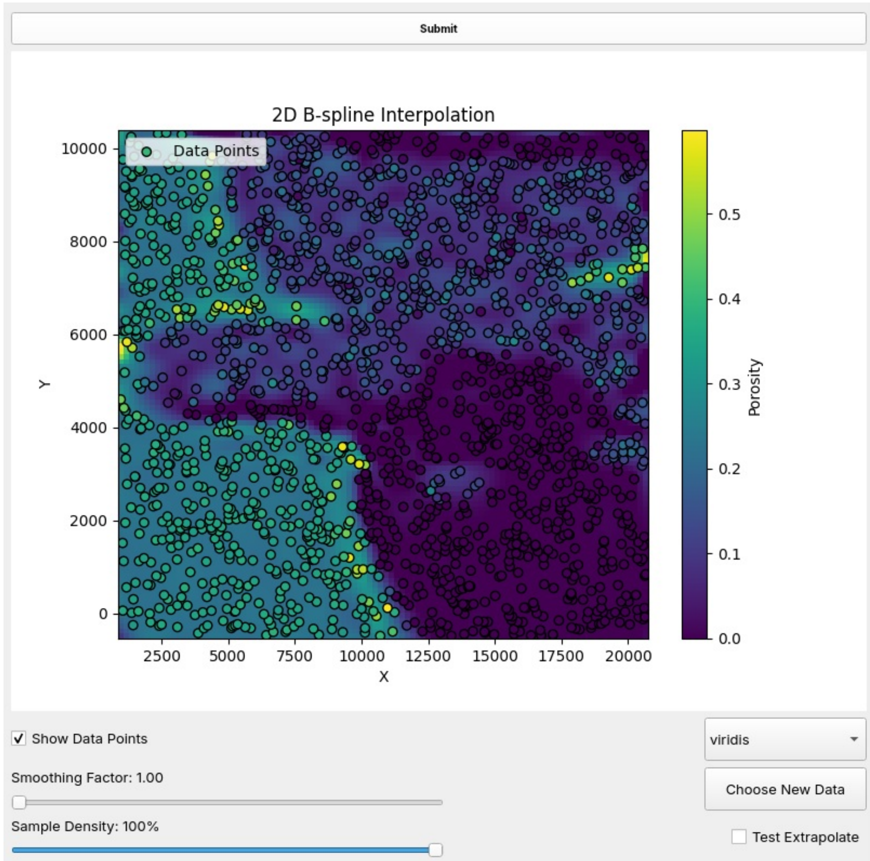

Figure 15: 2D B-spline window

The model also has the capability of overlaying the data points (coloured according to the heat-map's colour map), onto the spline plot. Furthermore, the model has a slider for the smoothness factor and a slider for the data sample density, which randomly reduces the percentage of data points of the dataset. Finally, the model has a checkbox which, when activated, selects all the points within a smaller convex hull smaller than the data set; a small external window appears, with a scatter plot of the points of the dataset being selected highlighted over the whole dataset. The subset of points selected is then used in 2D B-spline interpolation, and the resulting heat-map is placed side by side with the heat-map of the whole dataset. Notably, the grid that the spline of the reduced dataset is being interpolated onto, is the same grid used for the whole dataset, thus resulting in the borders of the heat-map being extrapolated rather than interpolated.

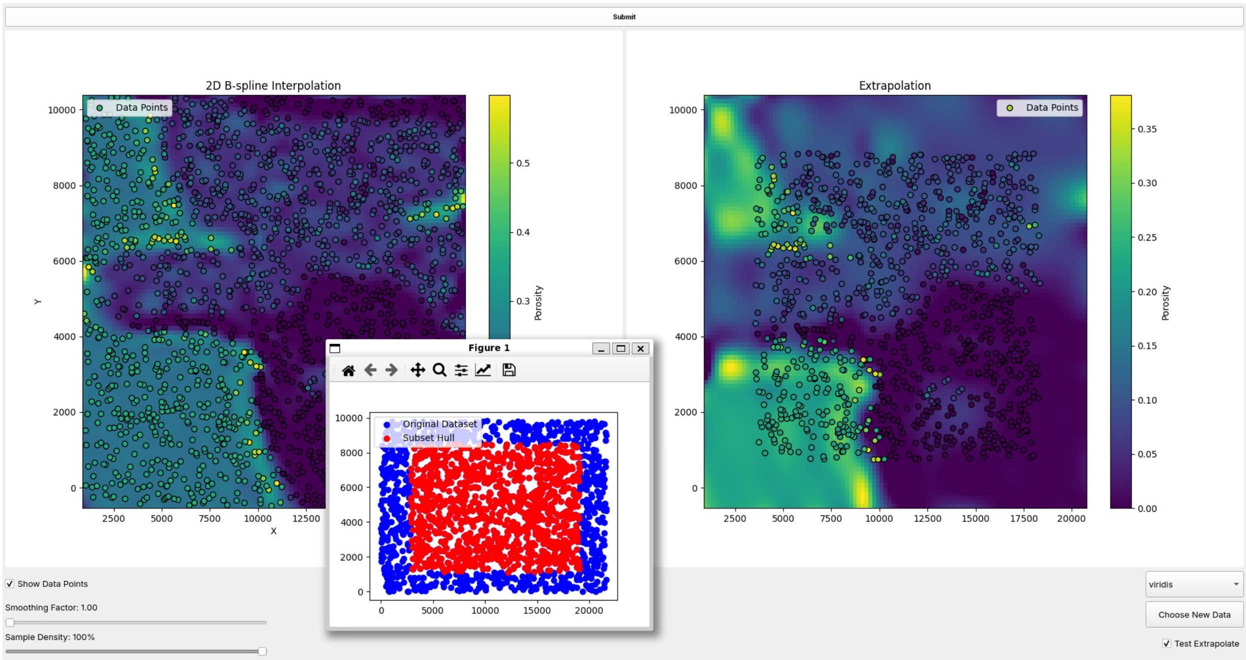

Figure 16: Extrapolation

4.3.5 3D B-spline interpolation

The process for the 3D B-spline interpolation model, with an appropriate input CSV file as described in the data section, has the following stages:

- Create grid
- Spline fitting
- Visualization

The grid is a three-dimensional grid made given a range and resolution for the x, y, and z coordinates. A regular grid is created over the spatial domain of the data exactly the same way as in the 2D B-spline model (the only difference being the added dimension). A spline is initialized by passing the arrays of x, y, z, and *property* to the `scipy.interpolate.Rbf` function, which returns a spline object. The Rbf function is used for radial basis function interpolation and requires parameters such as the function type and epsilon. The spline function is then evaluated on the grid, providing interpolated values at each grid point. Once the interpolation is complete, the result is displayed using `PyVista` for 3D volumetric rendering. A rectilinear grid is created using the interpolated values and grid coordinates. The interpolated values are then used to create a volume object through `PyVista`. Then, an opacity transfer function and a colour mapping are made in order to have varying levels of transparency based on the property value.

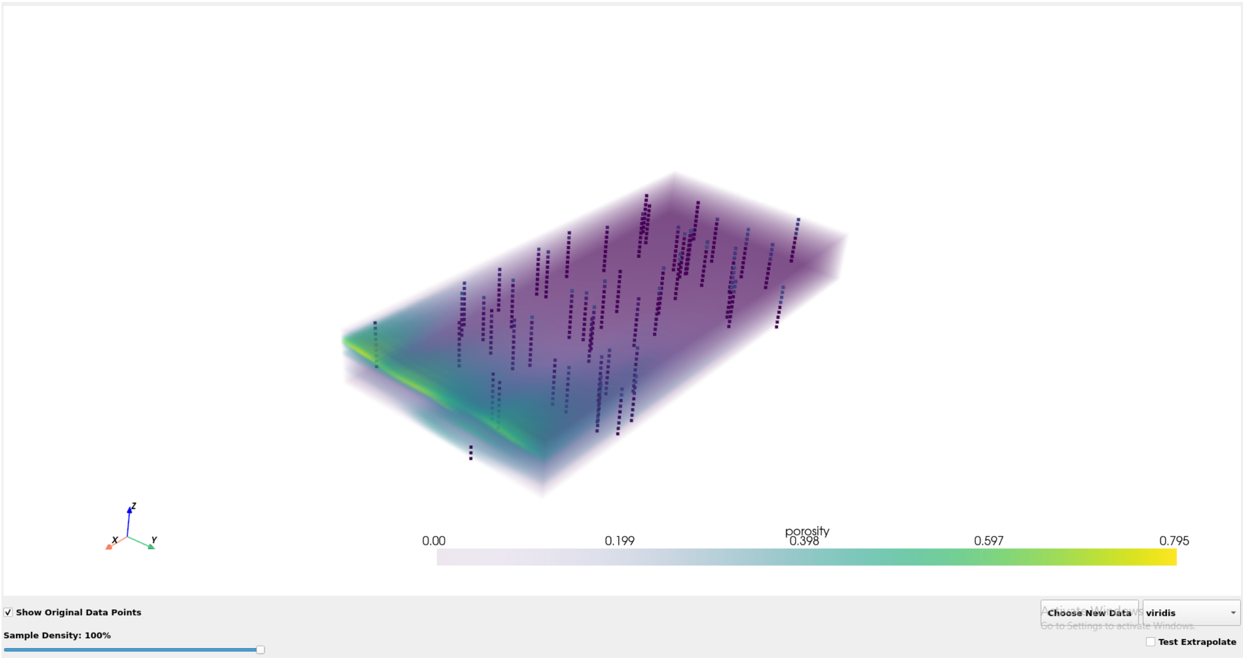

Figure 17: 3D B-spline window

The model also shares all the capabilities of the 2D B-spline interpolation model, except the smoothness slider.

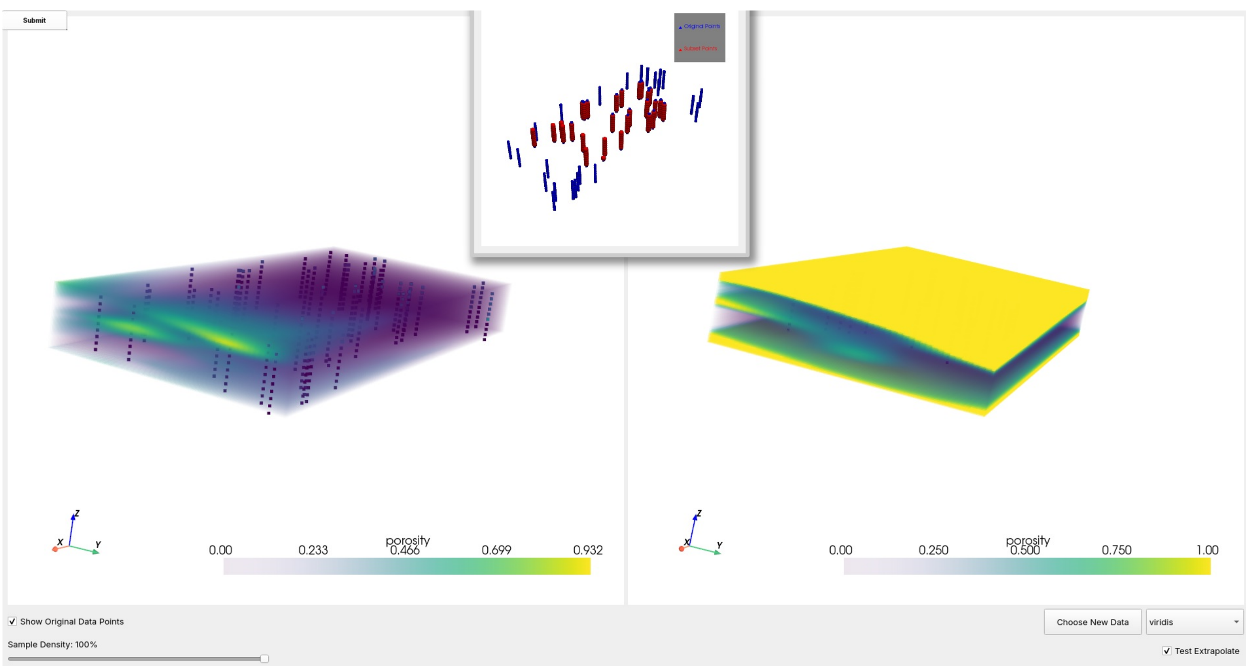

Figure 18: Extrapolation

4.3.6 Sequential Indicator Simulation (SIS)

The sequential indicator simulation model makes use of the GSLIB-based `geostatspy` library, written by Michael Pyrcz [12].
The first step is importing the CSV data and renaming the field names according to the algorithm's requirements. Secondly, there are numerous parameters to adjust, yet the most important are parameters about the facies (e.g. number of facies, global proportions). Before SIS is run, a variogram for each indicator is to be configured by calling `GSLIB.make-variogram`. Optionally a trend for the spatial distribution can be specified and passed into the simulation. The final step is performing the simulation realisations themselves and plotting them with a facies map (essentially a categorical heat-map) using `GSLIB.locpix-st` rather than a matplotlib heat-map. The user can specify the number of realisations, global proportions, search radius, and the colourmap.

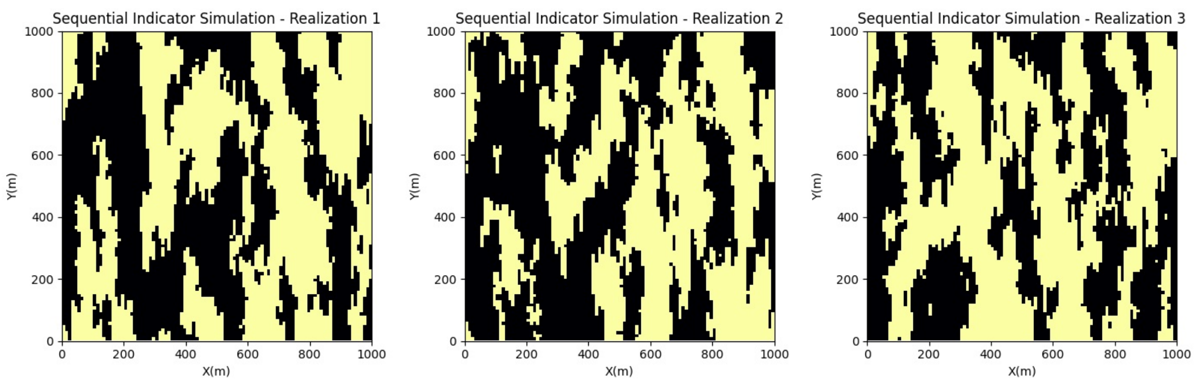

Figure 19: Sequential indicator simulation

4.3.7 Authoring System

The missions, lessons and exercises can be easily extended by a lecturer with minimal programming effort. All lessons must have their own directory, containing a markdown file with links to images and plots, the images themselves, and the Python scripts for the plots. The lecturer only needs to create the directories and place the aforementioned assets in them.
Similarly, exercises also must have their own directory, where the lecturer needs to create a simple Python class and three text files:

- questions.txt
- choices.txt
- answers.txt

The questions file contains question titles and question descriptions. The file should be formatted as follows (single line unless stated otherwise):

```
Question 1 Title
question body (multi-line)
END
Question 2 Title
question body (multi-line)
END
```

The choices file contains the possible choices for the multiple-choice questions, and indications of where buttons to launch models should be. The commands for the models are:

- model:2d b-spline interpolation
- model:3d b-spline interpolation
- model:sis

The choices file needs to be formatted the following way (single line unless stated otherwise):

```
A) option A
B) option B
C) option C
D) option D
END
model-command
A) option A
B) option B
C) option C
D) option D
END
model-command
A) option A
B) option B
C) option C
D) option D
E) option E
END
model-command
END
```

The first set of choices makes up a multiple-choice question; the second, a multiple-choice question with model inspection; the third, a fully practical modelling question.
The answers file, for the multiple-choice answers simply has a single line with the capital letter of the correct choice (e.g. A). The answers for the fully practical answers depend on the modelling tool being evaluated. For 2D B-spline interpolation, a line containing a list of exactly two lists of couples of integers defining ranges of values is expected.

The first list of couples determines the ranges of values that are marked as correct for the smoothness slider, whereas the second is meant for the density slider. For example [[(0, 703), (1000, 1200)], [(10, 500)]], means that correct configurations for the 2D B-spline interpolation model have the smoothness slider s and the sample density slider sd in $0 \leq s \leq 703 \vee 1000 \leq s \leq 1200 \wedge 10 \leq sd \leq 500$. When one of the lists is empty [ ] it means that there is no requirement for that slider. The answers text file is then easily encrypted with a Python script so that the students cannot see the answers or modify them (symmetric key and cryptographic signature).

More crucial constraints of the authoring system are listed in the appendix. These constraints can largely be ignored by creating a simple Python script that automates the process.

5 Results

Firstly the raw results of the user study will be laid out, followed by statistical tests and if the hypotheses are rejected or not.

The exercise the participants had to complete has the following answers:

1. B
2. C
3. C
4. C
5. C
6. C
7. B
8. B
9. B
10. B
11. A
12. B
13. $0 \leq s \leq 703$ | where s : smoothness slider
14. $2727 \leq s \leq 10000$ | where s : smoothness slider
15. $1100 \leq s \leq 4200$ | where s : smoothness slider

Questions 1 to 9 are multiple-choice questions, 10 to 12 are multiple-choice with model inspection, and 13 to 15 are fully practical modelling questions.

The results collected from the user study are:

Question Number	Participant A	Participant B	Participant C	Participant D
1	B	B	C	B
2	B	B	C	C
3	C	C	B	C
4	C	C	C	C
5	C	D	C	D
6	C	C	C	C
7	B	B	B	B
8	A	C	B	B
9	B	B	B	B
10	B	D	B	B
11	A	A	A	B
12	D	B	B	B
13	Incorrect	Incorrect	Correct	Incorrect
14	Correct	Correct	Correct	Incorrect
15	Correct	Incorrect	Correct	Incorrect

Badges	Participant A	Participant B	Participant C	Participant D
First steps	Yes	Yes	Yes	Yes
Diligence	Yes	Yes	Yes	Yes
Quick Thinking	No	Yes	No	No
Curiosity	Yes	No	No	No

Qualitative survey results:

Question	Responses
What is your level of study?	• Postgraduate • Undergraduate (Bachelor's) • Undergraduate (Bachelor's) • Undergraduate (Bachelor's)
Are you in a field related to geology?	• Yes • No • No • No
Do you have any predispositions or dislikes about gamification and/or games?	• I teach it. • no • Games are great, let them be there. As long as the game does not begin to feel like just another lecture material, everything is great. • I like the idea of gamification and I think it can be very beneficial. I also love Videogames so that helps
Did you encounter any difficulties while using the tool or during setup?	• It does require some boot-up time, but apart from that, all is fine. • none, worked properly • The tool worked fine! • No not at all

Question	Responses
How easy was it to use the geomodelling tool? 1 is easy, 5 is difficult	• 1 • 1 • 1 • 1
Did the gamification elements make the tool any harder to use?	• No • No • No • No
Did the gamification elements (badges and missions) affect your ability to use the tool?	• Positively • Neutral • Neutral • Positively
Please describe the attitude you had towards the gamification elements (missions/badges). Were you enthusiastic?	• I like the progress bar, which gives an indication of going-forward. I like the badges and the badge design. I liked the interactive elements at the associated places. • It's nice to see progression milestones. I wasn't jumping out of my seat over them but they're cool • Can't describe myself as enthusiastic, however, the idea of badges and "accomplishments" captured my attention. It made the idea of working more engaging. It felt a bit like unlocking the achievements on Steam games, which is always a great feeling. • I thought it added a fun aspect to learning and allowed for a sort of milestone which you can work towards too. It definitely did not feel the same as learning normally would and I enjoyed it more this way.
How did the badges impact your overall experience with the tool? In terms of engagement.	• Very positively • Positively • Positively • Positively

Question	Responses
How did the mission(s) impact your overall experience with the tool? Despite their minimal functionality demonstrated in the user study.	• Positively • Positively • Positively • Positively
Did you feel motivated by the gamification elements to complete the tasks?	• Yes, very motivated • Neutral • Yes, somewhat motivated • Neutral
Do you think the gamification elements were intrusive?	• No, not intrusive • No, not intrusive • No, they enhanced the experience • No, not intrusive
Additional Comments	• highlight the "submit" button on the models, it took a minute to find. Please have the graphs slide up when scrolling the lesson, they shouldn't stay on the screen when going down. Badges were cool, maybe show the badge name when gotten so I know what I just achieved. • Keep up the good work!

Lastly, none of the participants chose to stop the user study before completing it.

Analysis

Retention of Mathematical Principles

Some questions ask about material covered visually and interactively within the lesson (using abstract visual plots), and others about material only covered theoretically.

- Questions covered theoretically : 1, 5, 7, 8, 9
- Questions covered visually : 2, 3, 4, 6

Questions 10 to 15 are excluded from this categorisation because their content is covered theoretically, however it is assessed visually, making them hard to compare as there are two critical variables.

Thus, this section focuses solely on multiple-choice questions. Given the hypotheses, the measurement approach, and the analysis strategy described in the experiment setup (sections

3.1.1 and 3.1.2), the statistical significance of the differences in the scores between theoretical and interactive questions is determined.
Each correct answer is marked with a 1 and wrong answers are marked with a 0.

Question Number	Participant A	Participant B	Participant C	Participant D
1	1	1	0	1
2	0	0	1	1
3	1	1	0	1
4	1	1	1	1
5	0	0	0	0
6	1	1	1	1
7	1	1	1	1
8	0	0	1	1
9	1	1	1	1

Table 4: Scores by Participants

Average Scores

Participant	Scores	Average Score
A	1, 0, 1, 0, 1	0.60
B	1, 0, 1, 0, 1	0.60
C	0, 0, 1, 1, 1	0.60
D	1, 0, 1, 1, 1	0.80

Table 5: Average Scores for Theoretical Questions

Participant	Scores	Average Score
A	0, 1, 1, 1	0.75
B	0, 1, 1, 1	0.75
C	1, 0, 1, 1	0.75
D	1, 1, 1, 1	1.00

Table 6: Average Scores for Interactive Questions

A paired-sample T-test is used to compare the scores between theoretical and interactive questions for the mean of each participant.

- **T-statistic :** -13.000000000000018
- **p-value:** 0.000982801897719439

Furthermore, to analyze the combined effect of the number of badges and the distinction between theoretical and interactive questions, multiple regression analysis is performed.

	coef	std err	t	P>|t|	[0.025	0.975]
const	0.3463	0.119	2.901	0.034	0.039	0.653
Badges	0.0675	0.025	2.697	0.043	0.003	0.132
Question_Type	0.1625	0.056	2.904	0.034	0.019	0.306

Impact of Gamification on Usability
The results of the survey give insight into the perceived usability of the application, and how it is related to the game elements.
The following questions are about usability:

- Did you encounter any difficulties while using the tool or during set-up?
- How easy was it to use the geomodelling tool? 1 is easy, 5 is difficult
- Did the gamification elements make the tool any harder to use
- Did the gamification elements (badges and missions) affect your ability to use the tool?

None of the responses indicate any form of difficulty induced by the gamification elements. The only feedback was about the initial boot-time of the application which is entirely implementation dependent, and more importantly, it only occurs in the set-up phase of the application. The application is deemed to be the easiest it can be by all participants.

Enhancement of User Experience through Gamification
The results of the survey give insight into the perceived user experience of the application, and we also consider the participants' exercise score, the number of badges achieved, and whether they quit the user study or not.
The following questions from the survey, are about the user experience:

- Please describe the attitude you had towards the gamification elements (missions/badges). Were you enthusiastic?
- How did the badges impact your overall experience with the tool? In terms of engagement.
- How did the mission(s) impact your overall experience with the tool? Despite their minimal functionality demonstrated in the user study.
- Did you feel motivated by the gamification elements to complete the tasks?
- Do you think the gamification elements were intrusive?

Scores:

Participant	Scores
A	11
B	8
C	13
D	10

All participants achieved a passing grade of fifty percent. All participants achieved the first two badges, available in the lesson. Participants A and B achieved another badge each from the exercise. All participants completed the entire user study.

6 Discussion

As an opening part of the discussion, we return to the stated hypotheses, considering the significance tests that are previously shown. The hypothesis evaluation provides answers to the inciting research question: *"How does the integration of computer visualisation and gamification elements, such as 'Missions' and 'Badges', influence undergraduate geology students' understanding of geological modelling and associated mathematical principles?"*

6.1 Experiment Evaluation

Retention of Mathematical Principles
Null Hypothesis (H0): The integration of gamification elements and visualisation in geomodelling tools does not increase the retention of mathematical principles.
Alternative Hypothesis (H1): The integration of gamification elements and visualisation in geomodelling tools increases the retention of mathematical principles.

The analysis compared the scores from theoretical questions to those from interactive questions. The paired-sample T-test returns a T-statistic of -13.00 and a p-value of 0.00098, indicating a statistically significant improvement in scores for the interactive questions. Furthermore, the multiple regression analysis shows that both the number of badges and the type of question (interactive vs. theoretical) have significant positive coefficients, suggesting that gamification elements contribute to better performance.

The results indicate that the combination of gamification elements with visualisation enhances the retention of geomodelling content and mathematics (the null hypothesis is invalidated).

Impact of Gamification on Usability
Null Hypothesis (H0): The integration of gamification elements increases the usability of geological modelling tools for undergraduate geology students.
Alternative Hypothesis (H1): The integration of gamification elements decreases the usability of geomodelling tools for undergraduate geology students.

Results indicate that the gamification elements do not cause difficulty for any of the participants. All participants rate the tool's ease of use as '1' (easy), and no one reports that the gamification elements make the tool harder to use. However, two of the four participants state that the game elements affected their ability to use the tool to a neutral degree, whereas the other participants value them as a positive impact. I suspect this is partly because the tool itself is already so simple that the game elements could not make it much easier to use than it already is.

The findings support the null hypothesis. Participants perceive the tool as easy-to-use, and do not find the gamification elements to introduce difficulty. This suggests that gamification elements can be utilised in educational settings and workspaces, without compromising ease of use.

Enhancement of User Experience Through Gamification
Null Hypothesis (H0): The integration of gamification elements does not enhance the user experience of geological modelling tools for undergraduate geology students.
Alternative Hypothesis (H1): The integration of gamification elements enhances the user experience of geological modelling tools for undergraduate geology students.

Results indicate that participants had a positive attitude towards the gamification elements even before the experiment; this is crucial since a predisposition against gamification would immediately make it significantly less likely for the participant to have a positive experience with the tool. All participants complete the user study fully, thus indicating that the tool keeps them engaged throughout the entire study. All participants reported that badges and missions positively impact their overall experience with the tool, however, results regarding motivation range from feeling neutral (in terms of motivation) to being very motivated, making it very difficult to gain insight due to the small number of participants. All participants achieve a passing grade, despite most of them not being in a field related to geology. The lowest score is achieved by a student in a field outside of STEM, and this participant is the only one to achieve the quick thinking badge, suggesting a drop in attention when answering the exercise questions.

The findings do not support the null hypothesis, suggesting conversely that gamification elements enhance the user experience. While the responses do not give consistent opinions on motivation, the positive feedback on the badges and missions indicates that these elements make the learning process more enjoyable and engaging.

The leading research question is broken down into two sub-questions:

1. "What percentage increase in retention of mathematical principles used in geological modelling is observed among students after interacting with 'Missions' and 'Badges'?"

   The results show a significant improvement in retention of mathematical principles, as evident by the higher scores on interactive questions compared to theoretical ones. The number of badges achieved appears to enhance the retention of the instructional content.

2. "How do users describe their experience with the integration of game elements in terms of ease-of-use and engagement? What percentage of users report a positive impact on their experience compared to an equivalent tool without game elements?"

   Test participants report that the gamification elements increase usability, and describe their experience as more engaging but not necessarily motivating. All participants indicate a positive impact on their experience due to the gamification elements. Although these results are inconclusive they do affirm that the experiences are positively impacted by gamification, meaning that if it were to be removed, the experience may be worsened.

The user study is limited by the target audience of undergraduate geology students being underrepresented. This necessitates further user studies. Ideally, they should prototype the tool within an actual geomodelling course environment.

6.2 Limitations and Improvements

The biggest limitation of this project is the user study. Within its 30 minute duration limit, the participants of the user study cannot experience all the game elements, which are long-term features. Furthermore, the absence of a control group, using traditional geomodelling study material, is also a critical shortcoming. To mitigate the first issue, the badges were modified to better fit the short time scale, so that participants could experience a meaningful amount of badges. Other caveats of the user study are the very small number of participants and the lack of any participants from the target audience. Thus, I emphasise that the small sample size and the lack of representation from the target demographic necessitate caution when interpreting the findings. Future studies should aim to include a larger, more representative sample of undergraduate geology students.

In terms of implementation, the main limitation of the system is that the authoring system does not yet allow for easily extendable badges and badge logic. Currently, badges can easily be added to a specific item. However, adding new badges needs some involved programming. For future implementations, this is the primary feature to change. The second known limitation is the entanglement of JSON files in both user-activity tracking and the authoring system, which can lead to file conflicts. This could be solved by splitting the JSON file into multiple files, thus decoupling the program.

In terms of new features, new gamification elements could be introduced, more instructional content can be added, and a program with GUI for lecturers and instructors to effortlessly add content can be made.

6.3 Future Work

This project could be utilised to conduct further research in gamification. More game elements, such as a leaderboard and better sound design, could be added to the tool. A study on which game elements are most effective in geomodelling education, yet also education in general, could be held. A leaderboard could be added within each mission, and it could pull the student performance from the mission and use it to rank students on the leaderboard.

Another idea is for the application to be further developed and refined for it to be used in a university class. The authoring system could be improved by creating a program with a GUI program, which would handle the file naming constraints of the authoring system to turn the process of extending instructional content from simple to effortless. Moreover, a system for a lecturer to remotely update the application of all classroom students, along with seamlessly submitting exercise results to the lecturer, form a suite of features that would make the application fit to be used in a university class. This would make it simple to run a study on the effectiveness of the application in and undergraduate geology classroom. By doing so this project's results could be validated.

For that matter, the application could even be used to teach any subject that benefits from visual education. The lessons can be used to display the instructional content, and the plots can be used to visually display concepts from other subjects. The geomodelling windows can be replaced with subject-specific practical exercises. For example, if the tool were to be used for education in computer science, a fully practical exercise could consist of a window with a simple code editor from which small code snippets could be run (using `Jupiter notebook` cells for example)

6.4 Lessons Learnt

The library used for the project's GUI is `PyQt`, which is more modern and rich in features than `Tkinter`. The modern look was the main reason because I think the look and feel of the application needs to be inviting to the students rather than driving them away with 'legacy-looking' UI elements.

The B-spline interpolation algorithms were done using the scipy library because the parameters of the functions used were very well documented: for example, the implementation and parameters of the `spline` function are documented, yet they are also explained mathematically.

For the volumetric rendering of 3D B-spline interpolation, I used `PyVista` over other simplistic implementations in scipy. This is because scipy does not perform true volumetric rendering and can produce visual artifacts, whereas `PyVista`, based on `VTK`, which is made specifically for computer graphics tasks like 3D rendering, offers real volumetric rendering capabilities.

To implement the SIS algorithm I used the `Geostatspy` library. It has been developed by M. Pyrcz to interface `GSLIB` into Python. `GSLIB` is a professional tool specifically designed for geomodelling, in Fortran. It is capable of performing several geomodelling algorithms, including 3D SIS which could be implemented in this project in the future. In summary, all the libraries used were easy to learn and use, except the volumetric rendering which had a few deprecated objects which I needed to replace. The SIS algorithm was not difficult to set up since the repository of M. Pyrcz contains demos for most of the modelling algorithms; however, the algorithm has many parameters and requires you to generate variograms from the input data.

Programming in Python made data manipulation and file creation extremely easy, however finding a solution to structuring the menus of the application was a challenge. The current implementation in `PyQt` does not seem optimal, and I suspect it to be the cause of the short delays that occur when switching between certain screens.

In terms of the extensibility of content, adding new missions, lessons, exercises and datasets is all made trivial thanks to the authoring system. The current B-spline interpolation algorithms interpolate the porosity field, however it could easily be changed to interpolate any other discrete numerical geological property in the datasets. An easy solution that does not require programming is to change the field name of the property one wishes to interpolate to 'porosity'. A more practical solution would be to add a second dialog option to choose a specific field in the dataset when importing it.

7 Conclusion

This thesis details the development of a geomodelling visualisation tool, enhanced with game elements, and explores their effects on students' learning outcomes. Despite the limitations of the experiment, the findings provide valuable insights.

The primary research question was split up into sub-questions addressing key elements of gamification theory: retention of instructional content, usability, and enhancements to the user experience. The results show a considerable improvement in the retention of mathematical principles when gamification elements and visualisation are combined, suggesting that gamified, visual, and interactive learning enhances retention.

In addition, the findings on usability support that gamification elements increase the usability of geological modelling tools. In the qualitative survey, participants reported positive attitudes towards the badges and missions. All participants completed the user study, ensuring some level of engagement at a minimum. Although opinions on added motivation varied, qualitative feedback, in addition to their exercise scores, and number of badges collected indicate that the gamification elements make the learning process more enjoyable and engaging.

Despite the study's limitations, namely the absence of a control group and the lack of representation from the target audience, the results provide preliminary evidence that gamification elements can enhance can improve learning outcomes in geomodelling tools. However, future studies should include a larger sample of undergraduate geology students, and a longer-term schedule (possibly a couple of months of use in a university classroom), in order to validate these findings and provide more definitive conclusions.

In conclusion, the project has contributed an educational desktop application, capable of performing and visualising geomodelling algorithms (specifically: B-spline interpolation and SIS), and teaching them in a comprehensible way through the use of interactive and visual lessons, all enhanced by carefully implemented gamification elements.

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8 Appendix

Authoring System Constraints

- The plots need to be in the form of python files containing a python class inheriting from the abstract class 'BasePlot'. The class name must be the same as the file name, except the class name has to be in 'PascalCase' and the file name needs to be in 'snake case'.
- Lesson directories needs to have the same name as the lesson title, but it needs to be in 'snake case' followed by '_material'.
- Lesson markdown files follows the same naming convention as the lesson directory name, without the added '_material' string.
- Exercises should be named as follows: 'Exercise x' where x is the exercise number.
- Exercise directories should be named as follows: 'exercisex_material' where x is the exercise number.
- To add an image to a question, add the image to the exercise directory with the name 'x_name' where x is the question number and name is arbitrary. Just avoid other underscores.
- Mission directories need to have the same name as their associated mission, but in snake case and without any newline characters.
- Mission names must be added in the correct order to the 'mission_names.txt' file.
- A Mission JSON object needs to be appended to the 'user_progress.json' file. The JSON file needs to first be decrypted, modified, and encrypted.