University of Dublin

TRINITY COLLEGE

Understanding Covid-19

A simulation tool to aid in the teaching and understanding of viral diseases

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Declaration

I hereby declare that this project is entirely my own work and that it has not been submitted as an exercise for a degree at this or any other university.

Signed: ______________________ Date: ____________________

Acknowledgements

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Luke

Abstract

In the midst of an ongoing epidemic, it is now more important than ever for people to obtain an understanding of how viral diseases spread and the factors that can affect this spread. This is particularly prevalent for young people, a demographic whose behaviour can massively affect the rate at which a disease can escalate.

A variety of approaches have been used to attempt to educate this demographic on the complexity and significance of the factors at play. Varying from TV advertisements, to explanatory videos and articles, this study will analyse the efficacy of some of these techniques, in particular how innovative contemporary technology can aid in the teaching of this topic. The design of the educational software used in this project is influenced by a variety of pedagogical theories, centring around how the theories of constructivism and constructionism can be embodied within a micro-world simulation.

This project explores the design, implementation and evaluation of the effectiveness of a simulation tool which can used to delineate the key concepts and factors involved in suppressing and managing viral diseases. The simulator is designed for use by Transition Year students in secondary school.

The simulations within the tool are predicated upon classic compartmental epidemiology models, which classify individuals within a population into distinct discrete states. The model used to underpin this tool is the S.E.I.R (Susceptible, Exposed, Infected, Removed) model, as it is the most applicable to a disease such as Covid-19. The tool is designed as a low fidelity simulation, placing its focus on illuminating the key considerations involved in the decision-making process around Covid-19, rather than attempting to scientifically model or predict real-life outcomes. The simulator allows the learner to alter certain variables and witness the effects this has upon how a disease spreads, by clearly visualising the effects the choices they make within the program have upon the outcome. The tool is challenge based, setting out three key challenges to engage the learner and illustrate the important dynamics and trade-offs involved.

The fundamental technical challenges faced in the development of the tool are discussed, along with how these challenges were overcome and how this shaped the design of the simulator. The influence for the design explores a myriad of data visualisation and interactivity techniques, which were analysed and considered when designing the simulator.

Naturally, due to Covid-19 it was not possible to evaluate and test this tool in the classroom setting for which it was designed. However, a cohort (N=43) of Transition Year students were able to interact with and give feedback on the tool through a series of online classes run by Trinity Access – TCD's major outreach programme. An online survey was conducted to gauge the usability and effectiveness of the tool from a pedagogical standpoint. Analysis of the quantitative and qualitative feedback on the tool suggested that the tool was successful in its primary goal of building a simulator which encompassed pedagogical and constructionist characteristics to enhance the learner's understanding of viral diseases.

Table of Contents

List of Figures

1 Introduction

1.1 Motivation

The ongoing Covid-19 pandemic has thus far, been one of the most catastrophic viral diseases in recent memory. To date (12 April 2021) there have been over 135 million confirmed cases and over 2.9 million deaths worldwide (WHO, 2021). A significant early juncture in the pandemic was on the 11th of March 2020 when the World Health Organisation declared Covid-19 to be a controllable pandemic, stating that counter measures could be adopted by the countries at risk to mitigate their exposure to the disease (WHO, 2021). Since this declaration, countries across the globe have adopted an array of different prevention and reduction strategies to minimise their vulnerability to Covid-19. All of these preventative measures rely on the compliance and obedience of those they are set to protect. Research has found that the largest influence on compliance with public health advice related to Covid-19 is the belief that the precautions in place, will be effective in minimising the spread of the disease (Clark et al., 2020). Hence, it is of paramount importance that the consequences and potential ramifications of decisions made by both government bodies and by individuals in the midst of such a pandemic are understood.

To develop an understanding of the variety of complex factors at play and the effect these can have on the spread of a viral disease such as Covid-19, a basic comprehension of epidemiological models and theory is required. Epidemiological modelling is primarily predicated upon different variations of the original S.I.R. model (Kermack and McKendrick, 1927), and involves complex calculus and differential equations to determine the impact of a viral disease.

Simulations are the imitation or modelling of real-world processes and systems and can be used to engage young learners in complex topics, granting them an acute understanding of the fundamental concepts without having to engage in the complex mathematics underpinning the system (Wilensky and Papert, 2010). Contemporary technological developments combined with innovative data visualisation technologies, allow for simulators to be developed which can equip learners to explore complex disease modelling techniques which would have previously been too complex or unengaging. A particular type of simulator is a microworld, a digital learning environment in which the user can explore, navigate and test embedded ideas and concepts about real-world processes (Hoyles et al., 2002). Microworld simulators empower learners to engage in cognitive exploration which would not be possible without the use of contemporary technology.

Although Covid-19 poses significantly less of a threat to the health of adolescents themselves, their behaviour and willingness to comply with restrictions and public health guidelines can have a massive effect on the overall impact of the virus. Adolescents, more so than any other age bracket, possess a heightened need for social interaction and peer acceptance and are more inclined to partake in risk-tolerant behaviour (Andrews et al., 2020). This inherent nature can make it more difficult for young people to adhere to the social isolation that comes with following certain social distancing restrictions.

Consequently, it is essential that young people attain an astute awareness of the integral factors which can affect the rate at which viral disease can spread, and understand how their behaviour could help to suppress such a disease. A simulator which can aid in the teaching of these integral factors, then, has potential to engage young people and help develop an enhanced understanding of epidemiology and their responsibility as a citizen during a global pandemic.

1.2 Goal

The predominant goal of this project is to develop a simulator which can aid in the understanding of the spread of viral diseases and empower young people to investigate the fundamental dynamics and trade-offs involved in the decision making process when it comes to managing such diseases. The design of the simulator should:

1. require the learner to be cognitively engaged
2. be guided by best practice from Human-Computer Interaction (HCI).

The simulator should avail of contemporary data visualisation technologies to depict a population through which a viral disease will spread. The user should be able to configure a selection of variables in real time which will affect the spread of the disease. The effects caused by the users' changes should be clearly visualised and easily comparable with previous iterations of the simulation. This should allow the learner to develop their own understanding and appreciation for what factors are the most fundamental when it comes to pandemic containment. The simulator should be accessible and usable for Transition Year students (16/17 years of age), and should provide an engaging and informative experience for this demographic. The design of the tool should aim to combine both engaging visual stimulation with a high level interactivity for the user to create a tool that both visually and cognitively engages the learner.

The final goal of this project is to decide an adequate approach for testing the effectiveness and usability of the simulator. The testing carried out should provide analysis on the learning outcomes of the tool, and should gather feedback on the tool's ability to effectively engage and impact young people's understanding of Covid-19 and similar viral diseases.

The study will initially explore some of the relevant background research conducted in preparation for the project. It will then investigate some of the key design considerations and choices made for developing the simulator. The significant technical challenges and an overview of how the simulator was implemented will then be discussed, before providing analysis on the testing and evaluation conducted on the tool.

2 Background

This chapter discusses the background research carried out by the author of this project as preparation for the design and implementation of the project. This chapter is divided into five subsections: Epidemiological modelling, pedagogical and microworld theories, human computer interaction, epidemiology data visualisation techniques and similar applications.

2.1 Epidemiological Modelling

There are a host of different conventional disease modelling approaches, varying from complex mathematical models, to more flexible agent based ones. This study analyses four commonly used modelling techniques within epidemiology which are: System Dynamics, Agent Based Modelling, Data-driven modelling and Hybrid Simulation. The choice of which modelling approach to use in any given situation is usually made based on the complexity of the problem and the requirements of the decision maker (Borshchev and Filippov, 2004).

System Dynamics Models: are models based on complex differential equations which compartmentalise a population into classes, and use these differential equations to predict the spread of a virus (Volz and Meyers, 2007). The aforementioned S.I.R. (Susceptible, Infected, Removed) model is particularly prevalent, with variations of it being used throughout epidemiology. It has been used for everything from estimating the transmissibility of chickenpox (Deguen et al., 2000) to analysing the potential impact of measles epidemics (Bjørnstad et al., 2002). It is currently being used in a variety of studies as an attempt to model and predict the spread of Covid-19 (Chen et al., 2020, Wang et al., 2020, Toda, 2020). When vaccination is not yet a possibility for a disease, the disease can only be controlled through social distancing measures and through effective isolation of those diagnosed with the virus. The conventional S.I.R. model has no latent stage (asymptomatic individuals), rendering it inadequate to model Covid-19 (Carcione et al., 2020). An extension of the model is S.E.I.R. which classifies a total population (N_0) into those who are susceptible, $S_{(t)}$, exposed $E_{(t)}$, infected $I_{(t)}$, and removed, $R_{(t)}$ where t is the variable for time passed, making it a more suitable model for a disease such as Covid-19. Having compartmentalised the population into these 4 distinct states, the following differential equations can be used to model the impact of a viral disease:

$$
\begin{aligned}
\dot{S} &= \Lambda - \mu S - \beta S \frac{I}{N}, \\
\dot{E} &= \beta S \frac{I}{N} - (\mu + \epsilon) E, \\
\dot{I} &= \epsilon E - (\gamma + \mu + \alpha) I, \\
\dot{R} &= \gamma I - \mu R,
\end{aligned}
$$

Figure 2.1: Differential Equations of the S.E.I.R Model
https://www.frontiersin.org/articles/10.3389/fpubh.2020.00230

The parameters in the above equations are defined as (Carcione et al., 2020):
Λ: Per-capita birth rate.
μ: Per-capita natural death rate.
α: Virus-induced average fatality rate.
β: Probability of disease transmission per contact (dimensionless) times the number of contacts per unit time.
ϵ: Rate of progression from exposed to infectious (the reciprocal is the incubation period).
γ: Recovery rate of infectious individuals (the reciprocal is the infectious period).

These equations allow for the computation of how many people will be infected with, exposed to or die from a contagious disease depending on the values of the inputted variables. The model will predict a peak of infections and deaths as a function of time and can play a vital role in the decision making process around viral diseases (Li et al., 1999).

Agent Based Modelling (ABM): attempts to model, not only the disease itself but also the characteristics of the environment in which the disease is spreading. ABM can facilitate the modelling of the behaviour of individual agents and the interactions between said agents in an attempt to model and simulate complex phenomena in the population as a whole (Macal and North, 2009). ABM is often used to model recently emerging diseases, where many of the important functions and parameters of the disease are still unknown. Predictions or estimates for the characteristics of the virus can be reverse-engineered from the results of the simulation when given the typical behaviour of the agents within their environment (Miksch et al., 2014). ABM allows for stochastic modelling, meaning the variable and unpredictable nature of human behaviour can be incorporated into the simulation to allow for different outcomes from the same set of initial parameters (Epstein, 2009). ABM's ability to introduce interventions and changes to behaviour on the individual level as opposed to the collective makes it a very useful tool for modelling pandemic style scenarios, in which human behaviour is affected by both the social restrictions in place and by the individuals interactions with the virus.

Data-Driven Modelling: is another approach to epidemiological modelling which has been used to analyse the fundamental characteristics and potential impact of Covid-19 (Verity et al., 2020). Data-driven modelling focuses on taking a subset of a population and attempting to extrapolate the data from that subset to the population as a whole. It can be a very effective way of determining the potential impact of a contagious disease given only a small sample size, and hence is often used a prediction model when new diseases or variants first begin to emerge. However, the insights provided by the model can vary massively depending on the sample that is taken and hence other modelling approaches are often adopted once more data becomes available (Liu et al., 2018)

Hybrid Simulation Models: are simply models which combine two or more conventional modelling approaches, whether it be from those discussed above or from the multitude of other modelling techniques that are available. Hybrid simulations models are primarily used to capture a system in which some elements are better represented with one technique, whereas others are more aptly suited to another modelling approach (Mustafee et al., 2017).

Whilst all of the modelling techniques allow for complex and intricate simulations, agent-based modelling allows for the most flexibility and interactivity as it enables the behaviour of each individual agent to be modelled and controlled rather than only being able to dictate the behaviour of the population as a whole. Agent-based modelling requires a structure underpinning the model as a whole, hence it is often used in conjunction with another modelling technique.

2.1.1 The Reproductive Ratio

The reproductive rate, or ratio, is an essential measure of a how contagious viral diseases are and it appears across all of the epidemiology models discussed above. Often referred to as the R number, it essentially details, the average number of people who will contract a disease from each person with that disease (Diekmann et al., 2012). There is an important distinction to be made between the basic reproduction ratio (R_0) and the effective reproduction ratio (R).

The basic reproduction number R_0 is more of a theoretical figure which states the potential transmissibility of a virus if no one has been vaccinated, no one has had the disease before, and there's no way to control the spread of the virus (Diekmann et al., 2012). In reality, it is uncommon for all three of these conditions to be met, which leads to the effective reproduction number. The effective reproduction number (R) is the average number of secondary cases per infectious case in a population made up of both susceptible and non-susceptible hosts (Nishiura and Chowell, 2009). When fluctuations in the current R number are discussed in Covid-19 briefings on the news it is in reference to the effective reproduction number, as opposed to the basic reproduction number. The later should in theory remain the same throughout the life of a disease, assuming no fundamental characteristics of the disease change.

Each differing modelling approach contains a different way to approximate the reproductive ratio of a disease. For example, using the prior S.E.I.R., R_0 is calculated using this formula (Carcione et al., 2020):

$$R0 = \frac{\beta\epsilon}{(\epsilon + \mu)(\gamma + \alpha + \mu)}$$

R_0 can be used to predict the growth of a viral disease and more accurately reflects the reproductive power of the disease itself. It will remain constant throughout the life of a disease,

whereas R will vary over the course of an outbreak to reflect the external environment as well. When $R < 1$, the disease is said to be in the eradication phase, when $R > 1$, it is said to be in the epidemic phase, and when $R = 1$ it is said to be in the endemic phase (Delamater et al., 2019).

2.2 Pedagogical and Microworld Theories

Imitating the action of a real-world process or device over time is called simulation. Models are required for simulations; the model represents the main characteristics or behaviours of the chosen system or process, while the simulation represents the model's evolution over time (Banks et al, 2005). A simulation-based tool can be used to construct knowledge within the user in the following ways (De Jong and Sarti, 1994):

- tasks/challenges, learners should solve some specific task in a simulation environment
- demonstration
- experimentation, a structural way to explore a model
- explorations, a free discovery strategy, (play around with the simulation)
- testing hypotheses

Developments in technology over recent years have enabled web-based simulations to become a powerful tool in education and learning (Kirkley and Kirkley, 2005). Through web-based simulations, learners can interact with and attain experience in environments which would ordinarily be too costly, too time-consuming, too complex or too dangerous to experience through other means (Granlund et al., 2000).

Many researchers advocate that an effective simulator should build on the theory of constructivism, which argues that knowledge must be constructed by the learner themselves and cannot be simply transferred to the learner (Fosnot, 2013). Seymour Papert of M.I.T. argued that effective learning “will not come from finding better ways for the teacher to instruct but from giving the learner better opportunities to construct” (Papert, 1991).

This belief that to learn effectively a learner must be provided with sufficient opportunity to construct their own knowledge structures, drove the initial rationale behind microworld theory and design. Microworlds are a specific form of digital learning environments, which allow learners to explore and test their pre-conceived concepts and beliefs about elements of the world around them (Hoyles, Noss and Adamson, 2002). According to Brehmer and Dörner (1993) an effective microworld must contain three fundamental components:

Interconnectedness: Often referred to as complexity this essentially states that there should be several interconnected processes. This should render it impossible to do only one specific thing, as the side effects of each action by the user must also be taken into account within the microworld (Jervis, 1998). This interconnectedness means that the learner must be cognisant of multiple goals at once, and as they progress toward achieving their primary goal they must consider the effects their actions consequently have on a number of subgoals (Brehmer and Dörner, 1993).

Dynamics: In reference to microworlds, dynamics asserts that the decisions made by the user within the microworld change depending on previous actions within the simulation (Brehmer and Allard, 1991). It states that the decisions presented and made within the microworld must be made in real time as the context of the decision changes depending on the consequences of the decision makers actions. The decisions within the microworld are not independent and one decision can have a knock-on effect which can affect subsequent user decisions.

In-transparency: (or opacity) This states that actual underlying system that the user attempts to control cannot be ascertained easily. Instead, the user must actively interrogate and experiment with the system to attain a comprehension and understanding of the model upon which the system is built (Elliott and Coovert, 2017). Interaction and experimentation with the microworld should allow the user to gradually build knowledge of the underlying models and structure without having to obtain direct exposure.

These theories surrounding constructivism and microworlds coincide with active learning theory. Active learning attempts to cognitively engage students by having them partake in various innovative learning activities such as problem solving, role playing or debating to engage students and stimulate their desire to learn (Prince, 2004). Active learning is commonly associated with collaborative learning, where students are divided into teams and given a common goal to work towards. There have been several studies which have found that this methodology for learning is highly effective in improving students' understanding, engagement and long-term ability to recall upon knowledge of a particular topic (Hake, 1998; Prince, 2004; Silberman, 1996).

This research shows how simulations and more specifically microworld simulations can cognitively engage learners and enhance the learning outcomes of a tool. In conjunction with active learning and collaborative learning these theories can be used to shape a tool which is of great educational benefit to its users.

2.3 Human Computer Interaction

Human Computer Interaction is an ever-growing field of research which finds itself at the intersection of many different disciplines such as computer science, psychology, design and behavioural science. Human Computer Interaction (HCI) is *"a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them"* (Kjeldskov, 2003). According to Ware (2008) an interactive system should responsively return the most relevant information as the user interacts with the system which can allow the computer and the user to engage in a communicative dialog with the aim of achieving a certain task. As HCI simultaneously studies a human and a computer, it draws from research on both the human and the computer side. On the computer's side HCI focuses on techniques in programming, integrated development environments, computer graphics, operating systems and data visualisation (Hewett et al., 1992). On the side of the human, it focuses on supporting knowledge from cognitive psychology, human factors, communication theory, social sciences and linguistics among other things. Integral to the design of Human Computer Interaction is what is known as the "HCI Loop of Interaction" (Nguyen, 2012).

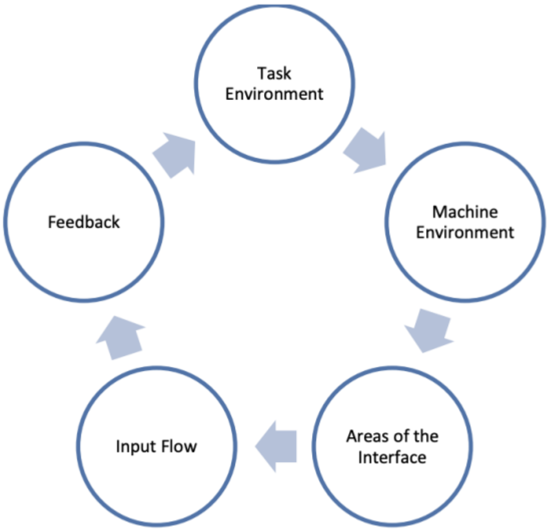

Figure 2.2: HCI's Loop of Interaction
https://www.theseus.fi/bitstream/handle/10024/43234/Nguyen_Hung.pdf?sequence=1&isAllowed=y

This loop essentially dictates the flow of information from the computer to the user and back again. The loop begins at the 'task environment' where certain conditions and goals are set for the user. The 'machine environment' stage of the loop, essentially dictates the hardware with which the computer relays information to the user, and the user can in-turn respond with. The 'areas of the interface' stage refers to the graphical user interface (GUI) which allows the user to receive information from the computer and respond accordingly. The 'input flow' and 'feedback' stages close the loop of interaction as the user's specific interactions are fed back into the system which then evaluates, moderates and confirms these processes before the loop starts over again (Nguyen, 2012).

An effective loop of interaction allows for the computer to act as an extension of the human brain's cognitive process to create a powerful cognitive feedback loop (Card er al., 1999). As technological developments improve, it allows these loops to become faster and more immersive allowing computer systems to more effectively expand the capabilities of digital learning as the mind and the computer interact as a single cognitive entity. When a Human Computer Interaction system achieves this successfully "*the computer display seems like part of the thinking process, rather than something to be consulted.*" (Ware, 2008)

Human-Computer Interaction theory can aid in the design and implementation of an effective interactive learning environment such as the one proposed in this project.

2.4 Epidemiology Data Visualisation Techniques

Advancements in technology and data visualisation techniques have allowed huge, complex sets of critical data to be communicated clearly to the general public, by displaying it in such a way that the human mind can easily comprehend (Kirk, 2016). This section analyses some of the common techniques used to visualise data within epidemiology and assesses their potential suitability for this project.

2.4.1 Techniques for visualising disease simulation

The effect that people's understanding of, and subsequently, behaviour around viral diseases can have on the overall impact and reproductive rate of these diseases, makes their understanding of paramount importance. A variety of data visualisation techniques have been used throughout this pandemic to innovatively depict the enormous amounts of data gathered everyday all across the globe, in an effort to attain a widespread public understanding of the risks that are associated with exponential growth in these contagious diseases. Some of the interactive data visualisation techniques discussed in this section are best viewed on-line at the link provided.

Map Visualisations

Map Visualisations depict the prevalence of a disease in certain geographic areas. Whether it be through dot density, or through colour shading, they effectually portray which regions are suffering the most and allow this data to be easily and intuitively interpreted by the user.

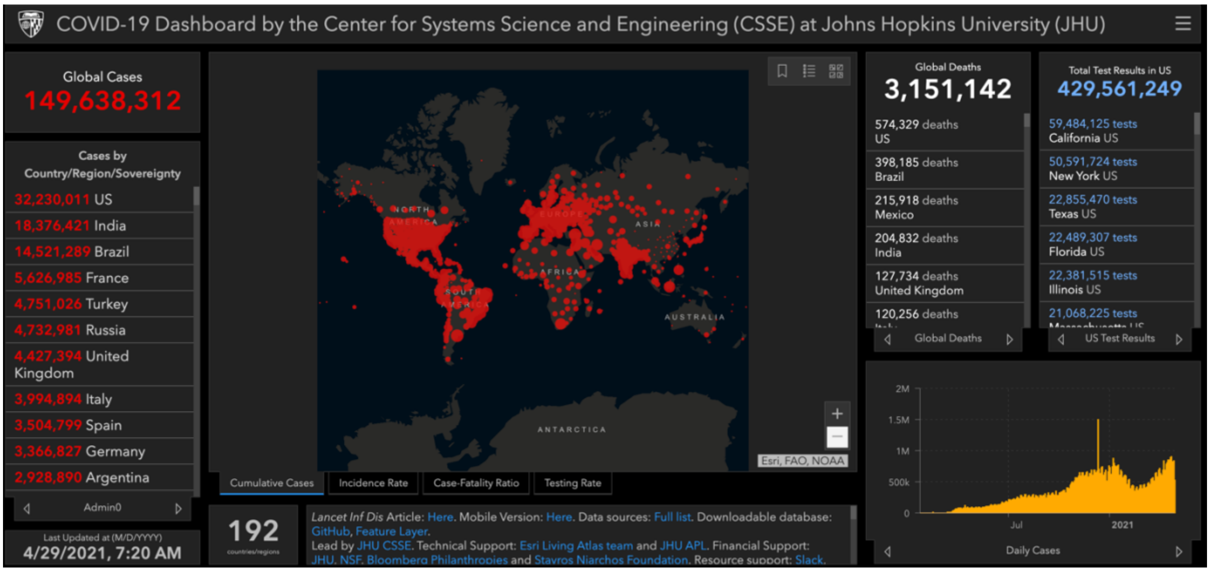

Figure 2.3: Global Covid-19 Cases
https://coronavirus.jhu.edu/map.html

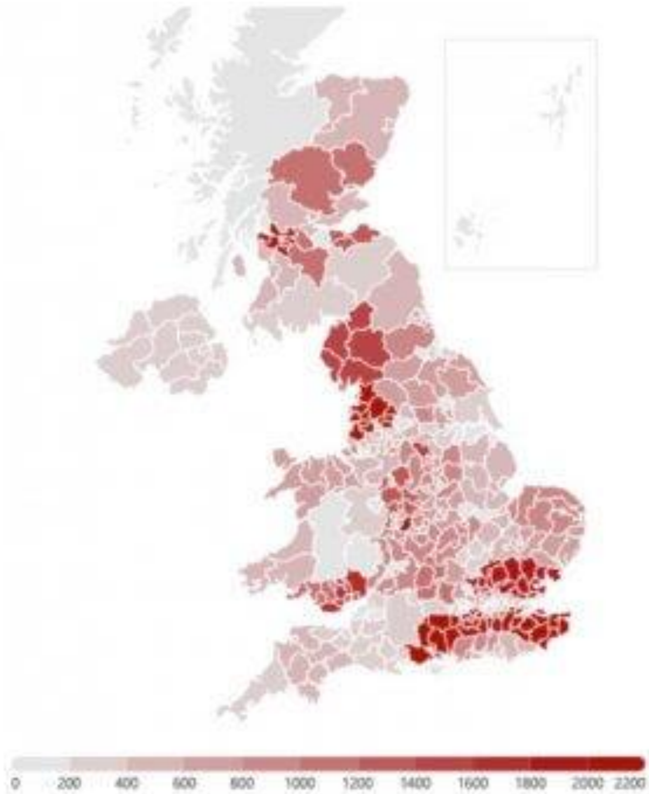

Figure 2.4: UK Cases by County
https://www.msn.com/engb/news/coronavirus

Conventional Charting Techniques

There exists an array of conventional charting methods which are used to depict disease data. From bar charts comparing country by country case and vaccination numbers, to line graphs used to explain the 'flattening of the curve' these can provide a useful and practical visualisation which can aid users in understanding and comparing vast amounts of data.

Whilst definitely an effective visualisation technique, when used as the basis for a simulation tool these charting methods can appear abstract and remove the user from the significance of the data. These charts are potentially better used as an accompaniment to a more engaging visual rather than the primary visualisation technique of a simulation tool.

The following is a line graph produced by HSE as an educational advertisement for how the peak of Covid-19 cases can be mitigated and controlled.

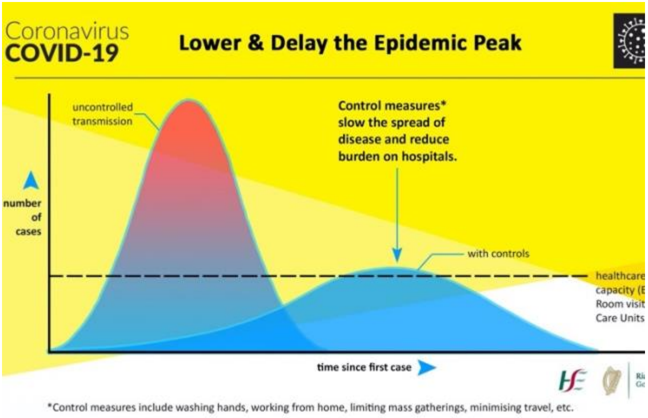

Figure 2.5: HSE chart explaining "flattening the curve"
https://www.thejournal.ie/what-does-flattening-the-curve-mean-5047757-Mar2020/

The second line graph depicts the outcome of a Covid-19 simulation built upon the S.E.I.R. model.

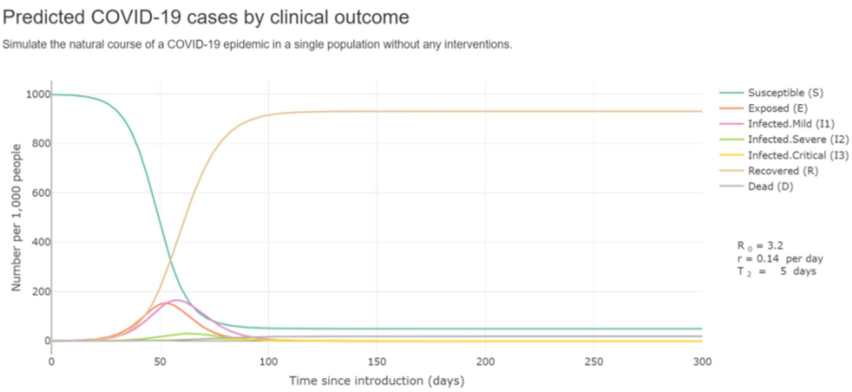

Figure 2.6: Line Graph of S.E.I.R. model prediction
https://alhill.shinyapps.io/COVID19seir/

Cluster Networks

Cluster network visualisations are a visualisation technique used to depict the connections between a large network of individuals, and can provide another fascinating and engaging visual technique which portray the interconnectedness of Covid-19 cases. The figure below shows an interactive network of cases in Singapore, within which a user can explore how clusters and outbreaks were started and track their reach.

These networks provide an interesting visual which is very useful for real-life traceability purposes, however it is not suitable for a dynamic, interactive simulation in which a disease spreads outward from an initial point depending on user-selected variables.

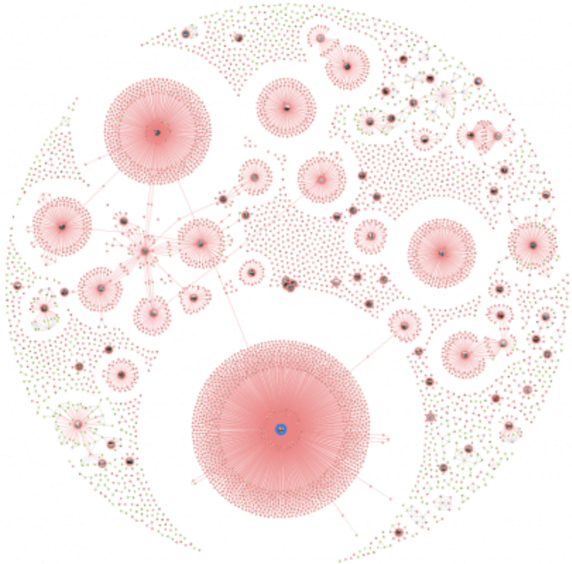

Figure 2.7: Network of Covid Clusters in Singapore
https://co.vid19.sg/singapore/cases

Square tile-grid

Another useful technique for visualising the spread of a viral disease is the square-tile grid. This motionless grid of square cells is used as a map of susceptible people. The disease starts with one initial cell (patient zero) and then spreads outwards to its surrounding cells depending on the contagiousness of the disease.

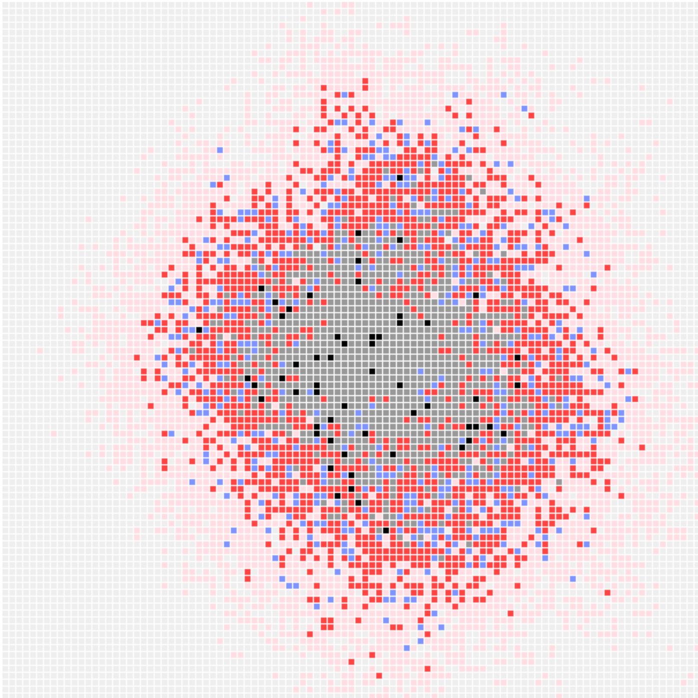

Figure 2.8: Square Tile-Grid used in 'Outbreak'
https://meltingasphalt.com/interactive/outbreak/

This grid visualisation technique can be improved further by adopting a hexagonal grid as it is the most circular shape which can be used to tile a grid which allows for the most realistic simulation of a viral disease outbreak.

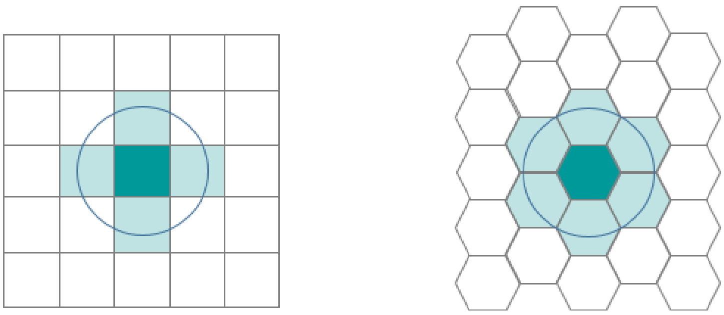

Figure 2.9: Why hexagonal grids give more accurate simulations
https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-statistics/h-whyhexagons.htm

This does provide an effective method to depict the spread of a viral disease, and could allow a user to alter a set of variables and clearly witness the differences their changes had on the rate at which the disease spreads, however the square-tile grid is quite impersonal and can be quite an abstract way to relay the data if the aim of the tool is to visually stimulate and engage the user.

'Billiard Ball Simulations'

Billiard Ball Simulations are simulations in which circular agents bounce around within a set space interacting with each other. These have been used to model many things, from atomic theory to Covid-19. In the context of the spread of viral diseases, these simulations allow infected agents to travel amongst a population of other agents, potentially transmitting the disease when they come into contact with one another.

This technique for visualising simulations provides a highly dynamic and engaging visualisation in which a user can clearly track both the rate at which a disease is spreading and also how and where it is spreading. Furthermore, a user can easily witness the effects of certain changes as the simulation runs on, allowing for consequences and user choices to be clearly visualised and understood.

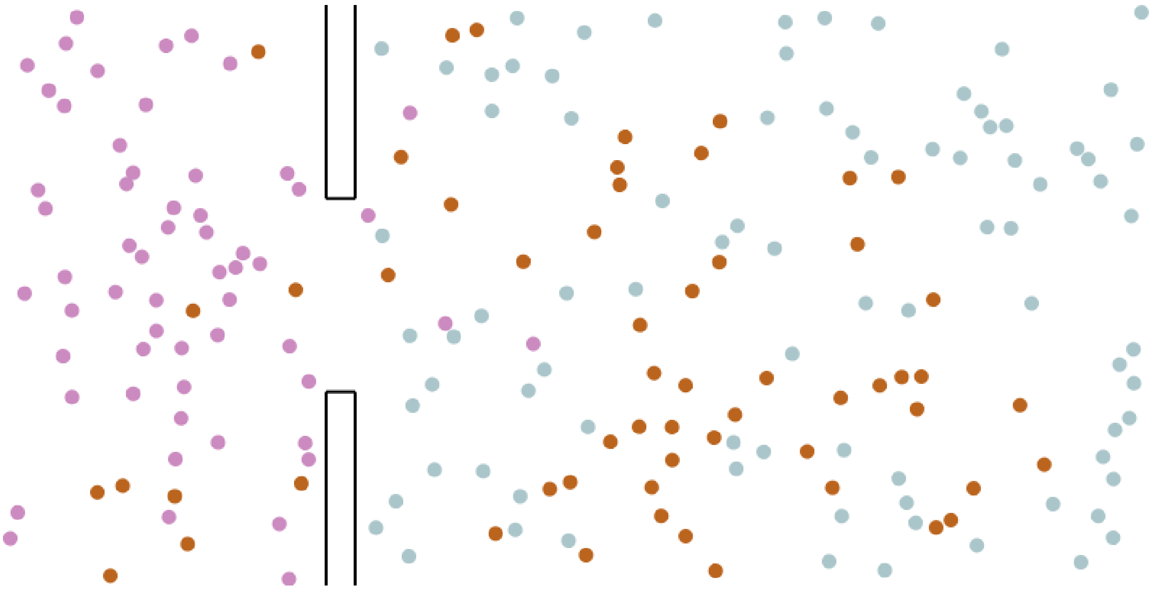

Figure 2.10: Billiard Ball Covid Simulation on the Washington Post
https://www.washingtonpost.com/graphics/2020/world/corona-simulator/

These visualisation techniques provide a broad array of different ways to depict Covid-19 data and simulations in an stimulating and engaging manner. Elements of these techniques were combined and altered to shape the design process discussed later in the report.

2.5 Similar Applications

There are a selection of similar applications and educational tools developed with the intention of teaching about this topic, but none that this author identified that combined both engaging visual stimulation with interactivity for the user. However, there were some applications that provided one or the other and would go on to provide inspiration for and inform later features.

2.5.1 Videos/ Noninteractive Simulations

This section analyses some of the interesting educational simulations and videos discovered by this author which provided interesting visualisation techniques but provided no element of interactivity for the user.

"Simulating an Epidemic" – 3Blue1Brown

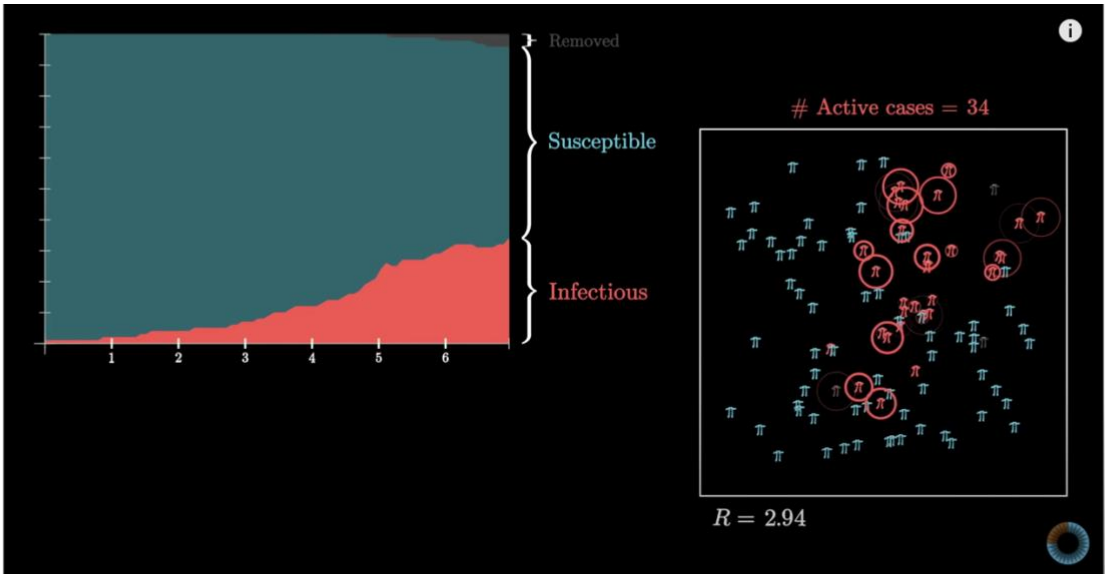

Figure 2.11: 3Blue1Brown pandemic simulation video

URL: https://www.youtube.com/watch?v=gxAaO2rsdIs

Platform: YouTube Video

Overview: This is an informative YouTube video by the channel '3Blue1Brown' in which a variety of simulations are ran to demonstrate how a virus can spread through a population and how changing certain variables can affect the rate at which this virus spreads.

Description: In this video the creator implements an SIR model (Susceptible, Infectious, Recovered) and runs various simulations of a population to show the viewer what changes can affect the spread of a contagious disease. The video delineates how altering variables such as probability of infection, proximity to others, and the percentage of asymptomatic cases can determine how fast a virus is spread. Key interesting concepts are introduced such as how a central hub like as a school or workplace can vastly increase the rate of transmission of a disease. The animations within the simulation are an alteration on the previously discussed billiard-ball model for visualising a population.

Evaluation: This is an interesting and educational video that implements several novel concepts for demonstrating the spread of a disease. The animations and overall aesthetic of the simulations are quite engaging in its simplicity and clarity whilst still being an effective way to visualise an epidemic. However, as this is a YouTube video it offers no element of interactivity for the user and hence does not offer the same element of cognitive engagement that an interactive tool does.

“Epidemic, Endemic, and Eradication Simulations” – Primer

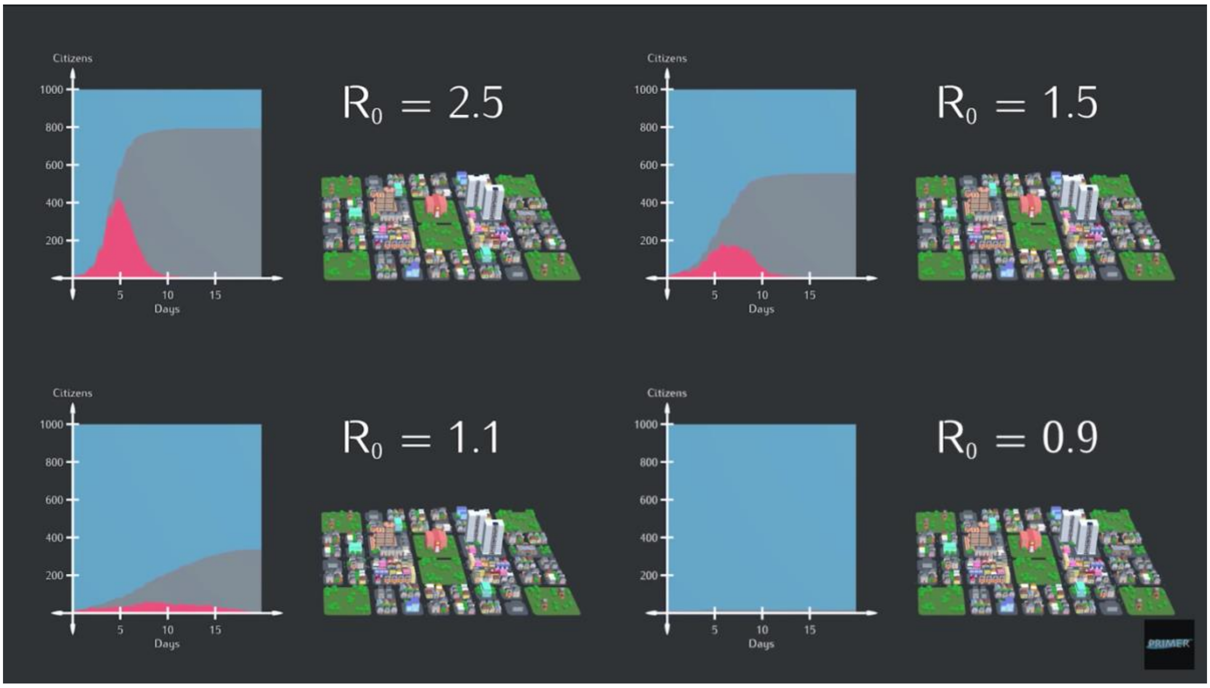

Figure 2.12: City based pandemic simulation video

URL: https://www.youtube.com/watch?v=7OLpKqTriio

Platform: YouTube Video

Overview: This video is very similar to the previous video mentioned, the primary difference being that this video implements a mock city to visualise the spread of the data.

Evaluation: While this video is another effective educational tool, the implementation of an artificial city, whilst novel does not offer much in terms of educational benefit and is not conducive to learning. It is quite obstructive in that it makes it hard for the viewer to see the actual transmission and spread of the virus. Once again, the video platform lacks the interactive element that is a central tenet of this project.

“Why outbreaks like coronavirus spread exponentially, and how to flatten the curve” - The Washington Post

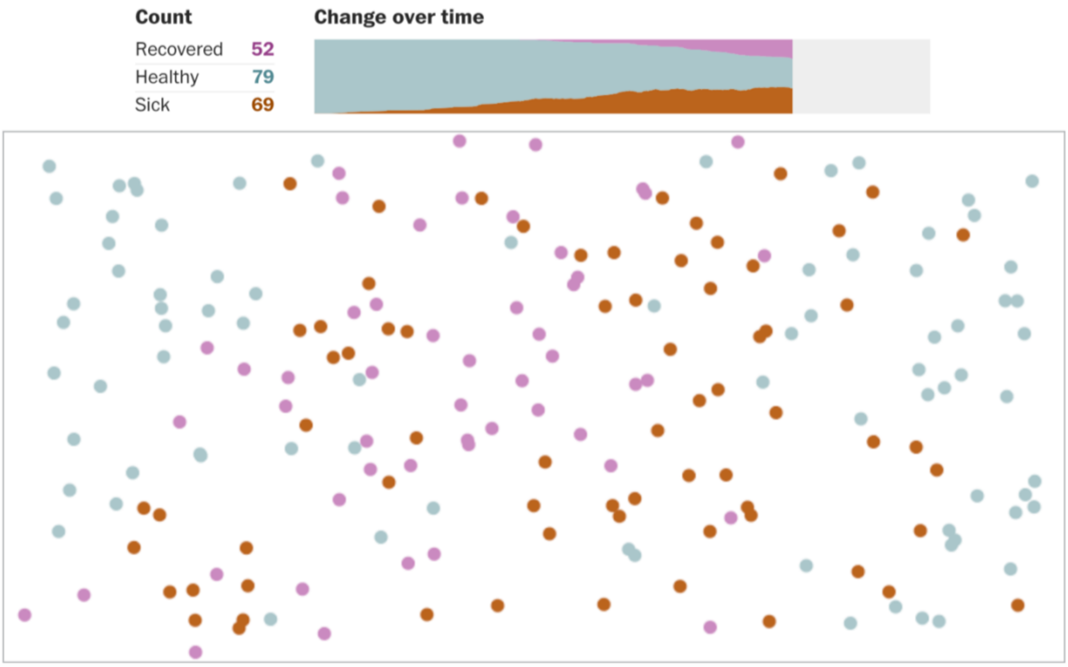

Figure 2.13: Covid simulation from The Washington Post

URL: https://www.washingtonpost.com/graphics/2020/world/corona-simulator/

Platform: Online Newspaper Article

Overview: This is an article in The Washington Post by journalist Harry Stevens, in which he discusses the dangers of exponential growth and demonstrates these dangers using intermittent simulations.

Evaluation: This is a very informative article, which eloquently integrates data visualisation in the form of billiard ball simulations (screenshotted above) to depict the exponential spread of a disease. The article is effective in portraying the effect that altering human behaviour can have on the damage caused by an epidemic. However, the simulations in the article are pre-set to demonstrate certain things and cannot be altered or interacted with by the user, limiting the educational capability of this article.

2.5.2 <u>Interactive Tools:</u>

This section explores some of the similar tools which offer interactivity.

The Epidemic Game Maker – Ken Kahn et al.

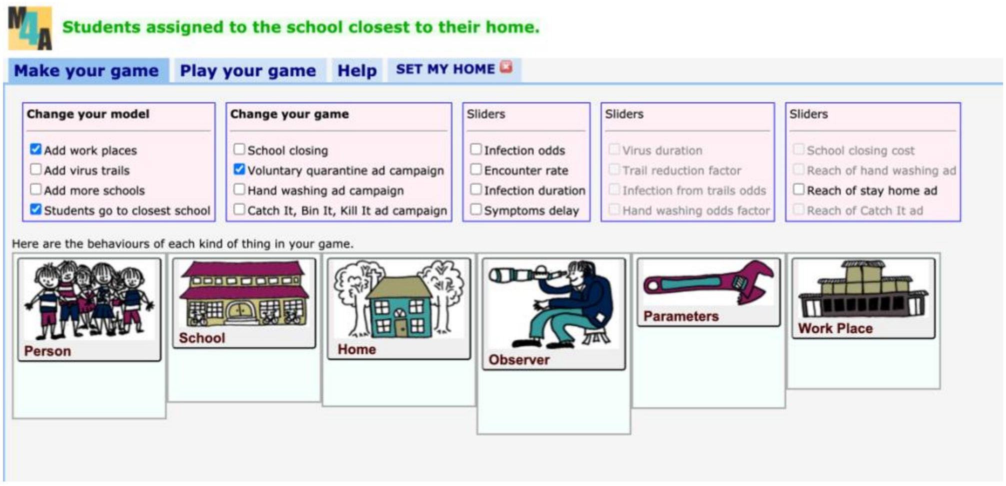

Figure 2.14: Initial options screen when building a game within the Epidemic Game Maker

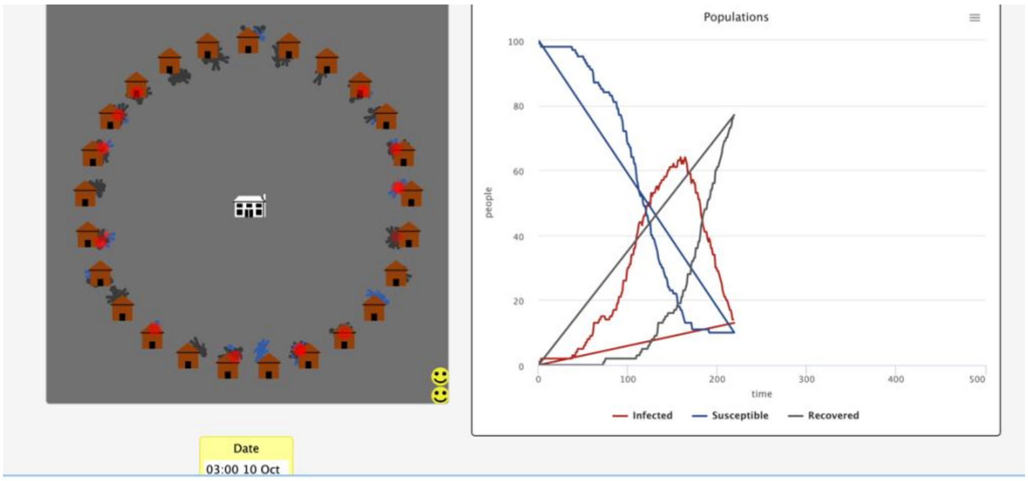

Figure 2.15: An example game built within the Epidemic Game Maker

URL: http://m.modelling4all.org/p/en/sse.html

Platform: Web Application (2012)

Overview: This web application allows the user to select from a variety of different options and configurations to build an epidemic modelling game.

Description: This constructionist learning tool gives users access to a myriad of different configurable variables in their goal of creating their own epidemic modelling game. The learner selects which aspects they want included in their game before submitting their choices at which point the game is developed and they can run it multiple times and interact with it. The simulations are built on a hybrid of the S.E.I.R. model and agent-based modelling which allows for behaviour to be programmed onto the population as a whole, but also allows for the behaviour of each individual agent to be independent and configurable through the variables. The website also allows the user to change the actual fundamentals of the models and experiment with the code its built on to allow even more flexibility to the simulator.

Evaluation: This is a very interesting educational tool which allows for a huge amount of variability in what games its users can create. Its hybrid modelling system which combines the S.E.I.R. model with agent based modelling works very well and allows for more configurable variables both on the macro and microscopic level. Its stochastic elements combined with the considerable flexibility allow for huge replayability as there are thousands of unique games which can be created. The visualisation techniques within the game have become somewhat outdated however, as developments in technology and data visualisation since the development of this tool have improved considerably. Furthermore, the lack of structure or narrative to the tool, whilst it does allow for considerable experimentation and exploration, can make it difficult to glean concrete knowledge from the tool. The tool could benefit from a narrative structure or challenge-based learning principles, if it were to be used as a classroom enhancing learning environment like the proposed system for this project.

"Epidemic Calculator" – Gabriel Goh

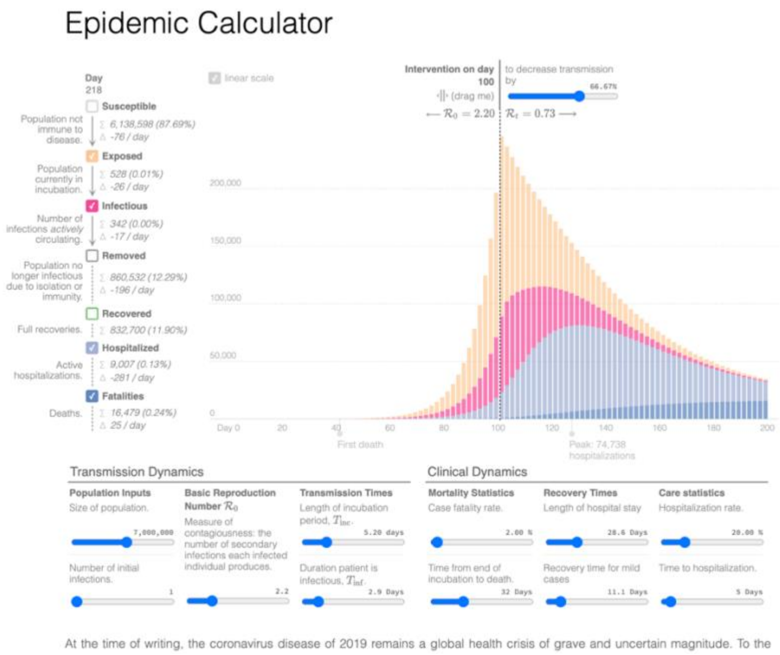

Figure 2.16: Epidemic S.E.I.R Calculator

URL: http://gabgoh.github.io/COVID/index.html

Platform: Web Application

Overview: This is a web application created by Gabriel Goh which allows the user to change a selection of variables using slider bars and then resonates this data on the graph above.

Description: This application uses complex models and algorithms to calculate a multitude of figures based on the users selected input levels. It is built upon the aforementioned S.E.I.R. model and allows the user to alter an array of variables which affect how disease is spread. The impact of these alterations can be seen instantaneously on the bar chart above and through the total figures on the sidebar on the left-hand side.

Evaluation: This is a very well designed and scientific tool for demonstrating how certain variables can affect the way in which a disease is spread. All of its output figures are backed up with scientific calculations and formulas. However, the user interface is somewhat overbearing, with too many figures being thrust upon the user at once. The complexity of the model combined with the overload of information can make it difficult to glean any actual sustaining knowledge from the tool, especially for users within the age group that this project is aimed at.

"What Happens Next? Covid-19 Futures, Explained with Playable Simulations" – Marcel Salathé

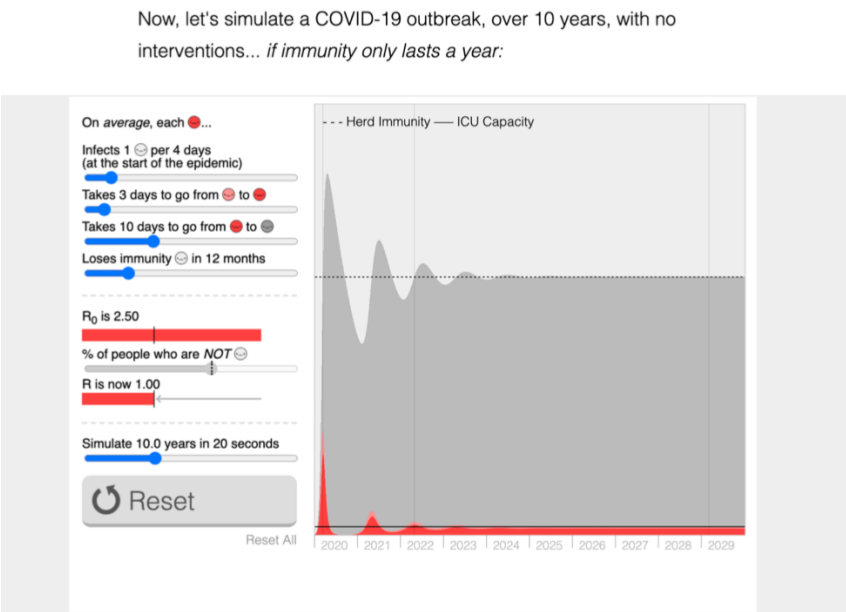

Figure 2.17: Future Covid Graph Simulator

URL: https://ncase.me/covid-19/

Platform: Web Application/Article

Overview: This is a web application/article which discusses possible futures for Covid-19, created by epidemiologist Marcel Salathé.

Description: This article also uses the SIR model to portray various different possible outcomes for how Covid-19 might spread in the years to come. The article gradually introduces new variables which may affect this future spread and then backs up these teachings by letting the user alter said variables and witness the affect it has on the graph seen above. The model becomes more and more complex as the article progresses, with an increasing number of factors which can be changed to attain different results.

Evaluation: This is a very informative article and a powerful educational tool for teaching about the spread of Covid-19. The way it introduces the variables one by one with a description of what it is and how it might affect change coming first, followed by a simulation in which the user can change this variable is particularly effective. It allows the user to piece by piece build up an understanding of how the final model works and at each point consider the effect each variable might have on the spread of the disease. However, the data visualisation techniques used throughout the article are not particularly effective for imparting knowledge upon the user. The simple graph shows the resulting outcomes but does not effectively portray how the disease is spreading like some of the videos and simulations discussed previously.

"Outbreak" – Melting Asphalt

Figure 2.18: Square-Tile Grid Covid Simulation

URL: https://meltingasphalt.com/interactive/outbreak/

Platform: Web Application/Article

Overview: This is another article/web application, quite similar to the previous one discussed in that it explains how certain variables could affect the spread of a virus within a population and then allows the user to alter these variables and witness the effects.

Description: Similar to the previous application discussed, this article gradually introduces variables which the user can alter with slide bars and then run simulations to observe the effects this has on the rate of transmission of a virus.

Evaluation: This is another very informative article which uses interactive simulations to great effect to allow the user to make their own observations and conclusions about what affects the spread of an infectious disease. However, whilst an improvement on the previous article the data visualisation technique used is not particularly captivating or engaging for the user. The square tile-grid pattern is quite impersonal and abstract and although it does provide an accurate demonstration of the spread of the virus, a more relatable visualisation technique such as the ones seen in the videos could further accentuate the didactic benefits of a tool like this.

2.5.3 Comparison of Similar Applications

	Interactivity	Engaging Visual Aid	Gradual Introduction of Variables	Explanation of Logic	Challenge Based Learning	Replayability
3blue1Brown Video	✗	✓	✓	✓	✗	✗
Washington Post Article	✗	✓	✓	✓	✗	✗
"The Epidemic Game Maker"	✓	✓	✗	✗	✗	✓
"Epidemic Calculator"	✓	✗	✗	✗	✗	✗
"Outbreak"	✓	✗	✓	✓	✗	✗

Figure 2.19 - Table comparing similar applications

This table compares the previously analysed similar applications under a few certain key criteria which this author identified as fundamental to the system required for this project. This author has identified the useful functionality and also the drawbacks and limitations of the systems currently out there and this analysis was used to shape the development of this author's systems, taking inspiration from the most effective features and developing further upon those that could be improved.

2.6 Discussion

Whilst a couple of the systems were particularly informative and possessed several key features, they lacked the engaging visual stimulants that some of the other, less interactive simulations possessed. This project aims to combine the engaging visuals of some of the YouTube videos analysed with the interactive elements of the other systems to create an application that can both, visually stimulate the learner whilst also cognitively engaging them to consider the effects of the changes they make within the simulation.

This author also identified several features lacking in any of the systems analysed above which could be implemented to enhance the user experience. Stemming from the previously discussed constructivism theory, a challenge-based learning element could be introduced to enhance the pedagogical effectiveness of this tool and advance its learning outcomes. These challenges could be designed to illustrate important dynamics and trade-offs and would help to engage the learner and allow them to construct knowledge about the key factors at play within the complexity of epidemiology. This would also allow for results comparison, a fundamental attribute in constructionist learning, and could be implemented so that the user could compare how effective their strategy was against what they had tried previously and also against what other users in their class or group implemented. Furthermore, the stochastic elements absent from the majority of these applications renders them essentially redundant after one watch/play through, which could be improved by incorporating variability into the simulations to grant the tool an element of replayability.

In conclusion, it is evident that epidemiological modelling and understanding can be very complex and difficult to comprehend. However, through the use of contemporary technology combined with pedagogical and human computer interaction theory, tools can be developed which can allow learners to develop a greater understanding of how these systems work in an engaging and innovative manner. This project attempts to combine these elements to build upon the similar applications discussed above and create a tool which can allow learners to construct their own knowledge and understanding of viral diseases, without having to learn the complexities of disease modelling.

3 Project Specification

3.1 Project Considerations

The simulator should be accessible and usable for Transition Year secondary school students (16/17 years of age) in Ireland, however should hold value for other demographics as well. With this in mind, certain considerations were taken into account during the design process.

- Prior Knowledge: Whilst epidemiology does not appear on the curriculum for Junior Certificate Science or any other subject, it is assumed given the global outreach of this ongoing pandemic, that the students will have some level of familiarity with Covid-19, the key factors at play and some of the metrics used to monitor and analyse these viruses.

- Learning environment: The simulator will primarily be used within a classroom environment, whether that be over Zoom or within a physical classroom with computers. However, the tool still may be used by an individual outside of the context of a dedicated class, so it must be self-explanatory.

- Accessibility: The tool must be intuitive, usable and accessible for all students regardless of technological literacy. Building on Human-Computer Interaction theory, it should provide a system which can be seamlessly understood and controlled by the learner.

- Ethics: The tool must take caution not to mislead or misinform students about viral diseases such as Covid-19. In this respect, it is important that the tool markedly clarifies that assumptions and simplifications are made within the model, and that it does not act as a scientific attempt to accurately model or predict real-life Covid-19 outcomes.

3.1.1 **Project Scope**

Taking into account the complexity and vastness of epidemiological modelling as outlined in the preceding chapter, certain constraints had to be placed on the scope of this project given the time restraints and overall objectives of the project.

- To make the tool as engaging and intuitive as possible for the learner a variety of assumptions and simplifications will have to be made when modelling the disease simulation. This will render the simulation tool a low-fidelity simulation which focuses more so on delineating the key concepts to the learner, rather than attempting to precisely model Covid-19. This avoids overwhelming the learners with complexity and too much variability which could detract from the fundamental educational benefit of the tool.

- The tool is designed for use by Transition Year students, however it could provide educational value to other age demographics as well. However, given the time constraints of the project and the ethical approval required to survey many different age groups in different contexts, it was decided that the focus for evaluating the tool would be solely with Transition Year students as opposed to testing it with other groups as well.

- Furthermore, it was decided that given the need for an expansive screen size to depict the simulations proposed within this tool, that development would be focused on accessibility for PCs and laptops and would not be suitable for use on small mobile devices.

3.1.2 Functional Requirements

Covid-19 Simulations:

- The user must be able to clearly distinguish people's states (healthy, infected, dead etc).
- The user must be able witness the transmission of the disease from an initial patient to other people within the simulation.
- The user must be able to configure certain variables in real-time, which have a clear visual impact on the outcome of the simulation.
- The simulations must have stochastic elements so that the outcome of the simulations vary with each run.
- Should the user exceed their monetary budget, the variables should be reset and locked at their initial value for the remainder of the simulation.
- The user must be easily able to pause, resume or reset the simulations at any point using buttons.
- The tool should set a series of challenges for the user, but should also have a free-play version available for experimentation.

Simulation Results:

- When the simulation has ended, either after a certain period of time has elapsed, or the disease has died out, the results of the simulation should automatically be displayed.
- The user must be able to see the effective R number, the percentage of the population killed and the total amount of money spent over the duration of the simulation.
- A live graph showing the proportion of the population who are susceptible, infected, immune or dead should be displayed in real-time whilst the simulation is running, and also with the other results at the end of the simulation.
- Whether the user has succeeded or failed the challenge set for them should be clearly displayed.

3.1.3 Non-functional Requirements

Accessibility:

- The tool should operate effectively on a standard laptop or PC.
- The tool should be compatible with at least the 4 most commonly used internet browsers (Google Chrome, Safari, Mozilla Firefox, Edge).
- The tool should be able to handle multiple users on the site at once and should be scalable for further growth if needed.

Documentation:

- The tool should provide an introductory guide giving a brief outline of what the purpose of the tool is and how it works.
- The tool should gradually introduce new elements to the simulation and should explain what each one is as it is added.

Usability:

- The tool should be suitably usable for the age demographic of Transition Year students.
- The tool should use effective data-visualisation techniques to allow the user to easily visualise the effect of the changes they have made.
- The tool should incorporate Human Computer Interaction principles to cognitively engage the user.
- The tool should be useful for an individual learner as well as in a collaborative learning environment.
- The tool should be intuitive and not present a steep initial learning curve to its users.

3.2 Initial Technology Choices

Given the functional and non-functional requirements of the system, a web application was deemed to be the most suitable methodology for the development of the tool. A web application is easy to access from multiple devices at once making it suitable for deployment in the classroom environment required for the testing of this tool. The fundamental drawback of a web application is that it requires a solid internet connection or else performance may suffer. This can provide an issue in online learning environments, where multiple users are using the application from various different places, with varying internet connections. However, technology in recent years has seen a paradigm shift from desktop applications towards web applications, and as such, many of the unique and innovative data visualisation technologies of today are developed for web applications. Furthermore, web applications allow for rapid development because updates can be pushed to the web and users do not have to install or download anything to access the latest version of the application. These advantages made the development of a web application a natural fit for this project. To develop a web application, several technologies had to be utilised.

HTML & CSS
HTML & CSS are two of the most prominent technologies used in the development of Websites. HTML (Hypertext Markup Language) dictates the contents of the page and how it is structured, while CSS (Cascading Style Sheets) dictates the aesthetic and styling of this content. In tandem with graphics and scripting, HTML & CSS provide the foundations of the development of Websites and Web Applications. Given the unique visualisations required for this tool, no out-of-the-box toolkits such as Bootstrap were used, as pure HTML & CSS allowed for more customisability and more seamless integration into the simulation.

JavaScript
JavaScript works in conjunction with HTML & CSS to provide scripting to web pages. This allows for the integration of interactivity and complex functionality within a web page. JavaScript is the most commonly used language to program the behaviour and interactivity of webpages, which means it has very wide support across many platforms. Furthermore, JavaScript has an enormous selection of frameworks and libraries at its disposal which can further accentuate the functionality of the language and provide some very useful visualisation and interactivity technologies for the development of this tool.

Heroku
Heroku is an online cloud platform which allows users to build, deploy, monitor and scale website applications. Heroku focuses on making the process of deploying, updating, scaling and tuning website applications as simple and straightforward as possible, which allowed for the focus of development to be on the unique functionality of the application and not on maintaining and managing its server infrastructure. Similar alternatives such as Google's Firebase and Amazon's AWS were considered as well, however Heroku was ultimately chosen as the platform to host this web application due to the author's familiarity with it, plus its integrated GitHub functionality made committing and pushing changes to the server an intuitive process.

3.3 Data Visualisation technology choices

There is a wide array of JavaScript libraries and frameworks available for data visualisation. In this section a selection of these libraries will be analysed and considered for their suitability for the requirements of this project. The criteria considered for use include the compatibility across various devices and browsers, the flexibility the library provides for designing and customising visualisations and the level of documentation and support available for the library.

3.3.1 D3.js

D3.js is one of the most widely used and popular data visualisation frameworks available. It is a powerful framework that helps to produce dynamic, interactive data of all kinds using the power of HTML5, SVG and CSS3. It uses web standards, and is framework agnostic, meaning it can work with React, Vue or any other JavaScript framework, offering excellent compatibility. Similar to jQuery, D3 works with selectors to select DOM elements. It then offers various manipulations and events to these DOM elements. In this sense, D3 is more of a lower-level library compared to some other strictly charting solutions, so it does require more boilerplate code to get the same results. However, in turn it offers greater capabilities for customisation and flexibility. Its functionality for such a wide array of use cases has led it to be labelled as far more than a data visualisation framework. D3 has remained at the forefront of data visualisation due to many more modern-day frameworks being D3 based, and as new technologies emerge the vast D3 community develops new libraries to keep it up to date.

- Very active community with a vast collection of examples and documentation.
- Steep Learning Curve
- Lower-Level so allows for greater customisation to design unique and novel methods for data visualisation.
- Many libraries built on top of D3 which provide the same functionalities as many of the other prominent data visualisation libraries and frameworks.
- A common choice amongst many developers and publishers, even the preferred library used by The New York Times.

3.3.2 Google Chart Tools

Google Charts is a classical data visualisation library that takes user-supplied data to create a vast array of graphical charts for all tastes and purposes and offers plenty of configuration options for developers. It only requires a basic knowledge of JavaScript, HTML and CSS to create visual custom charts.

- Visualisations can be made rapidly with very little background knowledge required.
- It is not open source, follows Google API's terms of use. However, Google regularly updates and maintains it, offering good compatibility across the web.
- Interactive elements are limited, and it is somewhat restricted when it comes to developing unique visualisations such as the ones required for this project.

3.3.3 p5.js

p5.js is a free and open-source JavaScript library based on the core concepts of the Java based Processing Language. It offers various capabilities that make it easy to develop animated and interactive unique programs. There is a large community of users and a vast repository of documentation and sample code available.

- Users benefit from over Processing’s 15 years of growth of their codebase and examples, all of which can easily be converted into p5 code.
- Offers excellent customisation and flexibility allowing the user to create unique and bespoke methods for data visualisation.
- It’s simplistic, accessible nature makes it easy to create minimalistic visualisations, which can then be developed to add more and more complexity.
- Does not offer built in rendering, the user must write all the rendering code within the drawing loop.

3.3.4 Chart.js

Chart.js is an open-source data visualisation library available for free for JavaScript. It allows for simple integration of interactive, animated charts into a webpage. It is compatible across all modern browsers and dynamically resizes graphs for different screen sizes. There is a wide range of ready to go graphs which can be customised and tailored to the user's specific needs.

- Visualisations can be made quickly and easily from pre-set formats.
- Formats can be easily customised and configured.
- Does not allow for bespoke, unique visualisations but caters for simple visualisations very effectively.
- Charts are animated and interactive.

3.3.5 Choice of Visualisation Technology

Below is a table comparing these libraries under the range of selection criteria.

Library	Simulation Visualisations	Chart Visualisations	Extensibility	Compatibility	Learning Curve
D3.JS	Allows for unique and bespoke visualisations stemming from a wide range of sample visualisations	Wide range of modules and community examples which can be tailored and customised	High	Compatible with all modern browsers	Steep, difficult to begin with but comfortable once familiar
P5.JS	Allows for unique and bespoke visualisations to be created from the ground up	Wide range of modules and community examples which can be tailored and customised, or developed from scratch	High	Compatible with all modern browsers	Easy to get started, can get tricky when building complex systems
GOOGLE CHART TOOLS /CHARTS.JS	Limited availability for customisable unique visualisations	Ready to go, customisable, easy to integrate charts	Low	Compatible with all modern browsers and older IE versions	Easy, very little background knowledge required

Figure 3.1 - Table comparing visualisation libraries

The libraries analysed above, are three of the most popular for visualising data not only within JavaScript, but also across the web as a whole. Based on the analysis conducted and presented above, D3.js was selected as the framework of choice for the development of this web application for several reasons:

- Despite its initial steep learning curve, there is a vast community of users who provide documentation and example code.
- It is the gold standard of data visualisation in JavaScript, with many other libraries based upon D3.
- The possibilities it offers for interactivity and customisation are endless, making it suitable for the unique and complex data visualisations required for this project.
- It is fast and light on system resources. Visualisations can be easily hosted on the web across browsers.
- There is a large repository of visualisation collections available, which can be easily customised and built upon to add extended functionality.

However, in the early stage of developing this tool it was decided that p5.js would be more suitable for the further development of the tool. Although D3.js is a very powerful library with a huge selection of visualisation techniques which can be built upon, in order to create the unique visualisations required for this tool it proved difficult to overcome and work around some of the pre-set functionality within the library. For this reason this author determined that the p5.js library was better suited to meeting the requirements of this project. There is little to no pre-set functionality within the p5.js library which means that all visualisations must be built up in their entirety by the user. Whilst this can prove tedious as all rendering code must be written from scratch, it allows for complete flexibility and customisation of the visualisations created. This ultimately proved to be the correct decision as it allowed for the efficient development of the final simulator. Chart.js was also used in conjunction with p5.js to create the animated real-time graph which would be displayed alongside the simulations.

3.4 System Architecture

This section explores a variety of system architecture options for rendering the tool. Responsiveness, load times, and compatibility with current technology options such as p5.js are among the selection criteria.

3.4.1 Client-side Rendering (CSR)

When rendering on the client side, a server sends the browser a basic HTML document (with the relevant styles and scripts), and JavaScript generates the rest of the web application dynamically.

- Can build interactive applications with quick response times.
- Initial load time can be slow, but application generally runs quickly after that.
- To boost load times, a static front-end can be hosted on a content delivery network.
- Reduces the amount of work that the server has to do.
- It's easy to set up.

3.4.2 Server-side rendering (SSR)

When using the more traditional server-side rendering, browser requests are sent to the server which responds with a completely rendered page.

- A new page is generated and returned after each interaction with the system which is fine for static sites but can cause latency issues for a highly interactive web page.
- Increases the server's load.
- Better optimisation for search engines.

3.4.3 Hybrid Rendering

Another common rendering technique is a combination of client and server-side approaches, in which the server sends the client a completely rendered page and then lets the client's JavaScript package handle the rest.

- Requires code to be integrated into both a client-side and a server-side framework
- Complex to set up.
- Increases the server's load.

3.4.4 System Architecture Choice

Stemming from the analysis conducted on these system architecture approaches, client-side rendering was chosen as the architecture for this system for the following reasons:

- CSR allows for highly interactive applications due to its quick response times, which suits the interactivity elements of the required application.
- Within the p5.js library, all of the visualisation and rendering is done within the browser on the client's side to enhance the user interaction, and thus it is more compatible with a system that also utilises client side rendering.
- Heroku, the chosen hosting and deployment platform, allows for simple integration of client-side rendering.
- Without the requirement for large server strain caused by the other architectures, CSR applications prove to be highly scalable.
- Whilst initial load times could be reduced by implementing a hybrid rendering system, it is not a functional requirement of this project and the complexity of implementation would not significantly improve the usability of the system as the responsive interactions would still be rendered at the same speed with CSR.

3.5 Model Design

One of the central tenets of this tool was finding a suitable way to model a population of people through which a viral disease could spread. A hybrid simulation model of the S.E.I.R. model and Agent-Based Modelling, similar to the technique used in the aforementioned *'Epidemic Game Maker'*, was chosen as the most suitable model for the requirements of this project as it enabled configuration of the most amount of variables, and by extension, interactivity. This allowed for the population as a whole to be compartmentalised into different states of health, whilst also allowing the behaviour of individual agents to be altered and have an effect on the outcome of the simulation. This hybrid modelling technique allows for configurable variables on both the macro and the micro level, enabling the user to control more elements of the simulation and allowing for a more interesting and engaging experience.

This model allowed for the configuration of a host of variables which would affect the outcome of the simulation. The variables included in the full version of the model were as follows.

- Probability of Infection - When an infected person comes into contact with a healthy person, how likely are they to transmit the virus. Essentially how contagious the virus is.
- Fatality Rate - How likely the virus is to kill its host at some point in the duration of the infection.
- Recovery Period - How long it takes for people to recover from the virus and re-enter the population.
- Asymptomatic Period - How long after first being infected does it take for symptoms to develop and the person to become aware that they are infected and begin their quarantine.
- Travel Restrictions – How often people move between communities. This could be broken down into internal and external restrictions.
- Hospital Capacity – How many people could be hospitalised by the disease before the hospital became overwhelmed which would increase the fatality rate.
- Vaccinations Rate – How many people would be vaccinated each day and become immune to the virus.
- Compliance – How much people obeyed the other restrictions and guidelines in place.

The configuration and interaction with these variables allowed for the design of a microworld simulation, within which the user could experiment and test their own ideas and beliefs about the effects that these variables would have on the spread of the disease. This enabled the development of a highly interactive computer system which could achieve the project goals of developing a tool that could combine interesting visuals and Human-Computer Interaction to aid in the teaching and understanding of the spread of viral diseases.

3.6 Challenge Based Learning

Building on the aforementioned principles of active learning, it was important to present the learner with learning activities which cognitively engage them and encourage them to consider what choices they are making and why. Hence, a set of challenges were designed based around the microworld simulator, which aimed to illustrate some of the desired learning outcomes and provide didactic value to the tool. The three challenges which were set were as follows.

1) Configure the Virus – The introductory challenge was designed to introduce the layout and workings of the simulator to the user, without initially overloading them with information. In this challenge, the user has to think from the perspective of the virus and try to configure the virus so that it kills over 50% of the population.

2) Suppressing the Virus – In the second challenge, the simulator is made considerably more complex. In this challenge the user is allocated a budget of €100 million and has to try to keep the death percentage under 10% of the population.

3) Country Governance – In the third challenge, the learner selects a country from one of five options and has to try to suppress the virus within that country. The simulator within this challenge is similar to Challenge 2 however there are certain key differences depending on which country is selected. This challenge was designed with collaborative learning principles in mind, in that the class is broken up into groups and each group is assigned a country. Each group then reports to the class on the situation their country was faced with, and what approach they took to dealing with this situation.

The simulator should also include a 'Sandbox' mode in which there were no challenges set or variables fixed and allowed the user total control to experiment with the simulation model. This would allow the user full flexibility to experiment and construct their own concepts and beliefs about the fundamentals of the underlying epidemiology.

3.7 Screen Design

Taking into account the visualisation techniques analysed in Chapter 2 and the requirements of the project to combine an engaging visualisation with a high level of interactivity the following initial mock-up was created to guide the design and development of the simulator.

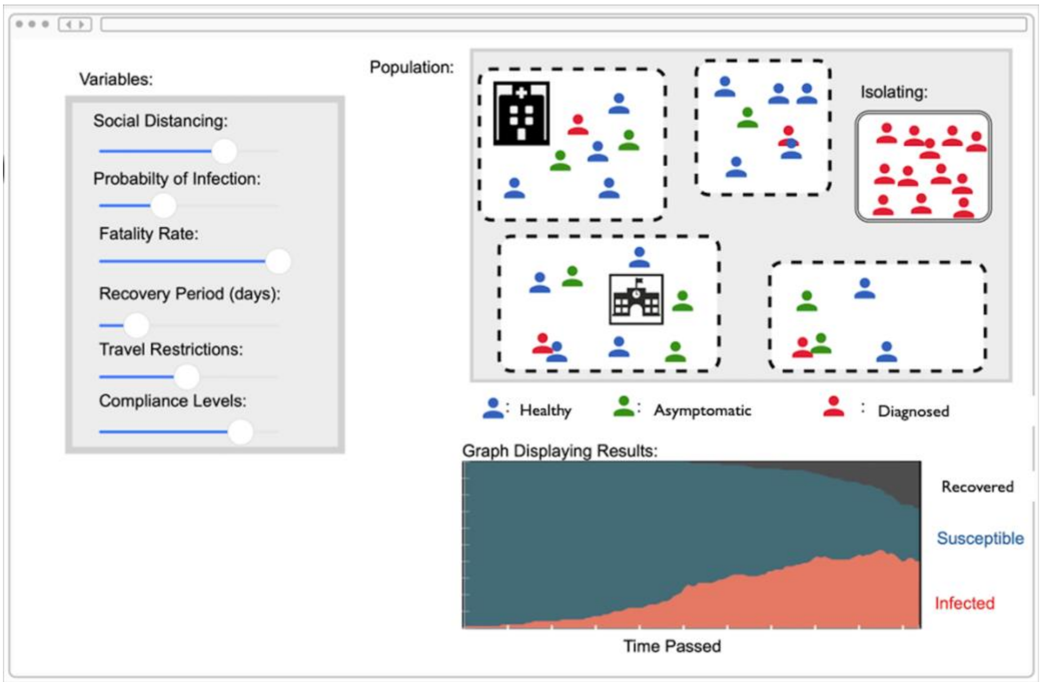

Figure 3.2 - Initial Mock-up of Simulator Design

This mock-up sets out a basic layout for a microworld simulation in which the user can control a set of variables using the slider bars seen on the left-hand side of the screen. These sliders would in turn affect the ongoing simulation of the population in the top-right hand corner in which the individuals would bounce around the population box spreading the disease and changing colour as they interact with each other and become infected. This twist on the billiard ball method of simulation visualisation would allow for the user to intuitively witness the spread of the disease and the introduction of people icons as opposed to the conventional coloured circles and would make the visualisation less abstract and more engaging for the user.

To contextualise the current situation within the simulation, it was useful to have an accompanying chart which displayed the current proportion of the population who were susceptible, infected, immune or dead. This visual aid was important as it allowed the learner to easily visualise how quickly the disease was spreading without having to keep track of the actual numbers themselves. The graph in the bottom right would display the proportion of the population that are infected, susceptible or removed and how these proportions changed as the simulation ran on. The initial design for the microworld simulation was created on this author's belief that it provided an effective, engaging visual in which to run a series of interactive simulations which could be used by a learner to experiment and construct knowledge about viral diseases.

This proposed system should build upon and extend the features of the similar applications explored previously and should add entirely new ones such as challenge based learning.

	Interactivity	Engaging Visual Aid	Gradual Introduction of Variables	Explanation of Logic	Challenge Based Learning	Replayability
3blue1Brown Video	✗	✓	✓	✓	✗	✗
Washington Post Article	✗	✓	✓	✓	✗	✗
“The Epidemic Game Maker”	✓	✓	✗	✗	✗	✓
“Epidemic Calculator”	✓	✗	✗	✗	✗	✗
“Outbreak”	✓	✗	✓	✓	✗	✗
Proposed System	✓	✓	✓	✓	✓	✓

Figure 3.3 - Table comparing similar applications to proposed system

3.8 Design Summary

In summary, the design of the tool built on the background research conducted to identify the most suitable techniques for modelling and visualising the spread of a disease through a population. The design was influenced by the strengths and weaknesses of similar applications in the aim of developing a tool which had real world value and distinctiveness. The most suitable technologies were analysed and chosen for the implementation of the tool.

4 Implementation

This chapter explores the implementation of the simulator, including how some of the core functionality was developed, why some of the key choices were made, and how certain problems were overcome. This chapter will discuss modelling people, simulating transmission, calculating the R number, simulating hospitalisations/deaths, creating the chart and introducing cost.

4.1 Modelling People

Building on the decision to use a hybrid simulation of the S.E.I.R. model and agent-based modelling, the first core component which had to be developed was the people themselves. Given the need for individuality within Agent-Based Modelling, each person within the simulation would have to have their own properties and behaviours. Hence, a class was developed with a constructor which allowed for many instances of people to be created each with their own attributes and values.

```
class Person {
  constructor(size, state, currentCommunity) {
    this.currentCommunity = currentCommunity; // area which person is contained
    this.pos = randomStartLocation(); // random starting position
    this.direction = new Coordinate(random(0.75, 1.5), random(0.75, 1.5));
    this.size = size; // size of people varies depending on screen size
    this.state = state; // Susceptible, Infected, Dead etc
    this.dayInfected = 0; // Records when person first became infected
    this.dayHospitalised; //If hospitalised, records when
    this.peopleInfected = 0; // Records how many people this person has infected          //
with the virus
  }
}
```

Figure 4.1: Person class snippet

This allowed for the simulator to be populated with many unique instances of people who could each interact with one another and possessed their own behaviours and characteristics. In terms of displaying these people, a circular person icon was chosen to represent each person and their state of health.

Figure 4.2: Icons used to display people

This visualisation was chosen as it allowed for the billiard ball method of simulation visualisation explored in Chapter 2 to be adopted. For the benefit of the user (students of the age 15-16) and to make the icons less abstract and easier to intuitively understand for the user, these ‘people icons’ were chosen for their visual impact.

4.2 Simulating Transmission of the Disease

Once this initial population had been established the next fundamental component which had to be developed was allowing for the transmission of the disease from one agent to another. The p5.js library includes a **draw()** function which is continuously called for the duration of the program. How often it is called depends on the frame rate of the program. This **draw()** function is used to render dynamic visualisations in **p5**, as rather than being drawn once the visualisations are drawn slightly differently every frame, generating the illusion of movement. Within **draw()**, several functions were placed which rendered the agents moving around the simulator and checked for stop conditions amongst many other key functions of the program. One such function that was developed and used within **draw()** was **checkContact()** which looped through all the people within the population and checked their location against every other person in the population. The **dist()** function in p5 allows for the Euclidean distance between two coordinates to be calculated. This was used to measure the distance between two people within the simulation. If they were in close contact with one another, the function then proceeded to check if one of them was infected. If not, the loop would simply move onto checking the distance between the next two people. However, if one was infected then transmission of the virus could occur depending on certain circumstances.

```
function checkContact(person, person2) {
 if (
  dist(person.pos.x, person.pos.y, person2.pos.x, person2.pos.y) <
   closeContactDist &&           //check if they're in close contact
  isOneInfected(person, person2) &&  //check if either is infected
  !isOneImmune(person, person2)     //check if either is immune
 ) {
  // A random number is then generated, if this number is less than the value selected by the user as the
probability of infection then transmission occurs. Ie If the users selects 100% then the virus will always be
transmitted at this point whereas if they select 0% it never will be.
  let randomNumber = getRandomInt(0, 100);
  if (randomNumber < probabilitySlider.value()) {
   person.infect();   //infect function is called on the person which will set
              // their state to "asymptomatic" and set their date of
//             infection to the current day
```

```
    person2.peopleInfected++; //increases the count how many people person2 has  //
infected, used to calculate R number



    infected.push(person);    //person is added to the infected and the
    asymptomatic.push(person);//asymptomatic array which are used to track totals
   }
  }
}
```

Figure 4.3: checkContact() code snippet

This function allows for the agents to travel around the simulator whilst constantly detecting whether any infected individuals come into contact with any susceptible people. Whilst in terms of computational cost it is a lot cheaper and more efficient to have a system based purely on the Ordinary Differential Equations (ODE's) which were outlined in the background chapter, these do not allow for variability or flexibility within the simulation. Combining the compartmentalisation of the S.E.I.R. model however, with the flexibility of the Agent-Based Modelling system used enables the user to control the behaviour of the agents and hence the outcome of the simulation in real-time. Consequently, the inefficiencies of Agent-Based Modelling are a necessary cost to create an interactive and engaging simulation which meets the project objectives. This approach could put a limit on future scaling of the program to massive simulations, however mass-modelling and simulation is not a future objective for this project.

4.3 Calculating the R number

Another key piece of functionality which had to be developed was the calculation of the R number within the simulations. Whilst differing modelling techniques present different methods for calculating the R number, such as the differential equation presented earlier, for the conventional S.E.I.R. model these usually calculate the basic reproductive number *(R_0)* as opposed to the effective R number (c.f. §2.1.1 for a discussion on the difference). Given that the user introduces several methods to try and suppress the virus, the effective R number is a better indicator of their success, as R_0 would remain constant regardless of their preventative measures. Agent-Based modelling allows for the calculation of the exact effective R number by keeping track of how many other people each infectious person transmits the virus to, and then averaging this across the population.

```
function calculateR() {
  let sum = 0;                //sum of transmissions of the virus
  let totalInfectedPeople = 0;
  for (let i = 0; i < population.length; i++) { //loops through the population
    let person = population[i];
```

```
  if (person.hasBeenInfected) {      // if the person has had the virus
    sum += person.peopleInfected; // add how many people they infected to the sum
    totalInfectedPeople++;        // increase the counter of infected people
  }
 }
 rNumber = sum / totalInfectedPeople; //finds the average number of other people    //
each infected person gave the virus to
 rNumber = rNumber.toFixed(2);     // converts to 2 decimal places
}
```

Figure 4.4: Calculating R Number Code Snippet

This function is called at the end of each simulation and provides an effective metric for the user to quickly and clearly measure how effective they were in suppressing the spread of the disease.

4.4 Simulating Hospitalisations/Deaths

With an agent-based simulated population through which a viral disease could spread, the next piece of core functionality which had to be implemented was people with the virus being hospitalised or dying. These outcomes were calculated using a probability function in a similar fashion to the 'probability of infection' technique used earlier. For hospitalisations, once a person within the population had been infected for the infectious period, they would either recover and re-enter the population or they would require further care and be hospitalised, depending on the value of the hospitalisation rate slider.

```
//if statement triggered when person has been infected for the infected period
if (
  person.state == "infected" &&
  person.dayInfected + infectiousPeriod < dayCounter
 ) {
  let randomNumber = getRandomInt(0, 100);
  if (randomNumber < hospitalisationSlider.value()) { //probability of going to
                                                     hospital

    person.inTransit = true;                //
    person.state = "hospitalised";          //
    person.currentCommunity = communities[4];// infected person is moved to the
    person.dayHospitalised = dayCounter;     // hospital section of the simulator
    hospitalisations.push(person);          //

  } else {     // else person recovers and returns to a random community
```

```
    person.state = "healthy";
    person.inTransit = true;
    person.currentCommunity = communities[getRandomInt(0, 2)];
    infected.pop(person);
  }
}
```

Figure 4.5: Hospitalisation code

This probability-based determination of health further accentuates the stochastic nature of the simulator and allows for variability within the simulations.

A similar technique was used to model deaths.

```
if (
  person.state == "hospitalised" &&
  person.dayHospitalised + hospitalisationPeriod < dayCounter
 ) {
  let randomNumber = getRandomInt(0, 100);
  if (randomNumber > fatalitySlider.value()) { //chance of recovery
     person.state = "healthy";
   }
    person.inTransit = true;             //
    person.currentCommunity = communities[0];// recovered person re-enters the
    infected.pop(person);                // population
  } else {
    person.state = "dead";               // else person dies and moves to the
    person.inTransit = true;             // mortuary section of the simulator
    person.currentCommunity = communities[5];//
    infected.pop(person);                //
    dead.push(person);                   //
    person.spot = spots[dead.length - 1];    //creates the effect of the dead
  }                                  //stacking up within the mortuary
  hospitalisations.pop(person);
}
```

Figure 4.6: Modelling deaths code snippet

The fatality rate of the virus is automatically increased if the number of people in hospital exceeds the capacity of the hospital, triggering the hospital overrun condition.

```
if (
  hospitalisations.length > capacitySlider.value()
```

```
) {
  fatalitySlider.value(fatalitySlider.value() * 2); //fatality rate doubles for
  hospitalOverrun = true;                          //duration of time that the
}                                          // hospital remains overrun
```
Figure 4.7: Hospital overrun code snippet

The percentage of people hospitalised or killed by the virus within the population are dependent on the value of the sliders which set the hospitalisation rate and the fatality rate. This allows the user to experiment with different levels of severity of disease and note the effects.

4.5 Creating the accompanying chart

A stacked line graph has been frequently used to demonstrate ‘flattening the curve’ during this pandemic. As it has a level of familiarity with the user and makes it intuitive to understand the data being visualised this type of graph was implemented as the accompanying chart at the design stage (see figure 3.2). It was important that the graph was animated as it allowed the acceleration/ deceleration of the growth of the virus to be effectively visualised as the simulation ran on. The Chart.js library was used to create this graph.

```
var ctx = document.getElementById("myChart"); //The HTML container for the chart
let config = {
 // The type of chart we want to create
 type: "line",
 // The data for our dataset
 data: {
  labels: [],
  datasets: [
   {
    label: "Infected",
    backgroundColor: "rgb(255, 104, 104)",
    borderColor: "rgb(255, 104, 104)",
    data: [],
   },
   {
    label: "Susceptible",
    backgroundColor: "rgb(232, 230, 230)",
    borderColor: "rgb(232, 230, 230)",
    data: [],
   },
```

```
    {
      label: "Immune",
      backgroundColor: "rgb(117, 0, 179)",
      borderColor: "rgb(117, 0, 179)",
      data: [],
    },
    {
      label: "Dead",
      backgroundColor: "rgb(18, 3, 43)",
      borderColor: "rgb(18, 3, 43)",
      data: [],
    },
  ],
},
```

Figure 4.8: Creating chart code snippet

This created a chart with 4 different labels and 4 arrays which data could be inputted into. After every frame of the simulation, data would be pushed to these arrays indicating how many people were infected, dead etc. The chart is then updated to reflect this new data, creating the final animated effect.

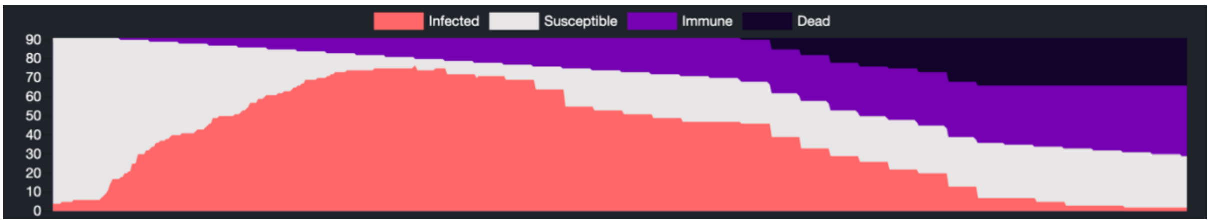

Figure 4.9: The final look of the accompanying chart

4.6 Introducing Cost

In order to cognitively engage the user, and create consequences for their decisions within the simulator, a cost function was introduced. This integration of resource allocation meant the user must carefully consider their choices when attempting to decide upon the best strategy for managing the virus. It also helped in the integration of challenge based leaning, a fundamental requirement of this project.

A cost was assigned to each of the preventative measures which the user could control to try and manage and supress the disease, e.g. vaccinating the population, increasing travel restrictions etc. At the end of each day within the simulation, a daily cost for these measures is incurred. With each day that passes, this daily cost is added to their accumulated spend as the user gradually spends more and more of their allocated budget. The vaccination rate, hospital capacity, and travel restriction costs are daily costs while increasing compliance is incurred as a one-time cost which goes straight onto the accumulated spend, and is dictated by how much the user increases compliance by. Once money had been spent the user was not able to get it back, e.g. by lowering their measures below their initial values and having a negative daily cost, however the user could offset some of their expenses by decreasing some measures below their initial value to allow for more spending on others. For example a user could decrease the hospital capacity while the case numbers are low to subsidise the cost of vaccination.

```
function calculateCost() {
  let complianceCost = 0;
// vaccine cost calculated as difference between user selected value and intitial value, multiplied by the cost of
vaccinations
  let vaccineCost = (vaccineSlider.value() - initVaccine) * costOfVaccinations;
// same logic for hospital capacity cost and restrictions cost
  let capacityCost = (capacitySlider.value() - initHospitalCapacity) * costPerBed;
  let restrictionsCost =
    (travelSlider.value() - initTravelRestrictions) * costOfRestrictions;
// when the user increases compliance above its current rate, the amount they //increase it by multiplied by the
cost of increase is added to the accumulated spend
  if (complianceSlider.value() > currentCompliance) {
    complianceCost = (complianceSlider.value() - currentCompliance) *       increasingComplianceCost;
    currentCompliance = complianceSlider.value();
    accumulatedCost += complianceCost;
  }
  dailyCost = vaccineCost + capacityCost + restrictionsCost;
  if (dailyCost < 0) { //doesn't allow for negative daily cost
    dailyCost = 0;
  }
  accumulatedCost += dailyCost; //daily cost added to total spend at the end of
//                              each day
}
```

Figure 4.10: Cost calculation method code snippet

To introduce consequence to this spending, the user was allocated a specific budget for the duration of the simulation. If their accumulated spend exceeded this budget, the measures they had in place would return to their initial values and would be locked at these values for the remainder of the simulation. This would remove the user's ability to dictate what was happening within the simulation, so the user must think cautiously about how they spend their budget and manage their resources.

```
if (accumulatedCost > allocatedBudget) { //if budget exceeded, values are reset and
  travelSlider.value(initTravel);     // locked
  vaccineSlider.value(initVaccine);
  capacitySlider.value(initCapacity);
  complianceSlider.value(currentCompliance);
  lockSliders();
 }
```

Figure 4.11: If budget exceeded code snippet

There was limited definitive research found on what the cost approximations would be in a real-world environment for things such as travel restrictions and increasing compliance and the numbers found (Coibion et al., 2020; Rowthorn and Maciejowski, 2020; Yamin, 2020) tended to vary massively from study to study due to the complexity of determining these values. For these reasons estimated values were assigned to the costing function which focused more on introducing a cost element to the user's choices, than modelling the actual cost of these choices in the actual management of the Covid-19 pandemic. The costings acted as an educational feature however the optimal values of each respective costing could not be defined as it was beyond the scope of this project. This could be an area for future work on the project if more accurate costing valuations could be found. This conforms with the low-fidelity nature of this simulator, acting more as an educational tool which aims to illuminate the key concepts and trade-offs, rather than being an attempt to model real-world scenarios. Despite, potentially not being 100% accurate in its simulation, this author believes that this tool still provides a strong educational environment, in which learners can explore and construct their own beliefs about the spread of viral diseases. *"All models are wrong, but some are useful"* (Box, 1976).

Having developed the simulator to a point where it reached its functional and non-functional requirements, it was then necessary to begin testing and evaluation to explore the extent to which the project achieved its goals and identify its strengths and weaknesses as an educational tool, feedback which could be used to shape the further development and improvement of the tool.

5 Testing and Evaluation

To determine the success of this project in its goal of developing a simulation tool which could help in the teaching and understanding of the spread of viral diseases, it was necessary to carry out an evaluation of the tool with real-world learners. The evaluation should measure the project's success in harnessing contemporary technologies and data visualisation technologies to create an effective interactive simulator, underpinned by Human-Computer Interaction. It should also evaluate the educational benefit of the tool and how effectively it achieved its intended learning outcomes. The timeline of the stages of the evaluation process can be seen in Figure 5.1 below.

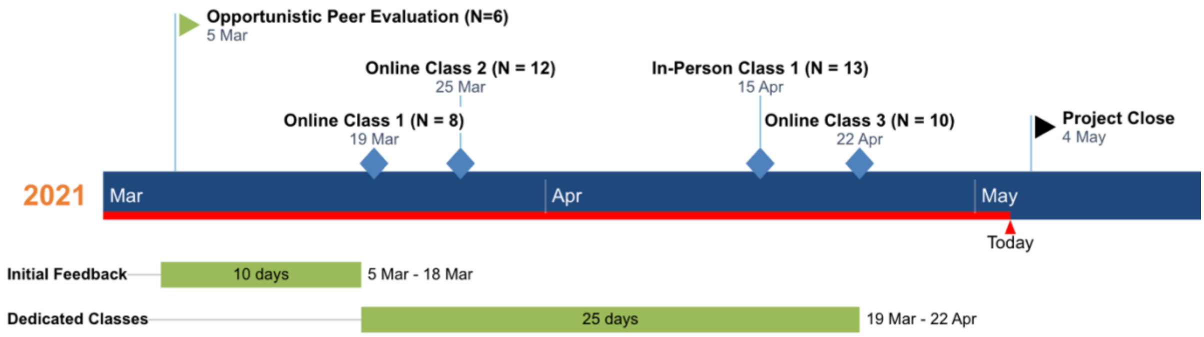

Figure 5.1 - Evaluation Timeline

5.1 Opportunistic Peer Evaluation

For initial testing and evaluation, the tool was shown to an opportunistic group of participants known to the author. The group (N=6) were in 5th Year in Secondary School which is very close to the age demographic of Transition Year Students for whom the tool was designed. Due to the Covid-19 pandemic, this was conducted via a group Zoom call with each of the participants able to interact with the simulator, and give feedback. This author attended the Zoom call with the initial six learners to explain the simulator and answer any questions or uncertainties that arose.

This allowed for the author to ascertain an initial understanding of the usability and effectiveness of the tool through an initial trial with students of a similar age to the target demographic. This provided valuable insights on changes which could be made to further enhance the tool before further stages of deployment and testing. At this stage, some browser compatibility issues with styling were noticed which allowed for these to be fixed before use in the online classes. Furthermore, it was discovered that the first of the three challenges proved too difficult for some of the users to successfully complete. This was rectified by lowering the target percentage of the population which was required to be killed to complete the challenge and by increasing the population density which allowed for the disease to spread more easily.

5.2 Educator Feedback

Having carried out an initial testing with some age-relevant users, the tool was then sent to a an opportunistic sample of domain experts in the areas of health and technology enhanced learning. Responses were received from the Head of Student Health in TCD, an educational researcher at Oxford who developed 'The Epidemic Game Maker' discussed in Section 2.5.2, amongst others. Useful qualitative feedback was attained from this stage of evaluation in which both strengths of the tool were outlined, as well as potential improvements. Some of the key feedback was ….

"Challenges make it more interesting than some earlier similar simulations. The challenges are well-designed to illustrate important dynamics and trade-offs."

- Educational Researcher

"I like the idea of displaying people as circles with heads inside since displaying them as whole bodies instead is visually distracting while plain circles seem too abstract."

- Educational Researcher

"It is very interesting and highly addictive! …. It is an interesting concept that would provide an excellent platform for TY students, or many others, who could use it to develop their understanding of the decision-making process around Covid 19. It also clearly identifies the consequences of all decisions as well as consequences of doing nothing."

- Physician

One caveat which was raised by the physician was that due to the widespread impact of Covid-19, students who were using the tool may have been affected by hospitalisations or deaths of friends or family during the pandemic, and thus could be impacted while using the simulator. To address this issue, precaution had to be taken in advance of any online classes conducted to make students aware of the nature of the simulation that would be conducted and to allow all students the choice to opt-out of participation if they preferred.

Another change which was made to the simulator based on the feedback received, was to slow down the simulations that are conducted. The speed of the simulations reduced the opportunities for the user to make calculated, informed decisions to reflect what was happening within the simulation. Due to the requirement for this tool to cognitively engage the user and provide a tool which can allow the user to experiment and construct knowledge on the importance of certain factors compared with others, the simulations were slowed down, allowing the user more time to consider their decisions.

5.3 Dedicated Online Classes

Bridge2College is a school outreach activity run by the Trinity Access programmes in TCD. The programme aims to explore the potential of technology to mediate a dynamic, creative, cross-curricular values-based learning experience for second level students. Students on the programme are mentored by undergraduate and postgraduate students who combine a very specific model of teamwork with the creative use of technology to provide an innovative educational model for 21st century learning. This provided an ideal medium within which evaluation of the tool could be conducted.

The primary vehicle for testing and evaluating this tool was a series of classes, within the Bridge2College programme, which were focused around the tool and allowed users to interact and experiment with it in a dedicated learning environment. Upon completion of these classes, the students were requested to fill out a post-session survey to gather feedback and data about their experience of the tool. Ethics approval from Trinity's Research Ethics Committee (REC) was requested and granted to conduct these classes and the subsequent survey.

The classes were ran throughout March and April of 2021 and were led by members of the Bridge2College team, in conjunction with this author. The Bridge2College team determined the best approach for running these classes, to maximise the learning potential of the tool and ensure that all the students had an adequate opportunity to try the simulator and give their feedback afterwards. The students were first introduced to the simulator and a general explanation on how to use it was given. They were then broken up into groups in which they attempted each of the three challenges. They would then come back to the class as a whole and present their findings. There were three dedicated online classes conducted using this simulator, and an additional in-person class was conducted towards the end of the study when restrictions allowed Transition Year Students to return to school. In total there were 43 (N=43) responses to the post-session survey across 4 dedicated classes, which provided a database of feedback and opinions from which the tool was evaluated.

5.4 Usability Evaluation

The testing of a system's usability is a frequently used method of discovering the extent to which a system's user can achieve their goals and hence was a central tenet of evaluating this tool. Within the broad spectrum of Human Computer Interaction (HCI), there are several methods to compare and evaluate the usability of interactive interfaces. One of the most commonly used methods, is through usability surveys. There exists various different standardised surveys which are designed specifically to ascertain the user's assessment of a system's usability. Two of the most prevalent standardised surveys designed for this purpose are the System Usability Scale (SUS) and the Post-Study System Usability Questionnaire (PSSUQ).

5.4.1 System Usability Scale (SUS)

The System Usability Scale is a standardised questionnaire, consisting of 10 questions, which attempts to ascertain the learnability and usability of a system. It utilises the 5-point Linkert scale which ranges from 1 (Strongly Disagree) to 5 (Strongly Agree) and calculates a score between 0 and 100 (Bangor et al., 2008). SUS is a very time and cost effective survey to administer and due to its widespread use, it is easy to compare and contrast results with other systems or with industry standards.

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

Figure 5.2 - System Usability Scale (SUS)
https://www.researchgate.net/figure/System-Usability-Scale-Questionnaire_fig1_306893875

5.4.2 <u>Post-Study Usability Questionnaire (PSSUQ)</u>

The Post-Study Usability Questionnaire provides a more complex standardised survey which attempts to measure the system usefulness, information quality and interface quality, giving a sub-score for each (Sauro and Lewis, 2016). PSSUQ consists of 16 questions and utilises a 7-point Linkert Scale. An overall score between 1 and 7 is calculated by finding the average of the 7 points of the scale for each of the 16 questions. This provides another standardised metric which can be used to compare a system with industry norms.

	The Post-Study Usability Questionnaire Version 3	Strongly agree 1	2	3	4	5	6	Strongly disagree 7	NA
1	Overall, I am satisfied with how easy it is to use this system.	O	O	O	O	O	O	O	O
2	It was simple to use this system.	O	O	O	O	O	O	O	O
3	I was able to complete the tasks and scenarios quickly using this system.	O	O	O	O	O	O	O	O
4	I felt comfortable using this system.	O	O	O	O	O	O	O	O
5	It was easy to learn to use this system.	O	O	O	O	O	O	O	O
6	I believe I could become productive quickly using this system.	O	O	O	O	O	O	O	O
7	The system gave error messages that clearly told me how to fix problems.	O	O	O	O	O	O	O	O
8	Whenever I made a mistake using the system, I could recover easily and quickly.	O	O	O	O	O	O	O	O
9	The information (such as online help, on-screen messages and other documentation) provided with this system was clear.	O	O	O	O	O	O	O	O
10	It was easy to find the information I needed.	O	O	O	O	O	O	O	O
11	The information was effective in helping me complete the tasks and scenarios.	O	O	O	O	O	O	O	O
12	The organization of information on the system screens was clear.	O	O	O	O	O	O	O	O
13	The interface* of this system was pleasant.	O	O	O	O	O	O	O	O
14	I liked using the interface of this system.	O	O	O	O	O	O	O	O
15	This system has all the functions and capabilities I expect it to have.	O	O	O	O	O	O	O	O
16	Overall, I am satisfied with this system.	O	O	O	O	O	O	O	O

Figure 5.3 - Post Study Usability Questionnaire (PSSUQ)
https://arl.human.cornell.edu/linked%20docs/Choosing%20the%20Right%20Usability%20Questionnaire.pdf

5.4.3 Questionnaire Choice

PSSUQ was the methodology chosen to evaluate this tool as the added number of questions and the increased complexity relative to the System Usability Scale allows it to more effectively target what aspects of the system the user liked/ disliked, and the 7-point scale allows for more expression from the user. Furthermore, the breakdown of the resulting overall score into the sub-scores for system usefulness, information quality and interface quality allows for analysis on what specific parts of the tool are most/ least effective. The questions in the PSSUQ are better tailored for a scenario-based tool, making it a more effective metric of measuring the usability of a challenge-based tool such as this one.

5.4.4 Usability Results

A total of 43 Transition Year Students filled out the PSSUQ included in the survey after the dedicated classes. As this was the first time this system was evaluated using this metric there were no previous results to compare the scores against. Instead, comparison was made against industry norms determined by Sauro and Lewis (2016) to help interpret the scores calculated from this study.

The graph below (Figure 5.4) compares the mean score from the simulator with the PSSUQ norm for that question. The scores can range from 1-7 with lower scores indicating better usability and satisfaction. The scores calculated for this system were very positive, with all but one of the questions performing better than the PSSUQ norms. The only question in which the application scored marginally worse than the norm was *"It was easy to learn to use this system"*. This result may be explained by the fact that for the most part this tool could not be used in the physical classroom environment for which it was designed, and the online nature of the classes increased the barriers to communication between the teachers and students rendering it more difficult for the users to learn how to use the system. Future work on the tool could improve this score by implementing more engaging tutorial techniques for the tool such as video introductions or explanations, which would be better suited to the online learning environment.

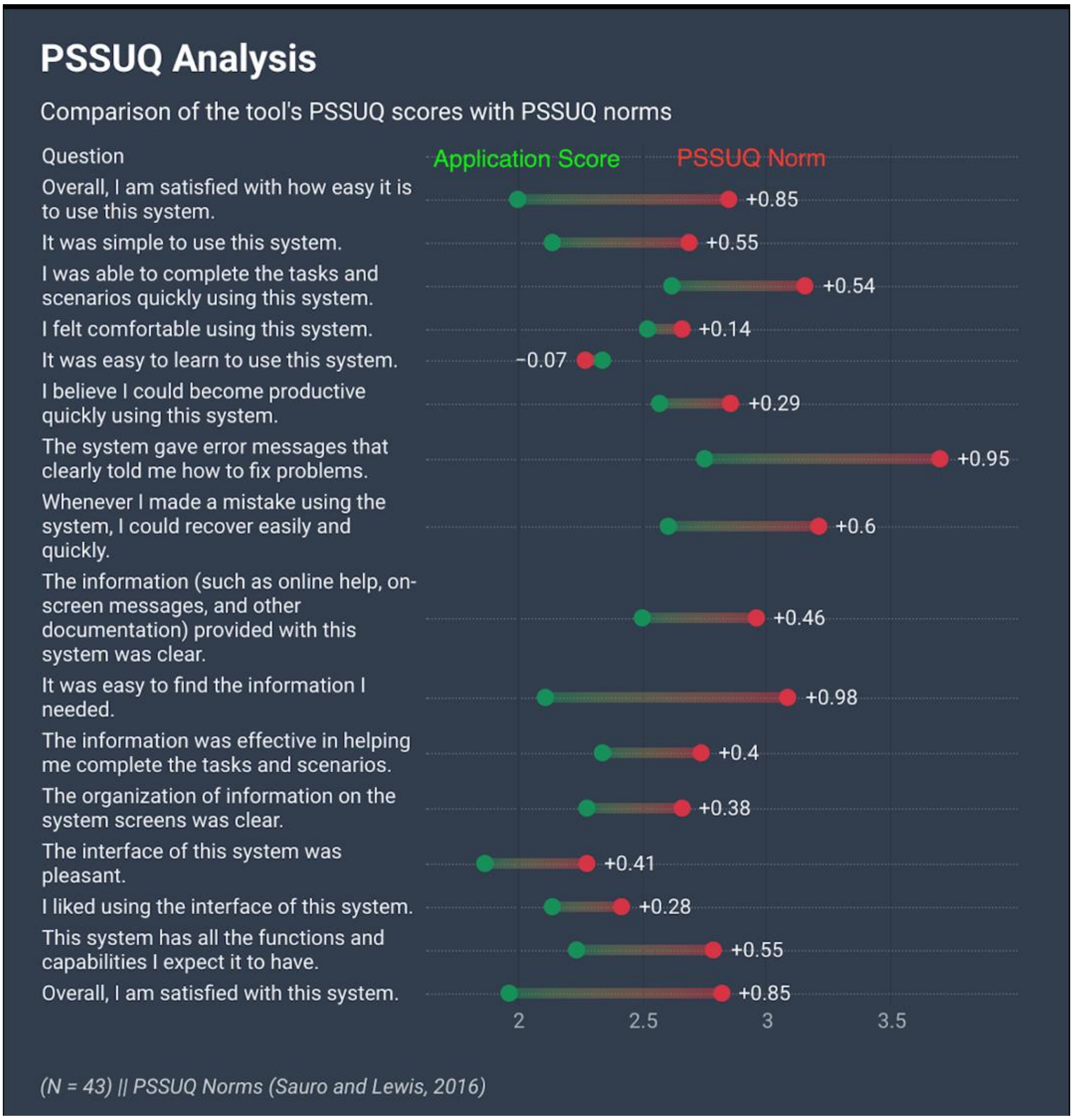

Figure 5.4 - Application PSSUQ scores compared with norms (Range-Plot)

Breaking the individual question results down into the three sub-scores and comparing these as well as the overall score to the PSSUQ norms, provided further positive results. The system scored better than the norm in each of the three sub-sections and scored 18% better than the norm in the overall score. This suggests a high degree of usability and satisfaction with the performance of the tool in terms of system usefulness, information quality and interface quality.

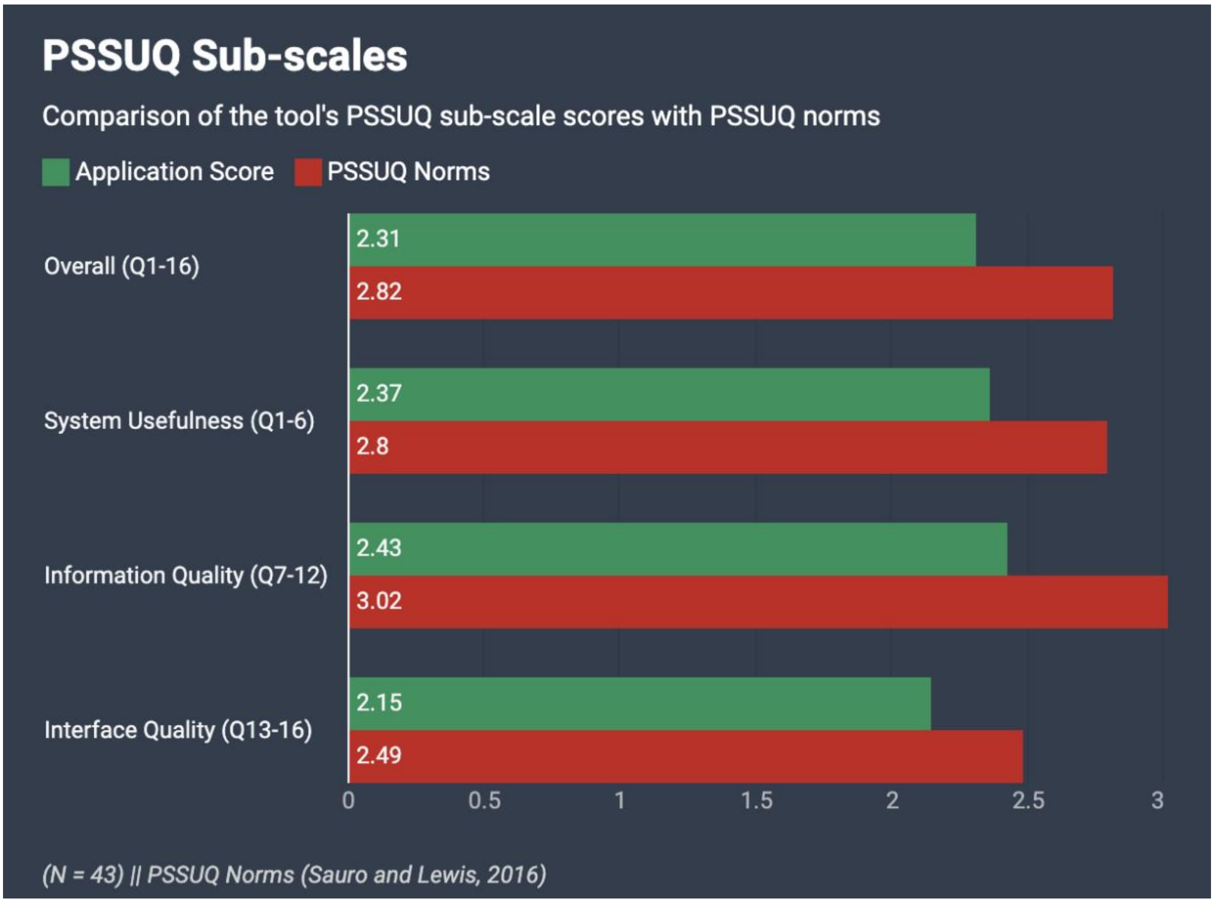

Figure 5.5 - Bar Chart comparing application's PSSUQ sub-scores with norms

Overall, this feedback suggests that the target demographic found the tool to be a highly usable system which achieves its fundamental goals as a Human-Computer Interaction system.

5.5 Educational Benefit

The fundamental requirement of this tool is that it is educationally beneficial to the user in its goal of teaching about the spread of viral diseases. The tool, built on the previously discussed pedagogical theory, must imbue learning outcomes upon the user. The survey used to gather feedback on the tool was designed to gauge the tool's educational benefit in a variety of ways. The survey was designed to measure the change in understanding of the users on a variety of topics. Whilst results may have been more accurate by using a pre-test survey and a separate post-test survey this would not have been feasible within the Bridge2College classes, so the post-test survey had to get the learner to indicate their own perceived change in understanding on these topics.

An initial analysis of the data gathered from the survey provided evidence that the vast majority of students (86%) felt they were more informed or much more informed about how diseases, like Covid-19, spread after using the tool as is shown in the Figure 5.6 below.

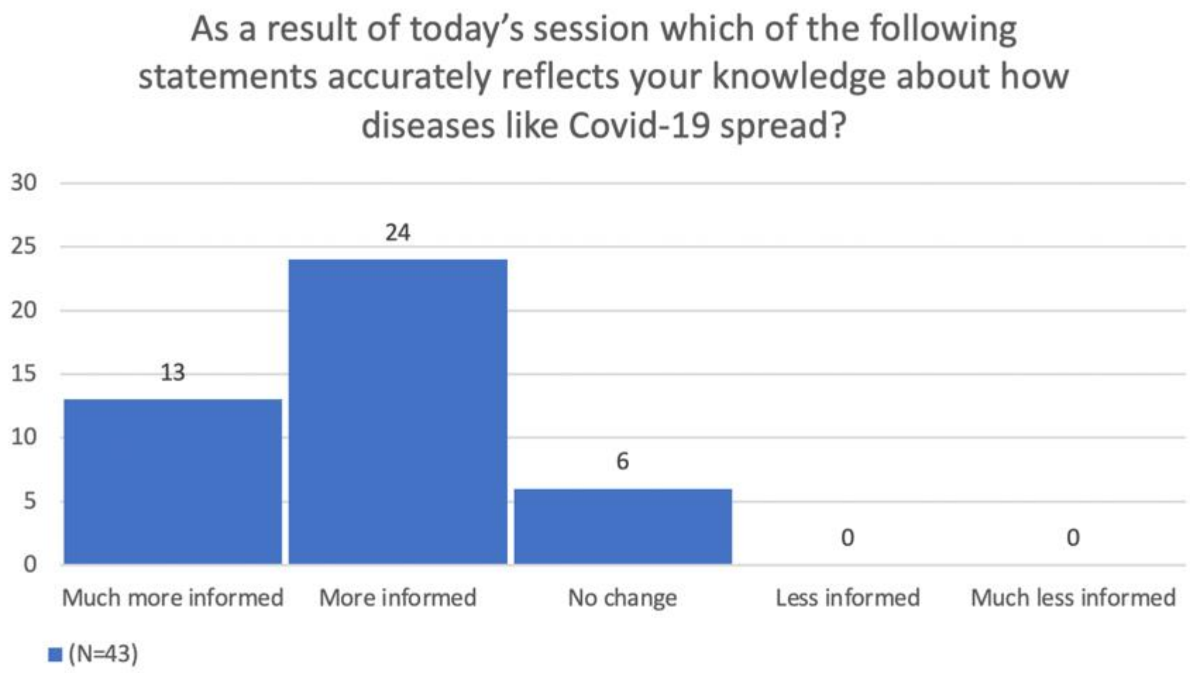

Figure 5.6 - Column chart comparing change in understanding

Another metric used to evaluate the educational effectiveness of the tool, was to gauge the user's opinions on certain topics before and after using the tool and analysing the effect the tool had on these opinions. This was executed by asking the users to what extent did they agree with a set of statements before using the tool, and to what extent do they agree with those statements after using the tool. The mean resulting change is depicted on the chart below (Figure 5.7).

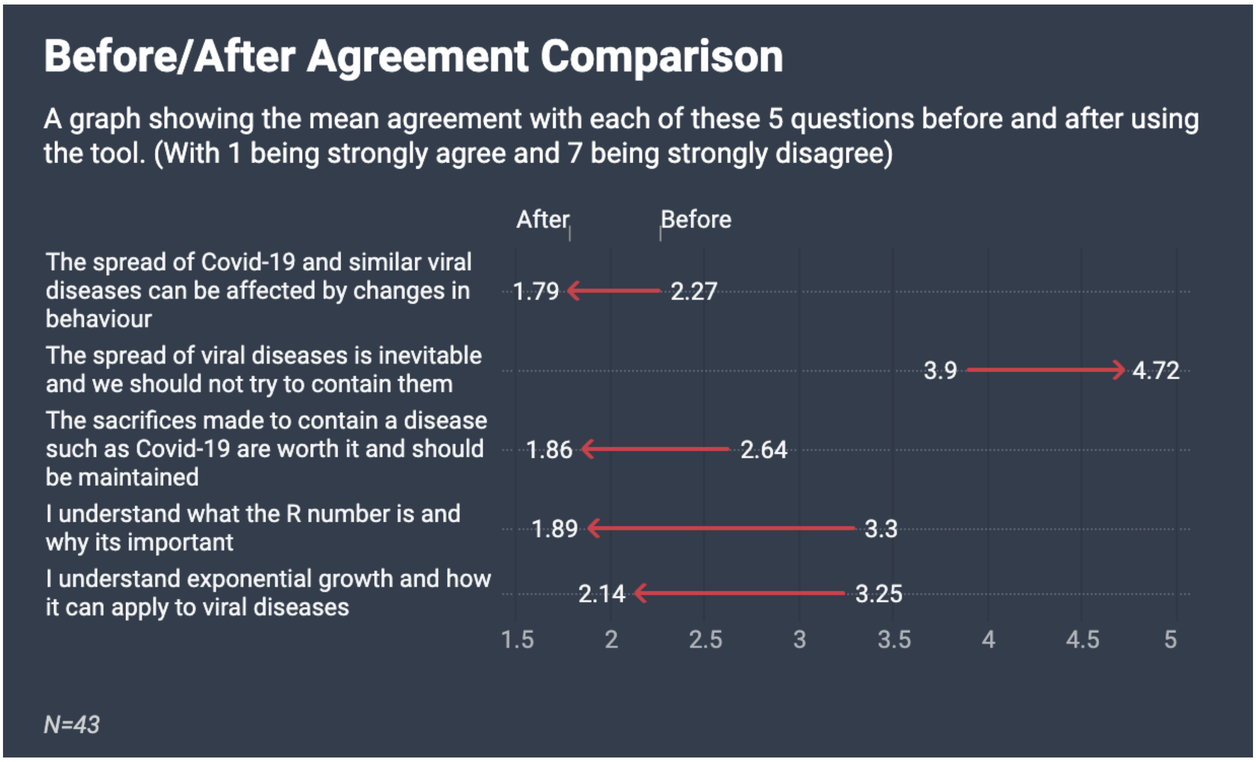

Figure 5.7 - Change in Agreement (Arrow Plot)

As is depicted on the graph above (Figure 5.7), users reported a significantly better understanding of some of the key learning outcomes of this tool after the classes. The largest change was in students' understanding of the R number, with similar reported increase in understanding of exponential growth and its effect on viral diseases. Interestingly, there was also a clear shift in opinion amongst the students on their agreement with the first three statements which suggests that their learning experiences within the simulator had a tangible effect on their opinion on their real-world Covid-19 beliefs. This indicates that the tool is effective in its goal of constructing a better understanding of viral diseases amongst young people and by extension potentially influencing the future behaviour and thought process of these students around contagious diseases.

This claim that the future behaviour of students could be changed by developing a greater understanding of viral diseases is further accentuated by the responses to the following question.

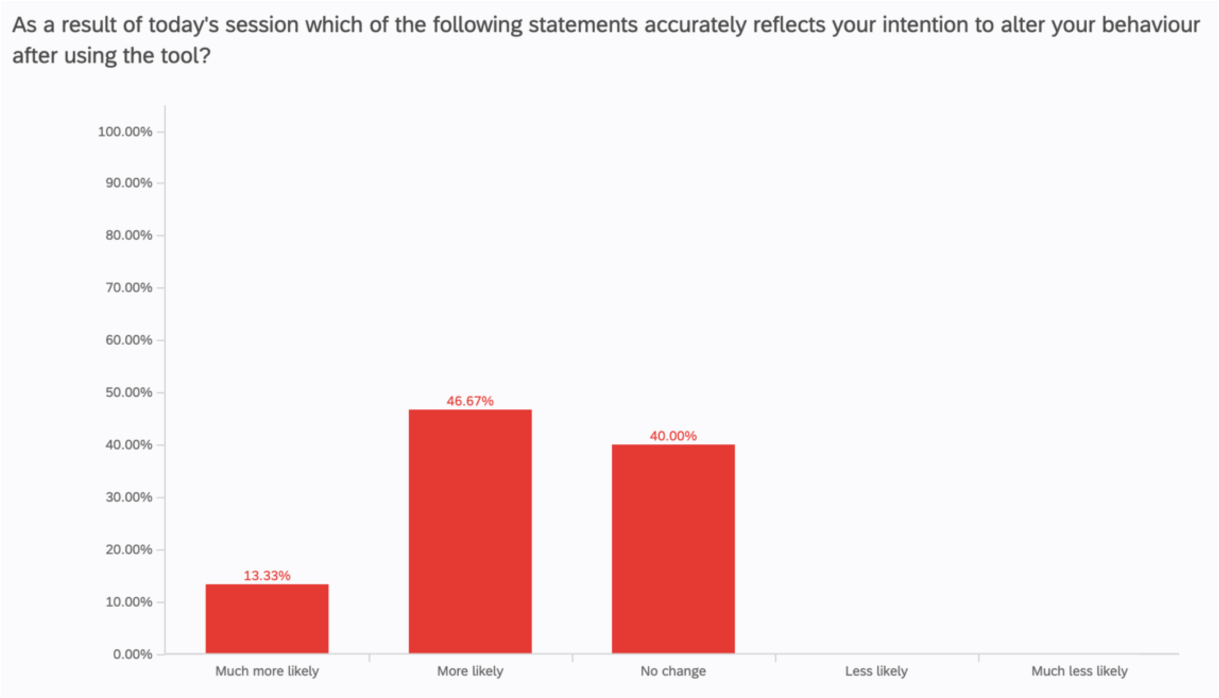

Figure 5.8 - Column chart showing student's intention to alter behaviour

60% of students reported that they would be more likely or much more likely to alter their behaviour around viral diseases after having used the tool. With the behaviour of young people being so pivotal in the outcome of pandemics, tools such as this one, which can enhance their understanding of the fundamental factors at play can help in the management and containment of these diseases.

Overall, the results from the evaluation techniques used strongly suggest that the tool is effective in its goal of providing a simulation tool built on pedagogical and Human-Computer Interaction theory that can help students to obtain a better understanding of viral diseases. This claim is further substantiated by the qualitative feedback received from the students taking the survey.

"I learned about the R number, how important compliance is, and what factors can affect how a disease is spread"

"I learned how easy the disease spreads, the importance of hospital capacity, and why travel restrictions should be complied with"

"Better understanding of how difficult managing the pandemic can be"

5.6 Evaluation Summary

In summary, the testing and evaluation conducted in this project provided ample evidence that the project was successful in reaching its goal of building a simulator which could aid in the teaching and understanding of viral diseases. The evaluation conducted provided a solid foundation upon which future versions of the tool could be developed with this feedback in mind to enhance the tool as it progresses through future testing and evaluation.

6 Conclusions

6.1 Summary

The aim of this project was to harness contemporary data visualisation techniques, innovative technologies and pedagogical and Human-Computer interaction theory, to create a simulation tool that could aid in the understanding of viral diseases. Stemming from the quantitative and qualitative evaluation conducted on the tool, it appears that the project was successful in achieving this goal.

Whilst the evidence suggests the goal of the project was achieved there were certain limits to the study which must be considered. The sample size of 43 Transition Year Students provided a limited amount of feedback which could be analysed when evaluating the tool. With more time, more dedicated classes would have been executed which would have provided a greater sample size, and by extension, more accurate results. Furthermore, the data acquired only indicates the user's intent to alter their behaviour and their perceived change in understanding but there was no evidence acquired of actual behavioural or understanding change. This could be tested for with follow up testing and research but that was not within the scope of this project.

The technologies chosen to create the tool provided a suitable and effective platform upon which to develop the tool. The decision to pivot development from the D3.js visualisation library to the p5.js library proved itself to be an advantageous decision as it allowed for greater flexibility of design when creating the bespoke and unique visualisations that were required to develop the simulator. Heroku allowed for sufficient and accessible deployment of the tool and there were no issues with server or hosting errors across any of the users.

A myriad of different data visualisation techniques were considered when shaping the design of the simulator which were utilised to enhance the learners' experience and the didactic benefit of the tool. The use of the billiard-ball simulation model with people icons rather than the conventional abstract coloured circles proved to be an effective method to depict the spread of the disease throughout the population and contributed to one of the fundamental goals of the project which was creating a tool which combined a dynamic and engaging visual component with the ability to interact and experiment with the simulations in real-time. The epidemiological modelling technique chosen to underpin the simulations further contributed to successful achievement of this projects goals. The hybrid simulation modelling which combined the S.E.I.R. model with Agent-Based modelling allowed for a highly flexible simulator in which the user could dictate parameters to configure the population as a whole and its environment, as well as interacting with the individual characteristics and behaviour of the agents. This allowed for a high level of interactivity within the simulator and created vast flexibility in the decisions the learner could make and experiment with when using the tool.

Based on the evaluation conducted, and the successful execution of the dedicated classes built around the tool, the simulator also successfully embodied the desired pedagogical and constructionist attributes required for the project. The calculation and presentation of the effective R number and death percentage were essential incorporations into the simulator as they allowed for the comparison of results, the contextualisation of said results and for challenges to be set based on these results, which were all fundamental for enhancing the potential learning outcomes of the tool. The production of a metric which can be compared and contrasted with peers is a fundamental attribute in constructionist learning (Papert, 1991).

In conclusion, the simulator successfully encompassed the requirements and goals set out for the project in the planning and design phase and demonstrated its ability to aid in the teaching and understanding of the fundamentals behind epidemiology and viral diseases in the evaluation that was conducted on the tool. Further evaluation and testing with a greater sample size however, could more provide more useful feedback which could shape the future design and work on the tool.

6.2 Future Work

This section presents some possible enhancements and extensions which could be made to the presented work.

6.2.1 <u>Further Evaluation:</u>

Deriving from the conclusions made, further evaluation and testing to attain a larger database of quantitative and qualitative data could help verify the successful results found from the initial testing stages. Furthermore, being able to conduct more of the classes in person as opposed to online would enable for a better explanatory dialog between teachers and students and would allow for the tool to be used in the physical classroom environment for which it was designed. Having tested the tool on a cohort of Transition Year Students, it could be interesting to trial the tool with different demographics to test its usability and effectiveness across a broad spectrum, and to see what changes may need to be made to tailor the tool to different target demographics.

6.2.2 <u>Real Covid-19 Data:</u>

As discussed previously, the costing functions within the simulator are approximations designed to enhance the engagement and interactivity of the tool. If real Covid-19 data could be used to accurately approximate the economic costs of certain decisions it would enhance the precision of the simulations. This could be further developed to use real-time Covid-19 data to present challenges to the user which accurately reflect real life outcomes, increasing the fidelity of the simulator and enhancing the tangible learning outcomes of the tool.

6.2.3 More Complexity and Features:

There exist several different features which were considered during the design and implementation of the project but were not included due to time restrictions that could be added to the simulator to make it more complex and allow for some more interesting simulations. For example, the people within the population could be broken up into different age brackets who behave differently or are more susceptible to the virus depending on their age. The broad nature and complexity of epidemiology allows for a vast array of factors and variables which can affect the outcome of models. More of these complexities could be incorporated into the tool to allow for a more challenging and increasingly complex simulator which could extend the cognitive engagement of the learners.

6.3 Author's Personal Reflections

Looking back on the project as a whole, I found it to be a very challenging but extremely rewarding experience. Having to plan, design, build and evaluate an application such as this was something I mostly only had experience with working in group projects, and even then those were usually not as in-depth or complex as the work required for the completion of this project. I had to combine many disparate skills I had learned across my four years in college in order to complete all elements of the task. From the simple programming basics learned in first year right up to developing server architecture and complex data manipulation this project really tested my abilities across a broad range of software skills developed over the years, and required me to learn plenty of new ones. Being the sole developer of an application such as this, I couldn't play to my strengths or shy away from elements of the development which normally wouldn't be my strong suit as is often the case in group software development projects. Instead, I had to put the time and effort into developing my weaker skills so that they didn't let down the rest of the project. Whilst at times tough to manage the workload of this project in the midst of an already busy Final Year, I am very glad for it as I feel I am much more well-rounded coder for having stuck it out.

The coding however, was only one aspect required in the completion of this project. Having to research and plan for a project of this magnitude was another massively challenging test. I had experience with formal writing and researching from the Business modules I have completed over my four years, but never to the size and scale of year-long project such as this. This experience definitely helped to shape the initial stages of researching and planning the project and meant I wasn't thrown in the deep end as much as some of the pure Computer Science students whose Final Year Projects are their first experience with formal writing. Furthermore, the regular meetings with my project supervisor and with the Bridge2College team who helped to carry out the evaluation of this tool, provided crucial guidance and a roadmap of how to tackle a project of this nature. Overall, this was a hugely challenging but infinitely useful experience. You don't know whether you have the capability of putting something like this together until you are challenged with it for the first time, so being able to reach the end of this project and be happy with how it turned out is a source of enormous pride for me, and is something that I will take confidence from as I move on from college education and into the working world.

Appendix

A working version of the simulator can be found at:
https://covid-simulator-tcd.herokuapp.com/

The survey given to the students for evaluation can be found at:
https://scsstcd.qualtrics.com/jfe/form/SV_cFIMh04w7a2ZccB

The source code of the application can be found at:
https://github.com/LukeFeely/Final-Year-Project-Covid-Simulator-

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