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Interactive Particle Track and Trace in the North Sea

Bachelor's Project Computing Science

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Abstract

Cargo loss from container ships in the English Channel threatens the ecology of the Dutch coastline. Public awareness is crucial for enacting relevant policies. This project investigates gamification, a method to increase user engagement, to raise public awareness of ocean debris. By focussing on reward schemes, a common gamification element, the project aims to qualitatively evaluate the impact of rewards on user engagement. We implement two interaction schemes, one with a reward scheme and one without, and compare those via a set of criteria that qualitatively evaluate interaction discovery and insight generation. We find that the reward interaction scheme had more permutation interactions and mental models that the user could identify and internalise than the base interaction scheme. Gamified science communication for North Sea ecological issues is a promising avenue for increasing public awareness.

Acknowledgments

I would like to extend my sincere thanks to my supervisors, Dr Christian Kehl and Dr Laura Gomez Navarro, for their invaluable guidance, feedback and support throughout the writing and learning of this proposal. I also thank Djairo Hougee for working with me on the base visualisation and simulation. I thank my peers who gave ideas, tested and gave feedback for the gamified interaction scheme and Laura María Quirós Conesa for help with some early designs and for listening to endless complaints about software difficulties.

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1 Introduction

The English Channel is a high traffic area for passenger and cargo ships. It separates the British Isles from mainland Europe and allows maritime freight transport between Scandinavia and the rest of Europe. This makes the Dutch coast a highly visited port hub for cargo ships. The Netherlands transport the highest gross weight of goods to and from ports in the EU [12]. Moreover, the four ports with the highest gross weight handled in the EU are all around the Dutch coast in Rotterdam, Antwerpen, Hamburg, and Amsterdam [9]. This freight throughput produces high maritime activity around the Dutch coast. See Figure 1 for a visualisation of the vessel ways in this area.

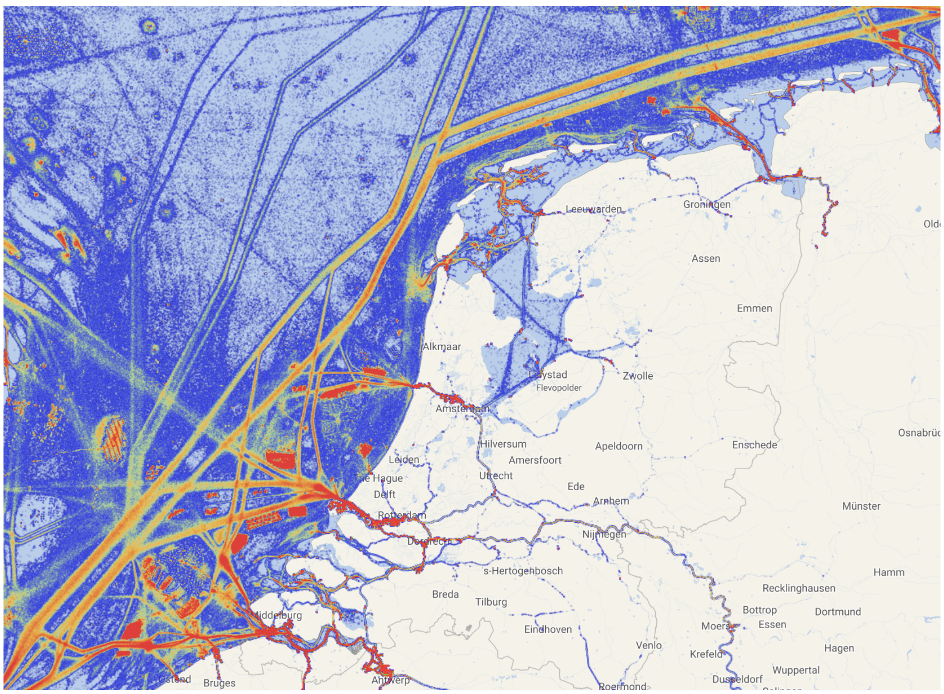


Figure 1: Density heatmap of vessels in the North Sea. Light blue is the lowest density area and dark red is highest density area of vessels in the North Sea. Visualisation from vesselfinder.com

Simultaneously, the Dutch coast, in particular the Wadden Sea, is an ecologically important and diverse region. It is important to migratory birds [4], phytoplankton [34] and fish [41]. There are many other stakeholders who are affected by the Waddensea in the sectors of medicine, tourism and energy [13]. It was made a World Heritage Site in 2009 due in part to this biodiversity as well as its supposedly undisturbed natural processes [17]. This status as a World Heritage Site implies that the Wadden Sea should be preserved for future generations.

Cargo is sometimes lost from container ships. For example, 270 containers fell off the *MSC Zoe* Panama-registered ship because of a storm in 2019. Debris from this incident was found washed up on the shores of 5 Dutch islands Texel, Vlieland, Terschelling, Ameland and Schiermonnikoog [30]. Due to the high number of vessels travelling through the area, these accidents are bound to happen again, as it did in 2023 to the *Freemantle Highway*. These accidents produce maritime debris that float to the coast. This causes harm to the ecology of the Wadden Sea [42, 15]. In particular, migratory birds can eat the plastics floating to shore [5, 4]. Additionally, marine transportation produces other negative environmental effects such as air pollution and oil and chemical spills [44]. The academic community has made many analyses on policy proposals [13]. Policies exist that could limit this harm, however they are not currently implemented [37]. Public awareness can generate political pressure that could bring about these policies. Science communication will therefore be important for increasing public awareness of this issue.

Gamification is the increasingly popular application of game mechanics to increase user engagement and hence increase public awareness. An encouraging interaction model could increase user interest for those interacting with the simulation as well as passers-by. Many schemes exist to promote user interest. One such scheme is the reward scheme, which involves keeping track of some form of score of the players and increasing it when the user interacts with it in the desired way [31]. A study on ocean literacy gamification concluded that reward schemes produce higher user engagement than more traditional interaction schemes [25].

Contributions

Our project answers the following research question:

How does a dedicated interaction-reward scheme impact the engagement with a visual simulation of floating marine debris?

This research question leads to the following contributions:

- a real time interactive visual simulation of marine litter
- a dedicated interaction-reward scheme for the visual simulation

2 Literature Review

This section begins by outlining the prevalent techniques in particule transport in fluids and evaluating their suitablity towards a realtime interactive ocean simulation. Next, we give context for the use of gamification in scientific educational applications through the lens of five principles of effective gamification, which informs our own gamification approach. Lastly, we put a spotlight on qualitative evaluation metrics for interaction schemes, which indicate possibilities to review and assess our approach without the need for extensive user studies in conclusion to this thesis.

2.1 Ocean Modelling and Litter Transport

Simulating ocean debris will require computing the trajectory of particles in a fluid. There are three principal methods for computing this. Firstly, the Eulerian perspective for this computation specifies fluid flow by discretising the considered region into a matrix. In this framework, particles are represented by a probability distribution function and the transport is represented by the flux i.e the change in probability in one timestep for each cell in the matrix. This technique has been used to communicate the formation of oceanic garbage patches to the general public [39, 43].

Secondly, the Lagrangian perspective for computing the transport of particles in a fluid specifies fluid flow by defining a set of particles and their displacement in the fluid through time. In that framework, the transport of simulated particles is intuitively represented by the end positions of those particles after some elapsed time. The predominant particle method within this domain is Smoothed Particle Hydrodynamics (SPH) [27]. This method is used extensively in coastal and ocean engineering [14].

Finally, methods based on a combination of Eulerian and Lagrangian perspectives are used for computing particle transport. This involves numerically integrating Lagrangian particles over a precalculated Eulerian velocity field with respect to time. This provides a Lagrangian answer to the question of particle transport in a fluid without performing SPH. The Eulerian velocity field of the oceans is computed by solving the Navier-Stokes equations taking into account conservation of energy and heat/salt flux with appropriate boundary conditions. The Nucleus for European Modelling of the Ocean (NEMO) is one framework for computing these Eulerian velocity fields [28]. Parcels is a numerical Python library for performing Lagrangian integrations over ocean velocity fields [23]. Ocean surface currents and Stokes drift data can be obtained from the Copernicus Marine Service Ocean Physics Reanalysis of the European North West Shelf[10, 11]. These ocean surface currents combined with Stokes drift velocity fields have been inputted into Parcels to model litter deposition quantities on the Dutch North Sea Coast [18]. Similar combination approaches are used in ecological research to model the movement of plastic litter in the oceans [24], trapping of plastic in coastal zones [32], invasive corals [40], and microplastics from cargo ships [42].

Ocean simulation models can be within the Petabyte scale [23]. While such models can produce the accurate results needed for the research of the oceans, they can't respond in real-time to user inputs. High simulation times in Parcels are caused by a reliance on 64-bit numerics, high temporal resolution of the data and a large amount of just-in-time conversion code between Python and the language-kernel C[22, 20, 7]. A lower-fidelity staticallycompiled software design is needed for an interactive demo where the lower accuracy is acceptable.

2.2 Gamification

A review of gamification as a whole identifies five main principles of gamification: **Goal orientation**, **Achievement**, **Reinforcement**, **Competition**, and **Fun orientation** [31]. This suggests that an interaction model to spread awareness about North Sea litter should also support some form of reward-based interaction. Badges are an exemplary reward element for explorative interaction that fits the principles of **Achievement** as well as **Goal orientation**.

Badges

Denny 2013 [8] conducted a large scale user study on a gamified application focusing on giving badges to students that contribute to a student community forum called PeerWise. This forum has students make exam style questions and lets others answer and rate those questions. An increase in interactions with the service increases the number of questions, answers and ratings, which ultimately improves learning. Badges were implemented to try to increase user engagement with the site and their effect was measured in a course about diseases in populations. The badges in this implementation can be categorised into two subcategories. The first kind is introductory, requiring only that a user makes a specific action with no qualitative requirement, e.g "For answering your first question on PeerWise" or "For either agreeing or disagreeing with at least 10 comments". The second kind has qualitative requirements e.g "For answering at least 10 questions 'correctly'", where the correctness of an answer is a string comparison with the model answer, but they did not evaluate which kind of question is best. They evaluated the badge scheme by comparing user engagement with a control group in the aforementioned course that did not have access to these badges. They found that badges requiring students to answer questions produced better outcomes than the control and they found that badges requiring students to create questions didn't produce better outcomes. The authors theorise that answering questions is a more familiar activity for students and one in which they immediately see value. A possible conclusion to draw from this study is that defining badges that reward students for actions in which they already see value has the greatest impact.

A quantitative study implemented leaderboards and badges in two undergraduate online physics courses by awarding students "Bronze", "Silver", and "Gold" badges. The badges were awarded based on the grade students received after taking quizzes on the course content [1]. Notably missing from this implementation is a motivational affordance targeted for **Fun Orientation**, as described by Nah et al. 2013 [31] above. These schemes were rated positively in a survey by the students. However, they did not produce better academic performance than the control group [1]. This suggests that **Fun Orientation** could be a crucial principle for developing a gamified application to spread awareness about North Sea litter.

Satire and Humour

Inoculation theory in the context of media literacy is a metaphor for medical inoculation where a weakened form of a virus is injected into an individual to immunise them [2]. The game "Cranky Uncle" is a gamified application based on inoculation theory. This game is about satirically and humorously pointing out fallacious science-denialist arguments so that players can better understand why a statement is wrong when they see it outside of the game. Cook et al. 2023 [6] claim that humourous corrections tend to attract more attention and are more likely to be shared than non-humorous corrections. They discussed three cases where this game was employed against climate misinformation. In one of these cases, a leaderboard was developed that let neighbouring towns and schools around Fairborn (Ohio / USA) compete for the most points in the game. They observed high activity (approximately 32 hours of total retention time) during the contest. This study did not quantitatively compare a humourous approach to a non-humorous approach to determine whether it made a statistically significant difference, however, it still suggests that satirical additions can increase engagement.

2.3 Science Communication & Interaction Evaluation

Effective science communication with the (non-expert) public, is the objective of this project. While statistical infographics can be easily understood by the public, geospatial results are complex and require optimal use of tools to convey the intended message [19]. Significant care will need to be taken when designing the representation of a particle simulation intended to be presented to non-experts.

Although gamification can generate interest and extend retention, effective science communication also requires that the material being interacted with is conducive to learning. Yi et al. 2008 [46] did a literature review on how people gain insight from information visualisation and categorised four distinct processes for gaining insight.

- **Provide Overview**. Processes that involve the user learning what they can learn from a visualisation.
- **Adjust**. Processes through which users can test hypotheses by adjusting the range of selection.
- **Detect Pattern**. Processes through which users find trends, outliers or structure in the simulation.
- **Match Mental Model**. Processes through which users can align their own mental model with the presented simulation.

This suggests an evaluation criteria that evaluates whether these processes can take place during a user's interaction with an interaction scheme.

The user must also know how to use the interaction scheme to be able to engage with it. Blascheck et al. 2019 [3] conducted a user study about discovering interactivity. They identified the following seven exploration strategies to discover functionality in interactive visualisations.

- **Eyes Only**. Visually examining the simulation.

- **Reading Text**. Reading the text in the simulation.
- **Opportunistic Interactions**. Take an arbitrary action and assess what changes.
- **Entry Points**. Taking an action that is personally relevant and familiar to the user e.g interacting with the coast close to where the user lives.
- **Structural Interactions**. Use the structure of the interface to discover all the possible interactions with one component.
- **Permutation Interactions**. Methodically testing permutations of options in the interface.
- **Leveraging the Familiar**. Expecting something about one component of the interaction based on similarities with a different component.

This analysis suggests that an interaction scheme should support many of these strategies and it suggests an evaluation criteria for interactive visualisations based on the number of exploration strategies the evaluated scheme supports.

3 Methods

We develop an explorative base interaction scheme for an Euler-Lagrangian particle simulation. Then we extend it to a gamified interaction-reward scheme. We qualitatively evaluate the two schemes under the criteria of interaction discovery and insight generation. Finally, we can compare the two schemes to answer the research question.

3.1 Lagrangian Fluid-Transport Simulation

This section details the Eulerian data, the formulation of the fluid-flow transport simulation and its boundary conditions.

3.1.1 Velocity Field Data

We use a 2D discretised precalculated Eulerian velocity field to perform a rudimentary Lagrangian particle simulation. We combine surface currents and Stokes drift data obtained from the Copernicus Marine Service Ocean Physics Reanalysis [10, 11] similarly as outlined in the literature review Section 2. We use surface currents data at 0m since we want to model ocean debris which floats.

This dataset is converted from a curvilinear grid to a rectilinear grid by Dr. C. Kehl (project supervisor) using Parcels-based [21] reformatting scripts from LOMUQ[1].

Spatial & Temporal Range and Resolution

The temporal sampling period is 1 hour and ranges over 1 year. The spatial coverage is between $-15.875°$ and $12.875°$ longitudinally and between $46.125°$ and $62.625°$ latitudinally with a spatial sampling period of $0.25°$ in both dimensions. We find that using a higher resolution with a spatial sampling period of $0.03°$ and a temporal sampling period of 6 hours results in qualitatively similar particle movement[2]. We use the lower resolution since it uses less computational effort without any difference to user engagement.

Velocity Units

Every cell defines zonal $U_{t,x,y}$ and meridional $V_{t,x,y}$ velocity ($\mathrm{m\,s^{-1}}$) at every time t (s), x (longitude °) and y (latitude °) in the range. The simulation is run in longitude-latitude space, which requires that we convert from metres to degrees using $1\mathrm{m} = \frac{1}{1000 \cdot 1.852 \cdot 60}°$. This is a geometric to geographic coordinates unit conversion implemented in Parcels[3].

3.1.2 Euler Lagrange Particle Simulation

We implement a rudimentary Euler-Lagrangian particle simulation using the aforementioned 2D discretised precalculated Eulerian velocity field. Inspired by Parcels, particles are ad-

[1] Uncertainty Quantification of Lagrangian Ocean Models (LOMUQ) - https://github.com/CKehl/LOMUQ

[2] This was done in an attempt to improve particle beaching see Section 7.2 for discussion on this.

[3] OceanParcels open-source repository - https://github.com/OceanParcels/parcels

vected by updating their longitude $x(t)$ and latitude $y(t)$ coordinates at time t seconds every $\Delta t = 15$ minutes. We use bilinear interpolation[33] and the conversion from Section 3.1.1 over the discretised grid to obtain the zonal $u(t, x, y)$ and meridional $v(t, x, y)$ velocities in degrees per second at time t (in seconds), longitude x (in degrees) and latitude y (in degrees). Using the fourth order Runge-Kutta method, we obtain $x(t+\Delta t)$ and $y(t+\Delta t)$. See Appendix A for detailed calculations.

3.1.3 Boundary conditions

We implement three boundary conditions: **time wrapping**, **space snap back** and **beaching**.

Time Wrapping

When the simulation reaches the end of the 365 day dataset the time is set to 0.

Space Snap Back

When a particle moves out of the rectangular bounds specified above, the particle is moved to the closest in-bounds point.

Beaching

Cells are indicated as land in the velocity field with zero. A natural method to identify beached particles would be to set particles whose velocity are 0[4] to beached. This method unfortunately does not work since a cell in water may have 0 velocity for some time step which results in false positives. Furthermore, this method also produces false negatives since particles that should be considered beached are usually on the edge of cells where some are in water and are are on land. Then, due to the interpolation scheme, these particles still have some small velocity and will incorrectly be considered not beached as illustrated in Figure 2.

With this in mind, we consider particles beached only if at least four of the eight nearest neighbouring cells have 0 velocity for some consecutive period. Beaching particles allows us to stop considering them for computation which frees up time for more particles. Further improvements are outlined in Section 7.2.

3.2 Base Visualisation and Interaction

The visualisation shows a map of the North Sea with particles represented by circles being advected according to the simulation described above. Users can interact with the particle simulation by placing particles in the ocean, which they can do with a mouse click. We also visualise the underlying velocity field using scaled vectors. Users can zoom in and out to inspect areas more closely. Moreover, we include play/pause functionality that also displays a splash screen explaining the controls. See a screenshot from this interaction scheme in Figure 3.

[4] $|u| < \varepsilon$ and $|v| < \varepsilon$ for some $\varepsilon > 0$ where u, v are the velocities of the particle

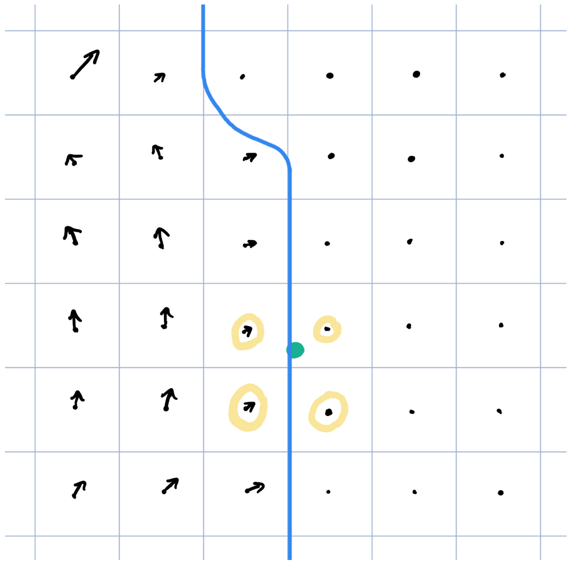
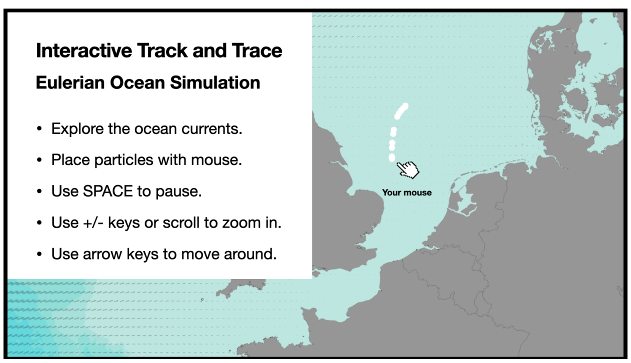
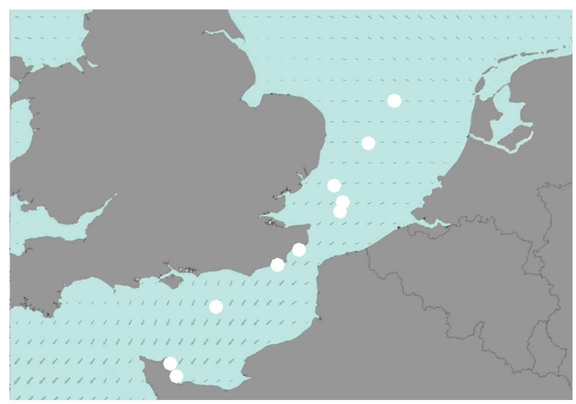


Figure 2: Illustration of beaching in velocity field. Arrows represent velocity. The blue line represents coast. The right side is land (since all the velocities are 0). The green circle is an advected particle that should be considered beached. However, its velocity is not 0 when interpolated with the yellow highlighted velocities.



(a) Screenshot of splash screen displayed before starting and when paused



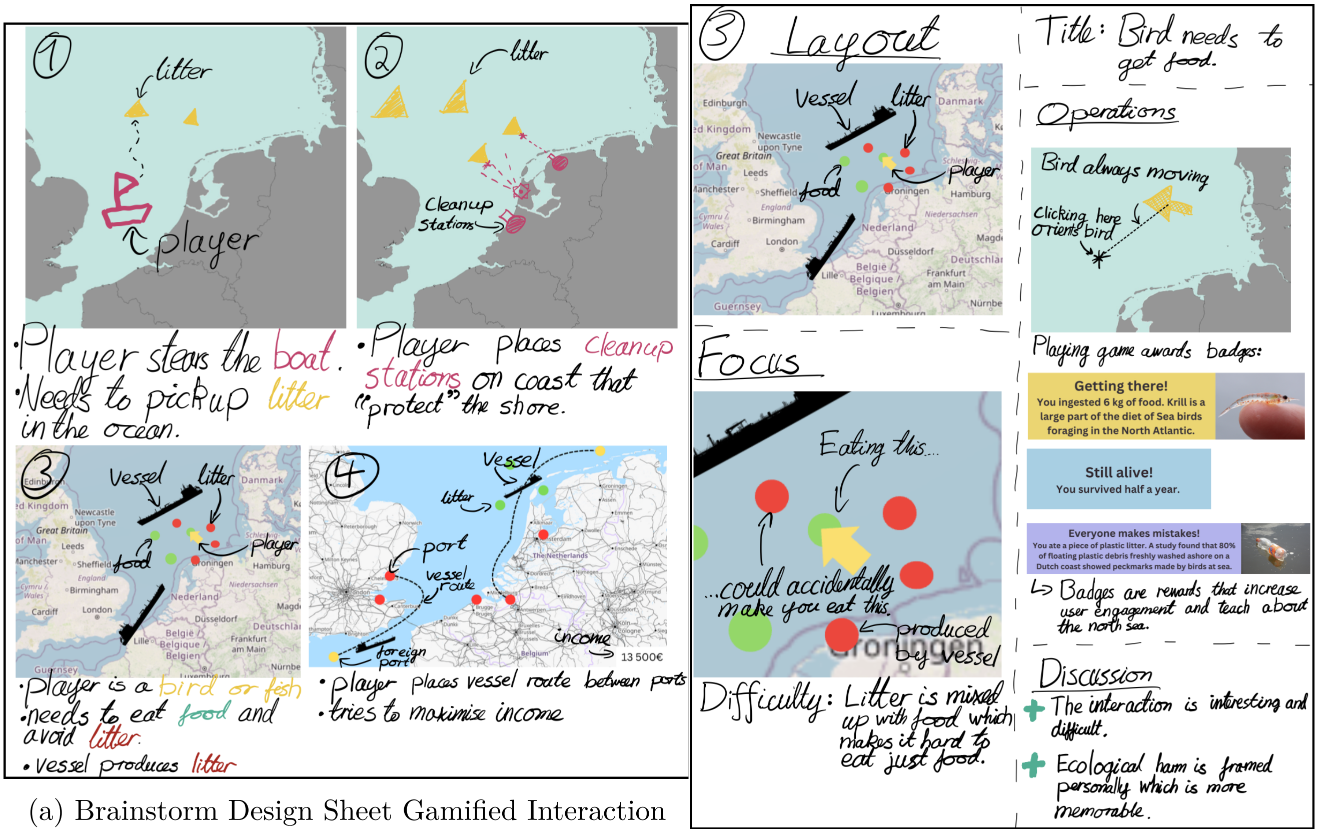
(b) Screenshot of application in use

Figure 3: Screenshots of base explorative interactive Euler-Lagrange particle simulation

3.3 Reward Scheme Design Method

Guided by our literature review in Section 2 we aim to produce a gamified reward interaction scheme. We require it to have (a) interesting interactions inline with the **Fun Orientation** principle, (b) badges inline with the **Achievement** and **Goal Orientation** principle, (c) interactions discoverable by strategies given by Blascheck et al. 2019 [3] and (d) processes to generate insight about the ecology of the North Sea.

We use the five design sheet approach[35] to design this interaction scheme. First, we brainstorm some ideas which can be seen in Figure 4a. Next, we detail and discuss some of the ideas from the brainstorming process in Figure 4b and Appendix B. In the later sections, we present the finalised gamified interaction scheme.



(a) Brainstorm Design Sheet Gamified Interaction Scheme

(b) Initial design of brainstorm idea ③

Figure 4: Sheets 1 and 2 of the five design sheet approach

3.3.1 Game Design

The user directs a migratory bird as a game avatar in the North Sea. The bird is flying at constant velocity and on initial target-location selection the bird is directed towards that location. There are two particle types: *debris* and *food*. There are vessels that travel autonomously on the seas and produce debris particles in the ocean. Food particles appear in arbitrary locations. These food and debris particles are advected in the ocean using the simulation described above. The bird can *eat* the food and debris. A *health-bar* is associated with the bird avatar which increases when food is eaten and decreases over time and when eating debris. It is the goal of the user to maintain their health-bar. The game ends when the health-bar reaches 0.

3.3.2 Input Method

Our interaction design initially used keyboard controls for controlling the bird where pressing the ⬅ or ➡ keys rotates the bird anti-clockwise or clockwise respectively. However, this had the disadvantage that the controls are in an unintuitive direction when the bird is pointing downwards since pressing ⬅ moves the head to the right. Instead, we decide to use a touch screen for manoeuvring the bird. The advantages with this approach are that it is more intuitive than the alternative and it is compatible with the large touch screen monitors[5] in some of our university class rooms. The latter advantage will be important for an upcoming science fair see Section 8.4.

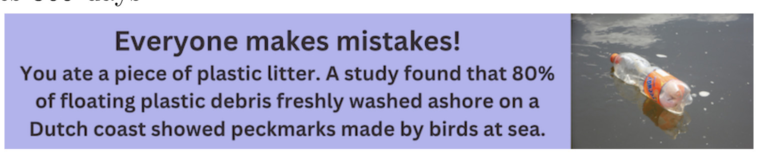
3.3.3 Badges

Motivated by our literature review we further implement a reward system that awards the user with badges when they continue the game for a certain period, when the bird eats an amount of food, or when it eats an amount of debris. We aim to encourage users with these badges to explore the whole space of possibilities. See Figure 5 for a sample of these badges.

Note that some badges contain statistics and other information which can be used to make users aware of issues concerning the ecology of the North Sea. These types of badges can serve as a secondary educational tool. However, due to our missing expertise in this field, we leave populating these badges with high-quality statistics and information as future work to domain experts. We pay particular attention to the application design so that badge additions are easy. We discuss this further in Section 8.1.

(a) Awarded after in game time reaches 365 days

(b) Awarded after eating 6 food particles



(c) Awarded after eating 1 debris particle

Figure 5: Three of the eight implemented badges

3.4 Qualitative evaluation

We qualitatively evaluate the base interaction scheme presented in Section 3.2 and the gamified interaction scheme presented in Section 3.3 to answer the research question. From the literature review, we construct two sets of qualitative criteria that we use to evaluate the two schemes.

3.4.1 Interaction Discovery

We construct a set of considered interactions for each scheme, these are given in Table 1. We aim to decide whether each interaction can be discovered by the exploration strategies

[5] A video demo of this input method can be found under https://drive.google.com/file/d/1askJoW9KZgn4T2hocWXa_N5sQsZD4yfk/view

Eyes Only, **Reading Text**, **Opportunistic Interactions**, **Entry Points**, **Structural Interactions** and **Permutation Interactions**. Note that we leave out **Leveraging the Familiar** from the strategies identified by Blascheck et al. 2019 [3] because our interaction schemes do not have multiple views.

Base scheme	**Gamified Scheme**
I1 Click to spawn particles	**GI1** Use mouse/hand to move bird
I2 Use '+','-', or scroll to zoom	**GI2** Manoeuvring bird into food to gain health
I3 Use arrow keys for moving camera	**GI3** Manoeuvre bird into debris to lose health
I4 Space bar to pause/play	**GI4** Space bar to pause/play

Table 1: Considered interactions for each interaction scheme. Each interaction has an ID $\langle \mathbf{I} \mid \mathbf{GI} \rangle n$ where **I** stands for base **I**nteraction, **GI** stands for **G**ame **I**nteraction and $n \in \mathbb{N}$

3.4.2 Insight Generation

We construct a set of considered insights that users could generate during interaction with the two schemes which are given in Table 2. We then attempt to identify and categorise all the insight generating processes in the two schemes into the types **Provide Overview**, **Adjust**, **Detect Pattern**, **Match Mental Model** as described in Section 2.3.

3.5 Collaborations

The implementation of this project is a teamwork between Robin Sachsenweger Ballantyne and Djairo Hougee. DH and RSB worked together on the base visualisation and simulation whereas everything else detailed in this project report is done solely by RSB.

Base scheme	Both
B1 There are ocean currents	**BG1** Particles get moved by currents
B2 Currents change	**BG2** Particles can beach on the coast
B3 Currents are on average strongest in the Central Atlantic area	**BG3** Particles stay floating in the ocean
	BG4 Travel distance of particles depends on their starting location
	BG5 Beaches accumulate particles

Gamified Scheme

G1 There are vessels in the ocean

G2 Vessels move through the water

G3 Vessels produce marine debris

G4 Marine debris accumulates since it does not biodegrade quickly

G5 There are birds in the North Sea

G6 There is food for birds in the North Sea

G7 The food and debris are located in the same place

G8 Food stays constant since it is eaten by animals as quickly as it is produced

G9 The ratio of debris to food increases over time as debris accumulates and food is consumed.

G10 Marine debris is eaten by birds

G11 It is difficult for birds to separate food and debris

Table 2: Possible insights that can be gained from interacting with each interaction scheme

4 Implementation

4.1 Technologies

The project is made in C++. Its visuals are made using The Visualization Toolkit (VTK)[6], an open source graphics and visualisation framework built on OpenGL[7].

4.2 Code design

The project has been designed to be extendable in several ways. Below we detail some of the decisions made to this end.

Badges

We separate the logic for badges into three abstract classes, `Statistic`, `Achievement` and `Badge`. `Statistic`s track a value throughout the game. `Achievement`s can use `Statistic`s to decide when the player has earned a badge. Finally, `Badge`s are the visual element that the user sees when they achieve a badge. See Figure 6b for an illustration of this process. Adding new `Statistic`s, `Achievement`s and `Badge`s is easy with this design. It just requires implementing a new concrete class of one of the three mentioned above and inserting it into the relevant component.

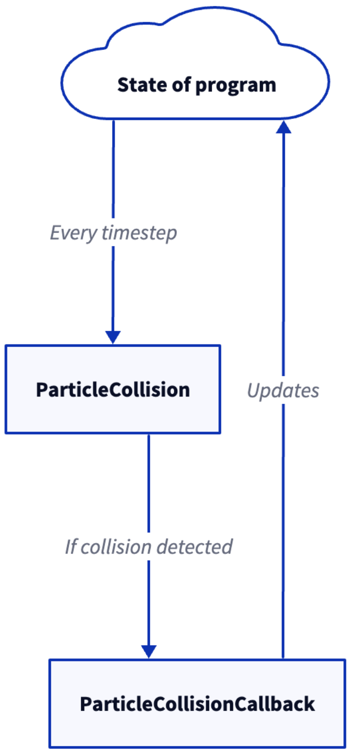
Collisions

The `ParticleCollision` class checks for collisions between sets of particles and the player using a naïve brute force approach every time step. If a collision is detected a `ParticleCollisionCallback` is called. See Figure 6a for an illustration of this process. This callback is an abstract class. Implementing new particle logic is easy with this design. It requires implementing a new class that inherits from `ParticleCollisionCallback` and then registering this new particle type with the `ParticleCollision::addPointSet` method.

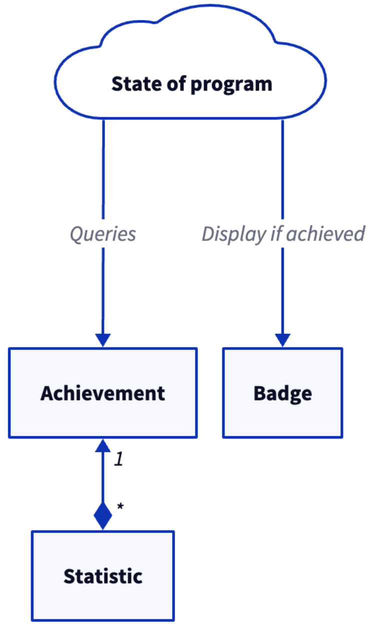
4.3 Base Map

We construct a base map of the Dutch coast and North Sea using GADM[8], Natural Earth[9], HydroLAKES[10] and ESRI Ocean Terrain[11]. These sources are combined in the program QGIS[12]. The map has country borders from GADM at 1:50m scale which help in orientation. The map displays bathymetry data which makes it more visually appealing. This base map is placed into the application as a raster image.

[6] vtk.org
[7] opengl.org
[8] gadm.org
[9] naturalearthdata.com
[10] hydrosheds.org/products/hydrolakes
[11] server.arcgisonline.com/ArcGIS/rest/services/World_Terrain_Base/MapServer
[12] qgis.org



(a) Particle collision



(b) Badge achievement

Figure 6: Diagrams for high level overview of particle collision and badge achievement

4.4 Data Handling

We load the whole dataset into memory at application startup since it is only 400 MB. This decreases IO wait time when compared to loading each day one at a time. The currents of the original dataset are given in curvilinear coordinates. In order to simplify the calculations for the simulation we ask our supervisor to convert the original grid to rectilinear coordinates.

5 Results

In the following section, we perform a qualitative analysis of the base interaction scheme and the gamified interaction scheme. Beginning with the exploration strategy evaluation, we evaluate a set of considered interactions for each scheme under the criteria outlined in the methodology section. The considered interactions are given in Table 1.

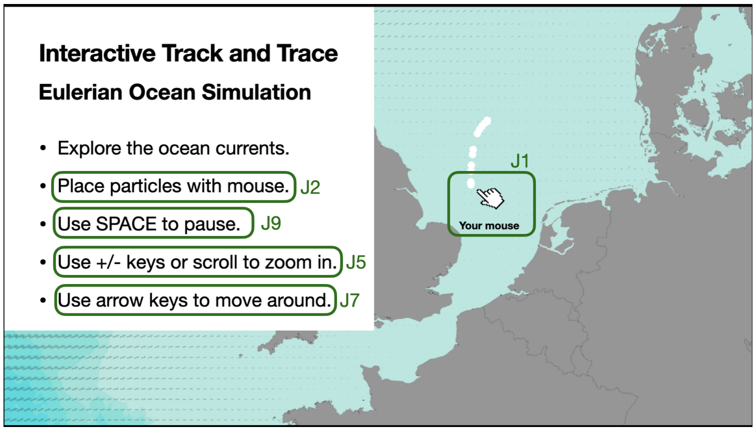
5.1 Exploration Strategy Evaluation

We enumerate every combination of exploration strategy and interaction and decide whether an exploration strategy can be used to discover an interaction. The results of this evaluation can be found in Table 3. We find that both schemes explain in text all the possible interactions and give purely visual examples for the primary interaction. The base scheme gains entry points by allowing the user to place particles themselves whereas the gamified scheme allows for permutation interaction with the different particle types. Lastly, we find that the number of supported exploration strategies is equal for both schemes.

ID	**I1**	**I2**	**I3**	**I4**	**GI1**	**GI2**	**GI3**	**GI4**
Eyes Only	**J1**	❌	❌	❌	**J10**	❌	❌	❌
Reading Text	**J2**	**J5**	**J7**	**J9**	**J11**	**J12**	**J12**	**J13**
Opportunistic Interactions	✅	✅	✅	✅	✅	✅	✅	✅
Entry Points	**J4**	**J4**	**J4**	❌	**J8**	❌	❌	❌
Structural Interactions	❌	❌	❌	❌	❌	❌	❌	❌
Permutation Interactions	❌	❌	❌	❌	❌	**J14**	**J14**	❌

Table 3: Interaction discoverability evaluation. Cells marked with ✅[13]or an ID **J**$\langle n \rangle$ for some $n \in \mathbb{N}$ indicate that the corresponding interaction can be discovered using the corresponding exploration strategy. The ID references a **J**ustification. These justifications can be found in Figure 7 and Figure 8. Cells marked with ❌ indicate that the corresponding interaction cannot be discovered using the corresponding exploration strategy.

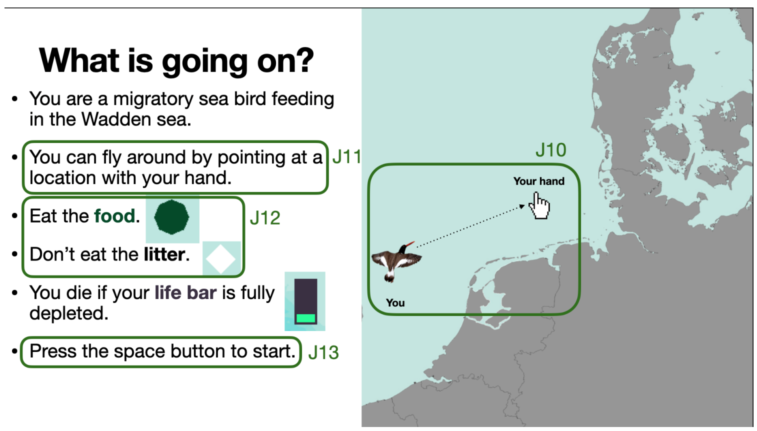
[13]Note that all interactions in the **Opportunistic Interactions** row are marked ✅ since they all give immediate visual feedback.



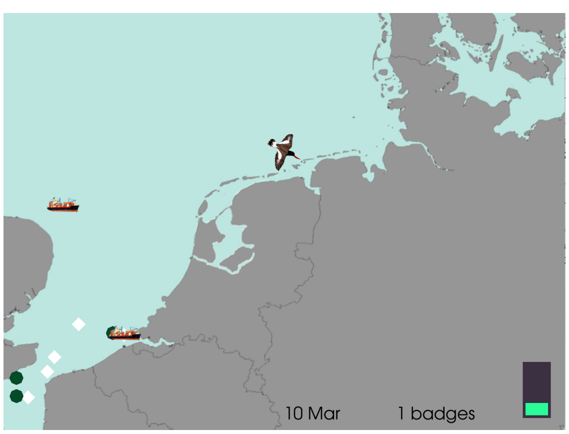
(a) Splash screen that lets users read and see how to interact with the simulation

(b) **J4**: Users have an entry point by zooming, spawning points close, or moving to a familiar location (e.g North Sea Coast of Groningen)

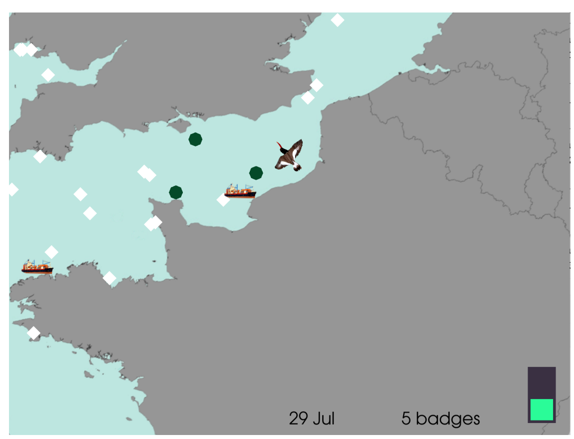
Figure 7: Justifications for exploration discovery evaluation in base interaction scheme



(a) Splash screen that lets users read and see how to interact with the simulation



(b) **J8**: Users have an entry point flying over a familiar location (e.g North Sea Coast of Groningen)



(c) **J14**: Users can permute the different particle types to see what interacting with each does

Figure 8: Justifications for exploration discovery evaluation in gamified interaction scheme

5.2 Insight Generation Evaluation

Next, we perform the insight generation evaluation. To begin we list all considered possible insights that one could gain from each interaction given in Table 2. In the sections that follow we identify processes that could generate the considered insights in each interaction scheme and classify them into four types as described in Section 2.3.

5.2.1 Provide Overview

The base interaction scheme and the gamified interaction scheme present different data to the user. For a user to gain insight from a visualisation, they must first see what can be learnt from it. This process type is identified as *Provide Overview*. Processes that provide overview to the user as to what insights from Table 2 can be learnt from the interaction schemes are given in Table 4.

Base scheme	**Both**	**Gamified scheme**
Ocean current direction and amplitude (**B1**, **B2**)	Particle movement (**BG1**, **BG3**)	Different particle types (**G6**, **G7**)
	North Sea map (*none*)	Bird (**G5**)
		Health bar (*none*)
		Vessels (**G1**, **G2**)
		Badges (**G10**)

Table 4: *Provide Overview*: Elementary visual elements that inform the user about which insights can be gained from each interaction scheme

5.2.2 Adjust

Allowing users to change the range of selection lets them explore the data that is most relevant to them. They can make hypotheses and test them by finding a relevant slice of the data and observing if it matches their expectation. The insight generating process that involves users adjusting the visualisation selection to test hypotheses is identified as *Adjust*. The interactions involved in these processes and the insights they could generate are given in Table 5.

Base scheme	**Both**	**Gamified scheme**
Zoom (Inspecting arrows **B3**)	Move camera (**B3**)	Eating food (**G6**)
Spawning points (**B3**, **BG4**)		Eating debris (**G10**)

Table 5: *Adjust*: Adjusting interactions involved in insight generating processes for each interaction scheme

5.2.3 Detect pattern

While users might have their own hypotheses which they test during the *Adjust* processes, some connections or patterns are unexpected or surprising such that users will not hypothesise them before interacting. The *Detect pattern* process involves the user being shown and then internalising relationships, distributions or tradeoffs [46]. Patterns that can be discovered in each interaction scheme are given in Table 6

Base scheme	**Both**	**Gamified scheme**
Particles move in same direction as arrows (**BG1**)	As time goes on there are more particles on the coast (**BG5**, **BG2**)	Attempting to eat food particles close to debris often results in losing health (**G11**) As time goes on, there is more debris than food (**G9**, **G8**)

Table 6: *Detect pattern*: Patterns that can be discovered in each interaction scheme

5.2.4 Match mental model

After one has identified a pattern in the data, finding the causes of this pattern can deepen one's understanding further. These causes can be incorporated for longterm understanding by updating one's mental model (possibly using metaphor). The causes that can be discovered in each interaction scheme are given in Table 7. This process of updating one's mental model is called *Match Mental Model* [46].

Base scheme	**Both**	**Gamified scheme**
Particles move because they are pushed by currents (**BG1**)	*none*	Ratio of food to debris decreases because the produced food is used up by birds whereas the plastic accumulates in the ocean (**G9**) Birds eat plastic because the plastic is close to the birds (**G11**)

Table 7: *Match Mental Model:* Causes that allow the user to match their mental model with the patterns they discovered interacting with each interaction scheme

6 Discussion

In the following sections, we interpret the results of this study and discuss the efficacy of the methodology and implementation.

6.1 Experimental Interpretation

In the interaction discovery evaluation in Section 5.1, we find that the base scheme has more entry points which indicates that it is more explorative. In contrast, the gamified interaction scheme encourages permutation interactions with food and debris using the badge system. The equality in the number of supported exploration strategies indicates that both schemes are similarly intuitive however, users require different methods to discover their functionality.

In the insight generation evaluation in Section 5.2 we find that users can learn about the movement of particles in the ocean in both interaction schemes. In the first, they can set up experiments by placing particles in different places and observing how they move. In the second, users can only observe the particle's movement. This on its own suggests that the first has more processes for gaining insight than the second. However, in the second users are required to concentrate on the movement of particles more if they want to do well in the game. We expect that this more concentrated focus is more conducive to generating insight. Therefore we expect the first visualisation to be more effective for learning about the movement of particles in the ocean in users who are already interested in ocean particle simulations, whereas the second visualisation is more effective for users who find the gamified scheme engaging.

Furthermore, we find that there are more processes for the gamified interaction scheme than for the base interaction scheme in the *Adjust* and *Detect patterns* categories. This suggests that the gamified scheme assists better in updating the user's mental models and therefore produces more memorable insight.

Moreover, we believe that the badges encourage users to interact for a longer time which further makes the identified insight generating processes more likely. This connection between the badges and retention time could be verified through a quantitative study, which is discussed in Section 8.3.

6.2 Ease of extensibility

The gamified application is designed to be modular and therefore extendable. We measure extendability inspired by the Open-Closed principle as described in chapter 3 of Meyer 1997 [29]. We consider extensions that can be realised by implementation and registration of a new class and without modification to existing classes to be easily extendable. Extensions that can be realised by modifying a single class are considered more difficult. Requiring modifications to multiple classes for an extension to be realised is considered difficult.

Particle advection kernels	Particle colours	Particle shapes/sprites	Particles collision interactions
Flow field visual layers	Spatial boundary conditions	Temporal boundary conditions	Assets[14] 🌟
Adding badges 🌟	Achievements	Game design constants[15]	Multiple birds
Input methods	Vessel routes	Food spawning	

Table 8: Summary of the extensibility of the application. Green cells indicate easy extensions, yellow cells indicate more difficult extensions, red cells indicate difficult extensions. A 🌟 indicates that the extension requires no modifications to code only replacement of assets or filenames.

We consider adding new badges easy since developers can add new badges simply by placing a new file in a directory. The assets directory has a directory named “badges”, the structure looks like this:

```
data
  /badges
    /litter
      1.png
      0.3.png
      0.0001.png
    /food
      6000.png
      0.0001.png
    /days
      366.png
```

Every directory in the badges directory represents a statistic. Every file image file represents one badge that is achieved only when the statistic is greater than the filename. So the badge with image “366.png” will only display after the number of days is greater than 366.

6.3 Technology evaluation

As a high level graphics library, VTK significantly simplified the implementation of all the graphical components of the application like text and sprites i.e images. The project could not have been completed in the required time frame without a library of this kind. We nevertheless faced some difficulties.

[14]e.g sound effects, sprites, splash screens or base map
[15]e.g badge display time, bird speed, or start location

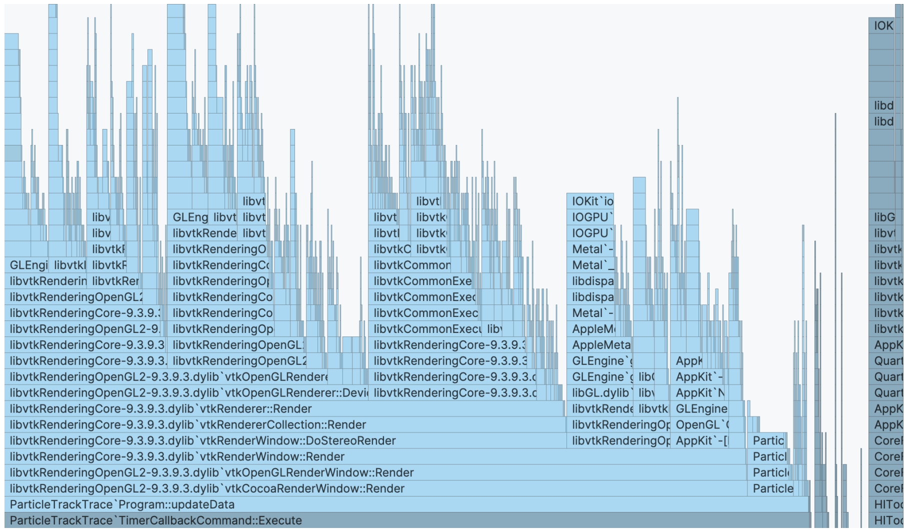


Figure 9: Results from running the gamified application using the CPU Profiler DTrace. We can see that the method `vtkCocoaRenderWindow::Render` represents 92% of the `Program::updateData` method runtime which is the main interaction loop.

Firstly, we find that the `GeoTransform` functionality is young and methods `vtkGeoTransform::InternalDeepCopy` [16] and `vtkGeoTransform::InternalTransformDerivative` [17] remain unimplemented. This produced two difficult to resolve bugs since this missing functionality is not in the documentation. Using a more mature geospatial library like GDAL [36] would have prevented this. However, this would have increased the overall complexity of the application making it overall more difficult to develop.

Secondly, we find that the performance of the application is limited by VTK. 92% of CPU time is spent in methods involving rendering which can be seen in Figure 9. The filter architecture [38] of VTK is not designed for high framerate applications since it requires recomputing many filters every frame. This computational cost limits the visual complexity of the design space in future expansion. Changing graphics framework could improve performance.

6.4 Design approach evaluation

We believe that the five design sheet approach produced a high quality gamified interaction scheme. Drawing out multiple designs and then filtering, collecting and modifying them helps break up the process into small accomplishable tasks. In future projects, we would improve the process by producing competitive ideas of vastly different styles and content in the brainstorming stage. Competitive designs cover a greater area of the design space and additionally are most likely to not have each other's flaws. This aspect of the five design sheet philosophy was not done in this project but could have further helped the design process.

[16] VTK Discussion post about this https://discourse.vtk.org/t/generaltransform-that-has-a-geoprojection-does-not-correctly-perform-inverse/14150

[17] Unimplemented method in source code https://gitlab.kitware.com/vtk/vtk/-/blob/ab2cc4ff282b284dc7b5ae8b11a982554fa62a5f/Geovis/Core/vtkGeoTransform.cxx

7 Limitations

In this section, we discuss some of the limitations of this research project.

7.1 Other plastic litter sources

We suspect it is impossible to design a gamified interaction scheme that gives users a comprehensive understanding of all the aspects of ocean sources and sinks. Naturally, our design also misses some aspects. We attempt to mitigate this by displaying a QR code at the end of the game that links to the International Wadden Sea School[18] for users to learn more about the subject if they wish. This end screen is given in Figure 10.

Our design only focuses attention on ocean debris sources caused by ships. It is not well known how much each source contributes to the total ocean debris. Li, Tse, and Fok 2016 [26] claim 20% of ocean debris comes from ocean-based debris and the other 80% is land-based. Certainly, land-based contributions are a major source and we consider this message missing and a limitation in our design.

7.2 Beaching

We see in the implemented simulation that very few particles beach on the North Sea coast, even though in reality we find that this does happen frequently. This is because of the naïve implementation of beaching. We do not see more particles beaching on the North Sea coast when increasing the spatial resolution of the velocity field. Global ocean current datasets are inaccurate in ocean cells adjacent to land [32]. This means that particles in the cells adjacent to land are not moved further to the coast when they should be. More complex beaching logic could reduce the reliance on coastal ocean current data. Factors such as tidal data, wind direction and speed, coast angle, and morphology [32, 45] are hypothesised to influence beaching. Certainly surface currents and the distance from debris to coast are important factors [32]. However, the distance from debris to coast depends on tidal data and the geometry of the coastline. Including this data is considered out-of-scope in this project and it represents an important limitation.

[18] iwss.org

Figure 10: End screen displayed to users when the game ends

8 Future Work

We acknowledge that there is more work to do for this project. This section details some of those ideas.

8.1 Additional badges

Badges can be a second tool for imparting information to the user. Experts in the ecology of the North Sea could include more badges to this end. We considerably simplified this process by providing multiple ways of increasing complexity of adding new badges.

8.2 Web deployment

WebAssembly is an instruction format that allows deployment to the web[19]. The visualisation framework VTK that was used for this project is under active development and supports a method of compiling to WebAssembly[20]. Therefore it seems plausible to deploy the base interaction scheme and the gamified interaction scheme to the web. This would simplify the distribution of the application and would enable the possibility of a larger scale user study.

8.3 Quantitative study

A quantitative study on the effect of reward systems like badges on engagement time could further provide evidence for the effectiveness of gamified teaching applications about North Sea ecology. We propose extending a deployed web version of the two interaction schemes to track anonymised statistics e.g engagement time. This would allow us to quantitatively study engagement of gamified interaction schemes. The web deployed version would allow performing a user study with a significantly higher sample size than otherwise possible with an in-person test, which is a limitation of many gamified user studies in academic literature [16].

8.4 Zpannend Zernike

We intend on presenting the developed application on a touch screen monitor in the Zpannend Zernike[21] event on October 5 and 6 2024 in Groningen. This event is a science communication- and outreach programme to the public, with focus on STEM subjects. Its name relates to the name of the campus “Zernike campus” in memory of Frits Zernike, a nobel price winner in natural science (1953) from Groningen. We present at this programme since this project is fittingly related to science communication, participants are of all ages and the Zernike campus has touch screen monitors.

[19] webassembly.org

[20] docs.vtk.org/en/latest/getting_started/using_webassembly.html

[21] zpannendzernike.nl

9 Conclusion

In this project, we identify the need for public engagement with North Sea ecological issues. We evaluate how public engagement with Lagrangian ocean simulations is affected by the inclusion of a reward scheme. Badges are a novel approach for improving engagement and learning outcomes. A gamified interaction scheme that uses badges is designed to increase user retention and clarify concepts. This thesis contributes two interactive Lagrangian ocean visualisations, which are compared qualitatively under the criteria of interaction discovery and insight generation.

Both interaction schemes allow users to discover their functionality in equal amounts. However, more entry points are present in the base interaction scheme and more permutation interactions are present in the gamified scheme, which implies that gamified interaction schemes might require more permutation interaction exploration than a conventional interaction scheme. The gamified interaction scheme has more patterns and mental models that the user can identify and internalise than the base interaction scheme. This is a promising result prompting further extensions to the gamified interaction application and a quantitative study measuring retention time in users directly.

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A RK4 Integration Calculation

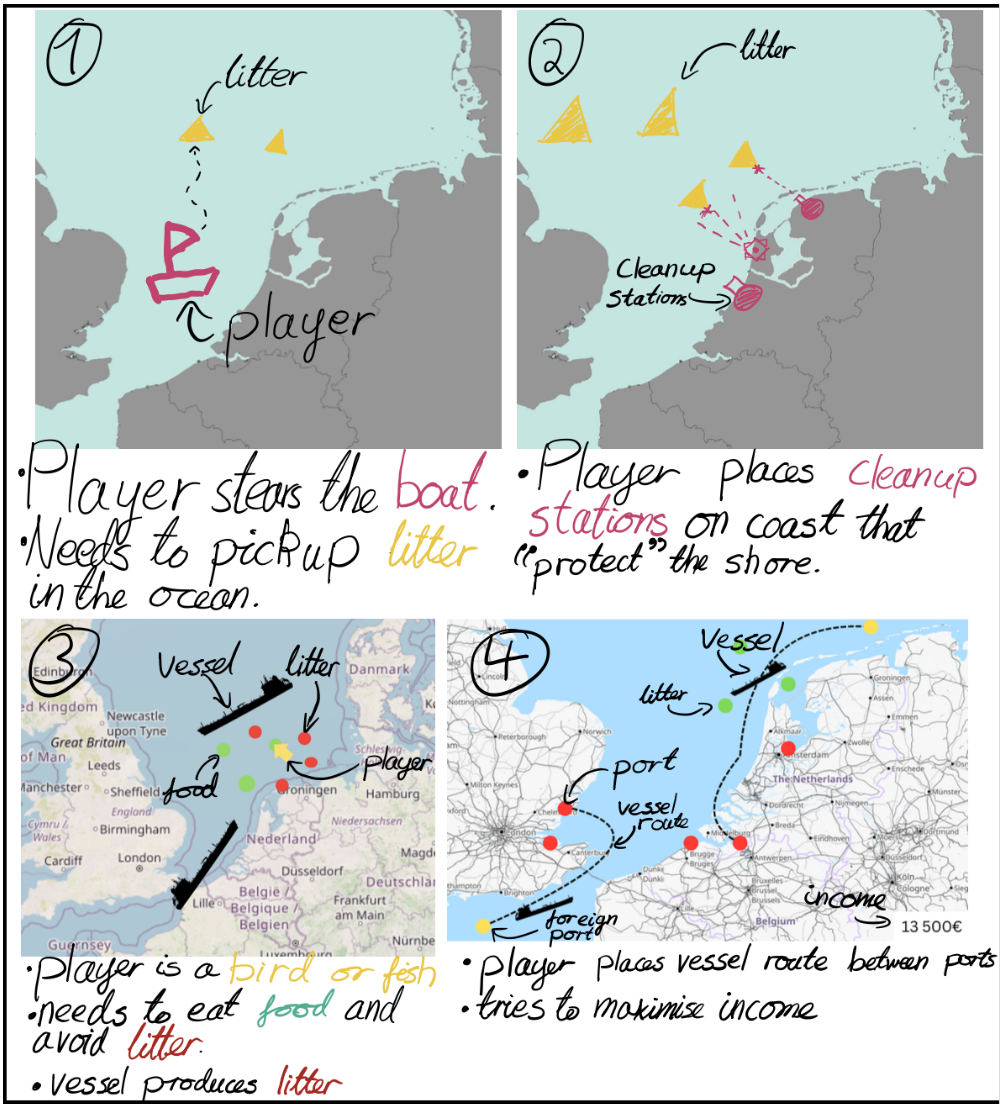
Showing how to obtain $x(t+\Delta t)$ and $y(t+\Delta t)$ from $x(t)$ and $y(t)$. Given some particle position $x(t)$ and $y(t)$, we obtain a new particle position $x(t+\Delta t)$ and $y(t+\Delta t)$.

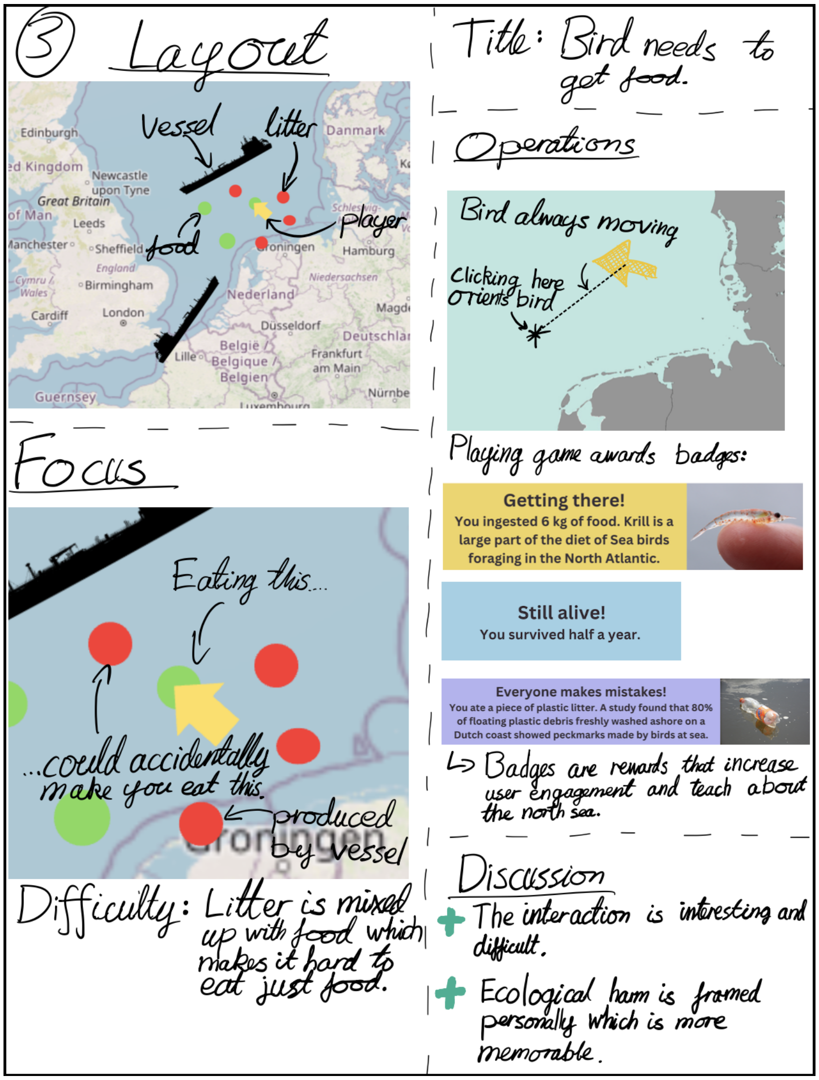
$$
\begin{aligned}
x(t+\Delta t) &= x(t) + \frac{u_1 + 2u_2 + 2u_3 + u_4}{6}\Delta t \\
y(t+\Delta t) &= y(t) + \frac{v_1 + 2v_2 + 2v_3 + v_4}{6}\Delta t
\end{aligned}
$$

where

$$
\begin{aligned}
u_1 &= u\left(t, x(t), y(t)\right) \\
v_1 &= v\left(t, x(t), y(t)\right) \\
u_2 &= u\left(t + \frac{\Delta t}{2}, x(t) + u_1\frac{\Delta t}{2}, y(t) + v_1\frac{\Delta t}{2}\right) \\
v_2 &= v\left(t + \frac{\Delta t}{2}, x(t) + u_1\frac{\Delta t}{2}, y(t) + v_1\frac{\Delta t}{2}\right) \\
u_3 &= u\left(t + \frac{\Delta t}{2}, x(t) + u_2\frac{\Delta t}{2}, y(t) + v_2\frac{\Delta t}{2}\right) \\
v_3 &= v\left(t + \frac{\Delta t}{2}, x(t) + u_2\frac{\Delta t}{2}, y(t) + v_2\frac{\Delta t}{2}\right) \\
u_4 &= u\left(t + \frac{\Delta t}{2}, x(t) + u_3\frac{\Delta t}{2}, y(t) + v_3\frac{\Delta t}{2}\right) \\
v_4 &= v\left(t + \Delta t, x(t) + u_3\Delta t, y(t) + v_3\Delta t\right)
\end{aligned}
$$

B Other sheets of the 5 design sheet process





Design sheet for brainstorm idea 1 - cleanup boat

going from ship to ship picking things up there

Cons

Cleaning up sends the message that if only we just did enough clean up then it would all be okay but this is not true since you cannot clean up microplastics for example.

#InteractionRewardSchemeIdea

Design sheet for brainstorm idea 2 - Tower defence North Sea Coast

#InteractionRewardSchemeIdea

There are vessels and vessel routes like in Design sheet of brainstorm idea 4 - Evil vessel boss and Medium freight manager however they aren't set by the the user.

Instead the user builds *defence cleaners* (purple arrows) which can be positioned anywhere on the coast that pick up trash that is close to it. Maybe they walk towards it. There is some limited amount that can place. You can place more as the game progresses, as you clean up more debris.

Badges

Pros

Interesting interaction scheme that involves the simulation

Cons

If the particles don't flow towards the coast it might get a bit boring.

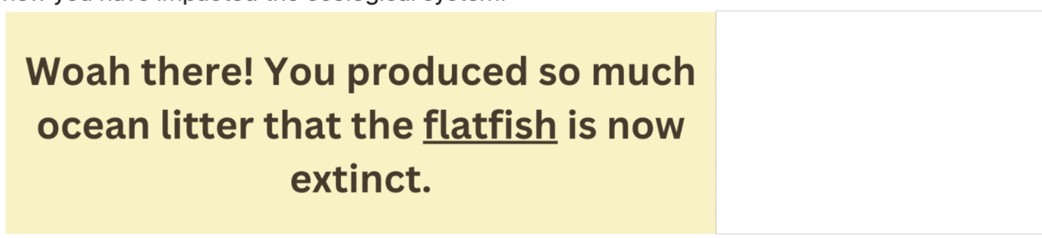
Design sheet of brainstorm idea 4 - Evil vessel boss

#InteractionRewardSchemeIdea

You're trying to produce as much pollution as possible. In the spirit of **Plague Inc.**
Beached particles at some point disappear indicating that they've caused damage.

The Badges

There is some pollution metre and as it reaches a certain number you get an achievement on how you have impacted the ecological system.



Pros

It's funny which makes it memorable see citations in starting form.

Cons

How does the user interact with the simulation?
What is the difficulty?
beaching simulation is hard