University of Amsterdam

Master in Computational Science

Optimising Sustainable Transit Policies

Agent-Based Modelling

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1 Introduction

In 2022, citizens of the Netherlands travelled an average of 11.4 thousand kilometers per person, using various modes of transportation, with 42% of trips taken by car [1]. The European Union has noted that passenger cars emit 16% of all EU CO_2 emissions. Since CO_2 is one of the main greenhouse gasses driving climate change, the EU, among other organisations, feels the need to reduce CO_2 emmissions by means of changing transortation habits of society [2].

To change people's transportation habits, promoting the use of public transportation, such as trains and buses, can discourage individual car usage. One way to make public transportation more appealing than private transportation is by lowering the fare prices. Additionally, increasing the capacity and frequency of public transportation services promotes higher usage by reducing crowding and travel time. Our primary objective is to determine the more effective government investment strategy for promoting public transport use among island commuters: reducing ferry prices or increasing ferry capacity.

This study employs a custom-developed hypothetical island model utilizing Agent-Based Modeling (ABM), where each citizen is modelled as an agent making transportation choices based on previous experiences, based on the El Farol model. In the context of this study, this model simulates the choice of the agents between public and private transportation, influenced by prior experiences related to cost, travel time and crowding. Agents predict the cost, travel time and crowdedness of the ferry based on previous commutes. A decision process compares the utilities of different transportation modes based on the agents' preferences for travel time, density, and cost. The mode with the highest utility is selected by the agent. Based on research from the Ministry of Infrastructure and Water Management of the Netherlands, we hypothesise that reducing public transport prices is not an efficient method to incentivise people to switch from car to public transport [3].

2 Model Description

2.1 Purpose

The objective of this study is to examine policy strategies for governments to enhance the attractiveness of public transportation compared to private transportation. We aim to analyse how commuter behaviour adapts to various characteristics of different transportation modes and how this affects the overall transportation dynamics. This research employs a hypothetical island model, where public transportation is represented by a ferry and private transportation by a speedboat.

2.2 Entities, state variables and scales

The entities in this model are commuters, characterised by attributes such as travel time, transportation mode density, and the cost of transportation. Each commuter is initialised with a starting location (either Island A or Island B in a two-island model) and sensitivities for density, price, and travel time. The scales for evaluating attributes in the utility function are standardised from 1 to 10. This range is used uniformly across travel time, density, and cost, ensuring equal impact on the utility calculation, which is then weighted according to each commuter's individual preferences. This model is based on the principles of the El Farol model. Agents employ a memory-based strategy, evaluating the density, cost, and duration of each transportation mode over a fixed memory of the previous 5 times they used that mode of transport. This memory span is uniformly applied across all agents to inform their decision-making process.

The model is driven by policy changes, specifically reducing ferry prices and increasing ferry capacity. Initially, the model starts with two islands, but this is expanded to include three, four, and five islands to observe the effects of creating new routes. These changes prompt agents to adapt their travel strategies accordingly. The model does not incorporate real spatial components. Time is discretised, and each commuter must travel at every time step. Consequently, the primary state changes involve the locations of the commuters, determining which island they are on at each time step.

2.3 Process Overview and Scheduling

For scheduling in our model, time is considered to be discrete; events occur at distinct, separate points in time. At each time step, commuters perform a series of tasks to simulate their decision-making and travel process. A pseudo-code representation of the scheduling algorithm is shown in Algorithm 1. Initially, commuters and transportation modes are initialized. Each commuter starts at a specified location. At each time step, commuters perform the following tasks: identify all available modes of transportation, calculate the utility for each mode, select a transportation mode based on the calculated utility, update their location upon completing their journey, and update their memory accordingly. The experience of density and travel time is influenced by the number of commuters using each mode of transportation. After all agents have been activated, information about the current time step is gathered and saved by the data collector.

Algorithm 1 Pseudo-code for Agent Scheduling

```
Input: Number of time steps N, Number of commuters M
Initialize: commuters, transportation modes
for t = 1 to N do
    for each commuter i in 1 to M do
        available_modes = identify_available_modes()
        utilities = calculate_utility(available_modes, commuter i)
        best_mode = arg max(utilities)
        update_location(commuter i, best_mode)
        update_transportation_modes_experience(best_mode)
        update_memory(commuter i, best_mode)
    end for
    collect_data()
end for
```

3 Design

Basic Principles This model employs a discrete choice framework where each agent selects from a set of transportation modes between the islands (ferry or speedboat). Agents make their choices based on utility maximisation, opting for the mode of transportation that offers the highest perceived utility.

Individual Sensing and Decision-Making Each agent computes the utility for each available mode of transportation. The utility is calculated based on the average score of three attributes—price, density, and travel time—over the agent's memory span of the previous five times they used that mode of transportation. The utility function is represented in Equation 1. The error term ϵ introduces stochastic variability into the agents' decision-making process, accounting for unobserved factors that might influence the choice of travel mode, such as personal preferences or external conditions. For each agent at each timestep, a random number is drawn from a normal distribution with a mean of zero and a standard deviation of one for the error term.

$$U_{mode}(P, D, T) = -(\omega_P \cdot P_{avg}) - (\omega_D \cdot D_{avg}) - (\omega_T \cdot T_{avg}) + \epsilon \tag{1}$$

where ω represents the sensitivities (or weights) for each attribute, P is the price, D is the density, T is the travel time, and ϵ is the error term.

Since the model does not incorporate real spatial components, agents do not perceive each other's locations. Instead, each agent independently responds to policy changes, such as reduced ferry prices. All agents have access to the same information regarding policy implementations.

Interaction The interactions between agents are indirect, with no direct communication between them. These interactions are reflected in the density and travel time calculations. For instance, if more agents choose the ferry, it becomes crowded, similarly, increased use of the speedboat results in congestion and longer travel times. Thus, agent interactions are manifested through changes in travel time and density.

Heterogeneity During initialization, each agent's preference for travel time, density, and price is drawn from a truncated normal distribution between 0 and 1, resulting in heterogeneous agents. Consequently, each agent has a different utility function as defined in Equation 1.

Observation To determine which policy will make public transportation more appealing, we collect the number of ferry users for each policy scenario. We vary the ferry capacity from 200 to 2000 in increments of 200, and the price from 1 to 10 in increments of 1. For each capacity value, we record the number of ferry users across all price points. Conversely, for each price point, we record the number of ferry users across the entire range of capacities. Additionally, we generate a 3D plot with capacity and price on the x and y axes, and the number of ferry users on the z-axis. Another 3D plot is created where the z-axis represents the gradient, indicating the rate of change in the number of ferry users with respect to small changes in capacity and price.

4 Details

4.1 Implementation Details

In this model, agents base their decisions on three attributes: travel time, transportation mode density, and price. Each attribute impact is quantified on a scale from 1 to 10, facilitating comparative analysis. The model includes two transportation modes: speedboat (private) and ferry (public), with density and travel time gouverned by predefined functions.

4.1.1 Density

Density varies based on the number of commuters, with different functions for the ferry and speedboat as shown in Equation 2. For the ferry, $D_{Ferry,1}$ applies when usage is below capacity, showing a linear increase up to 5 points, and $D_{Ferry,2}$ applies when usage exceeds capacity, showing an exponential increase from 5 to 10 points. For the speedboat, $D_{Speedboat}$ depicts a gradual rise in discomfort until 60% of agents choose the speedboat.

$$
\begin{aligned}
D_{Ferry,1} &= 1 + 4 \cdot \left(\frac{n_f}{N}\right) \\
D_{Ferry,2} &= 5 + \frac{5}{1 + e^{-15 \cdot \frac{\alpha_{\text{user}}}{\alpha_{\text{max}}} - 0.2}} \\
D_{Speedboat} &= 1 + \frac{9}{1 + e^{-10 \cdot \frac{n_s}{N} - 0.6}}
\end{aligned} \tag{2}
$$

where n_f is the number of ferry users, n_s the number of speedboat users, N the total number of commuters, α_{user} the number of ferry users minus the ferry capacity, and α_{max} the total number of commuters minus the ferry capacity.

4.1.2 Travel Time

Travel time is influenced by delays for the ferry and congestion for the speedboat, as described in Equation 3. The initial score for ferry and speedboat travel time to a range of 1 to 10, where speedboat gets a score of 1 and the ferry a score of S_f. For the ferry, T_{Ferry} shows minimal delays until capacity is reached, then increases significantly. For the speedboat, $T_{Speedboat}$ reflects an exponential rise in travel time once 35% of commuters opt for the speedboat.

$$
\begin{aligned}
T_{Ferry} &= S_f + \frac{norm}{1 + e^{-2 \cdot \frac{n_f}{C_f} - 1}} \\
T_{Speedboat} &= 1 + \frac{9}{1 + e^{-20 \cdot \frac{n_s}{N} - 0.35}}
\end{aligned} \tag{3}
$$

where n_f is the number of ferry users, n_s the number of speedboat users, N the total number of commuters, S_f the initial score for the ferry, $norm$ a normalization factor, and C_f the ferry capacity.

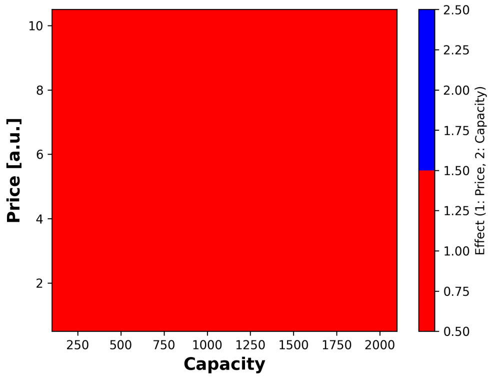
4.1.3 Price

The speedboat price remains constant at 6 points, while ferry prices vary from 1 to 10 points as part of the experimental policies.

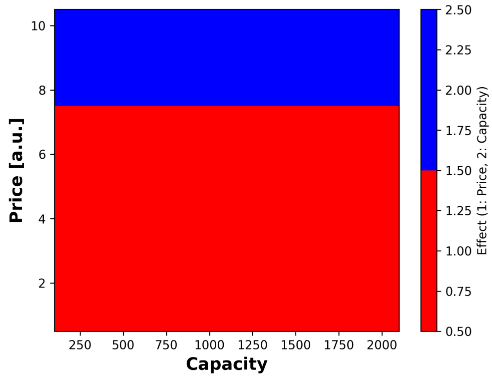
4.2 Initialisation

The model starts with two islands and 1000 agents. There are an infinite number of speedboats and two ferries operating round trips. Each agent has a five-time memory of previous travel experiences (density, price, and travel time) and preferences drawn from a truncated normal distribution ranging from 0 to 1.

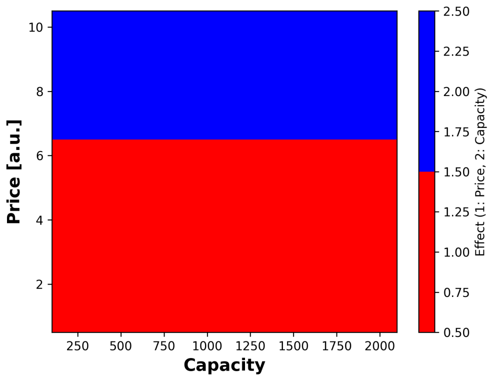
5 Results



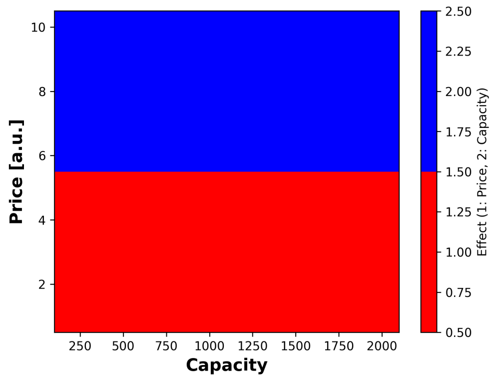
(a) Price versus capacity for two islands.



(b) Price versus capacity for three islands.



(c) Price versus capacity for four islands.

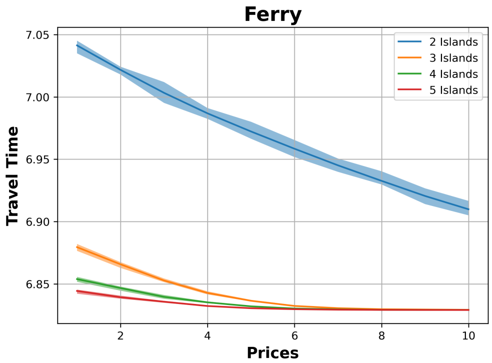


(d) Price versus capacity for five islands.

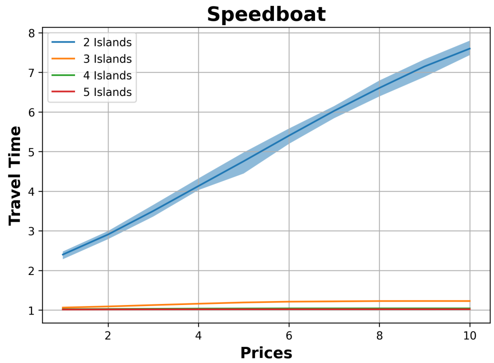
Figure 1: Price versus capacity for various numbers of islands.

Figure 1 shows for two, three, four and five islands whether price or ferry capacity is the best option for investment in terms of government policy. For two islands, over the entire range of capacity variety price is always more important. As the number of islands is increased, the number of ferries are also effectively increased, lowering the density of ferry occupation. For three islands, if the price of ferry is approximately 7.5 the capacity is more important than the price; for four islands it is approximately 6.6, and for five islands it is approximately 5.5.

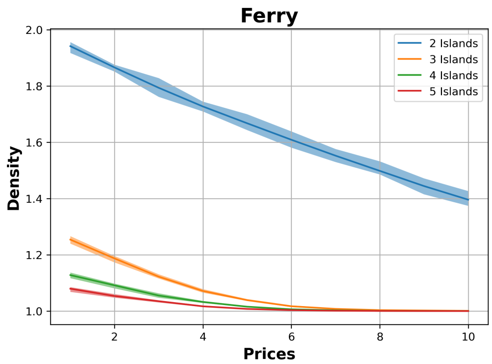
Figure 2 shows the comparison of ferry and speedboat travel time and density over different ferry prices. The shade around the mean line shows the 95% confidence interval (CI). Focusing on the ferry metrics of 2a and 2c, it shows that as the price of the ferry increases less agents use the ferry as a mode of transportation, especially in the two island case. For three, four or five islands, increasing the price does slightly decrease ferry usage but this effect seems to stabilize after the price reaches 6, equivalent to the speedboat price. The CI of two islands is much wider than for three, four or five islands, where it has concentrated very closely to the mean. It follows from the same figure (and from logical reasoning) that the number of speedboat users increases as the price of ferry use increased; again this increase of usage is most apparent for two islands and seems to stabilize around price 6. This increase of usage also increases the travel time of the speedboat, where eventually the travel time will be longer than that of the ferry. As with the other two subplots the CI of three to five islands is much wider than with two islands.



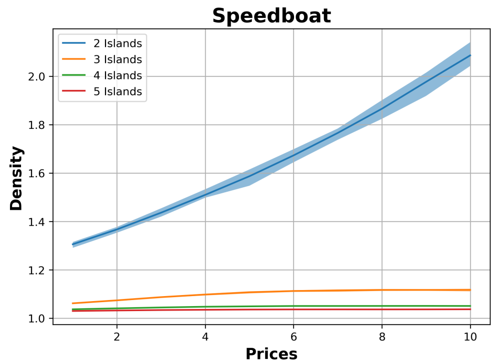
(a) Ferry price over time.



(b) Speedboat price over time.



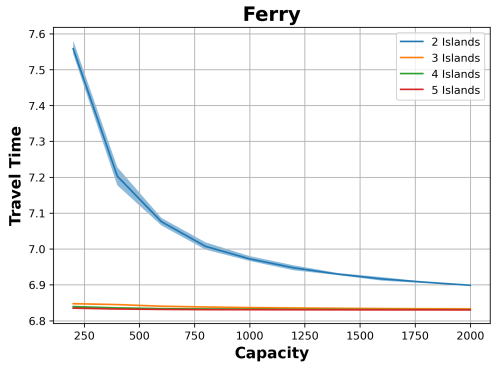
(c) Ferry density vs. price.



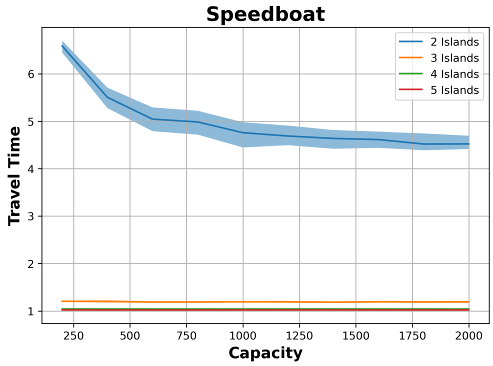
(d) Speedboat density over time.

Figure 2: Comparison of ferry and speedboat metrics.

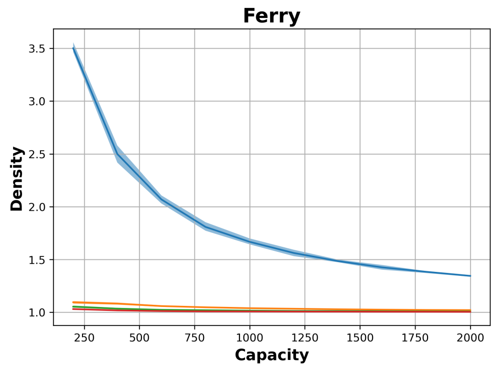
Figure 3 shows how travel time and density is influenced by the ferry's capacity, again with a 95% CI around the mean. For two islands, the ferry and speedboat travel times decrease as the capacity of the ferry is increased, with a wider CI for the speedboat. As the capacity is increased from 250 to 500 there is a big jump downward in travel time for both ferry and speedboat, with additional capacity also lowering travel time but to a much lesser degree. There seems to be stabilization of travel time reduction after the capacity is greater than 1500, or 150% of total agents. There is hardly any change of travel time for either ferry or speedboat with three to five islands. The density of the ferry and speedboat follows the same trend as the travel time, with a large decrease when the capacity grows from 250 to 500, a larger confidence interval around the speedboat mean and (almost) no change for three to five islands.



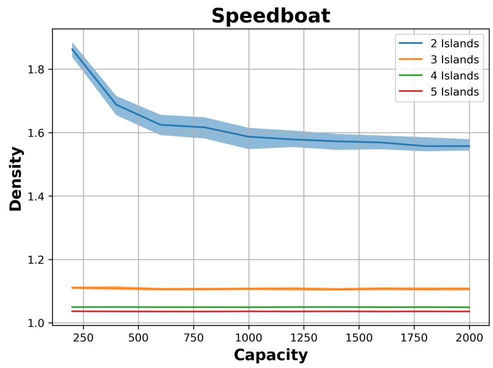
(a) Ferry travel time over capacity.



(b) Speedboat travel time over capacity.



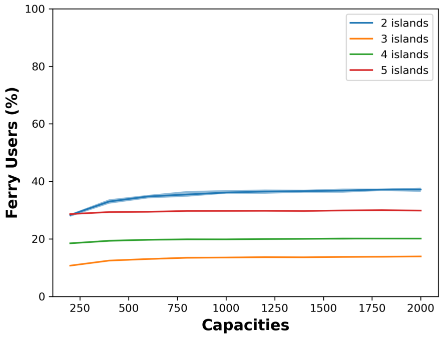
(c) Ferry density over capacity.



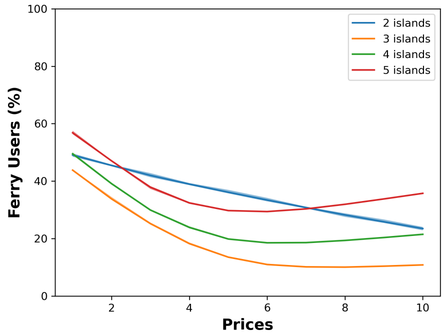
(d) Speedboat density over capacity.

Figure 3: Comparison of ferry and speedboat metrics.

Finally, Figure 4 shows the percentage of agents using the ferry at different prices and capacities. Looking at Figure 4a, we see that differing capacities has little to no influence on the percentage of ferry users. It only seems to increase a little between 250 and 500 for 2 and 3 islands. The rest stays approximately the same. Looking at Figure 4b, for two islands, there is a steady decrease of users as the price of the ferry increases. But for three, four and five islands interesting dynamics can be observed. When the ferry is same price as the speedboat, the decrease seems to stabilize. If the price of the ferry is higher than the price of the speedboat the percentage ferry users even increases, especially in the four and five island scenarios.



(a) With fixed price 5.



(b) With fixed capacity 1000.

Figure 4: Percentage of ferry users over price and capacity.

5.1 Sensitivity Analysis

A first and total order global sensitivity analysis has been performed to research the significance of the parameters over the entire input range for our model. It is shown in Figure 5. As can be seen in the figures, the Sobol indices for both the first order and total order sensitivity analysis for the parameter that indicates the number of islands in the model include 0 in their 95% CI So we can conclude that the number of islands does not influence the output of the experiment. Speedboat travel time is the most significant parameter, followed by ferry travel time and speedboat base price. Ferry price and ferry capacity are very close to each other. In the first order sensitivity analysis, the ferry base price has a higher index than the ferry capacity. In the total order sensitivity analysis, this order is reversed. Furthermore, the total order Sobol sensitivity index is approximately equal to the first order Sobol sensitivity index for all parameters, indicating that parameter interactions are limited if not non existent.

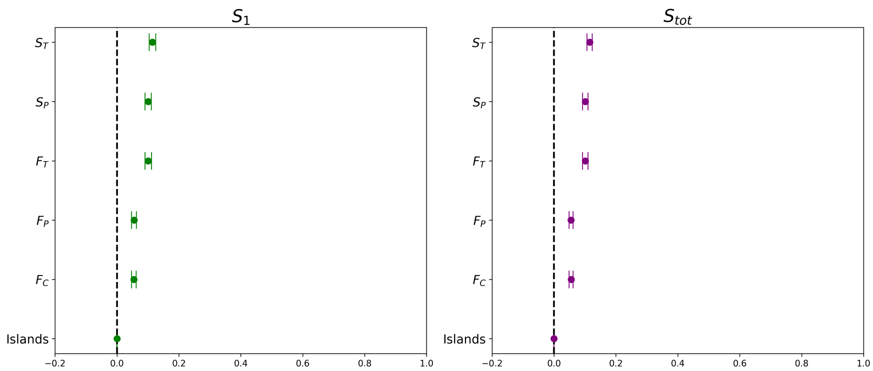


Figure 5: First order (left panel) and total order (right panel) sensitivity analyses of the system.

6 Discussion

The aim of our research is to investigate how applying a certain strategy would change the ratio of public and private transport users in favor of lowering CO_2 emissions. We perform this research by applying Agent Based Modelling. The goal of our experiment is to validate our hypothesis: "reducing public transport prices is not an efficient method to incentivise people to switch from car to public transport [3]." Initially, we created a 2 island setting where we mimic public and private (car) transport using ferry and speedboat respectively. To answer our hypothesis we carried out two experiments, we varied the ferry price against a fixed ferry capacity and vice versa, while keeping the other factors constant. In the case of increasing the ferry price we initially see a logical reaction; as the price gets increasingly larger, more people tend to travel using the speedboat, because the price difference between the two travel methods is not attractive enough to prioritize public transport over private transport. Meaning that for higher prices less people tend to use public transport and for lower prices more people tend to use public transport compared to private transport. But, there are some caveats to implementing strategies. As stated in [3], lowering public transport prices results in a considerably higher volume of new public transport users, and the question is: can public transport as it is, handle this increase in volume. Or is there also a need for additional capacity in public transport, or maybe even more frequent travelling options. The other experiment involved varying the ferry capacity for a fixed ferry price. Varying the capacity as a parameter has less effect on the amount of ferry users, especially compared to varying the ferry price. However, it does affect the metrics of the model, namely it significantly reduces travel time for both ferries and speedboats. But, this does not seem as an efficient strategy which seems worth implementing. Furthermore, we expanded our experiments to contain more islands, which is essentially adding more (different) routes. We extended our model to account for 3, 4 and 5 islands. Running our experiments with the new island settings brings totally new dynamics to our results. As the addition of the new islands decreases the density of the ferries, the cause and effect relationship as it was for 2 islands does not count anymore. This could be explained by the increase in travel time: as more and more price and density conscious agents choose the ferry, the travel time increases more and more. After a certain point agents who strongly prefer travel time over cost and density will prefer the ferry over the speedboat, which leads to more agents choosing the ferry.

A global sensitivity analysis was done on the model. This concluded that the most important parameter is the speedboat travel time, followed by the ferry travel time and speedboat base price respectively for both the first order and the total order sensitivity analysis. These parameters are followed by ferry capacity and ferry base price where the latter is more influential in the first order and less influential in the total order sensitivity analysis than the former. It is also concluded that the number of islands is a parameter that has no influence on model output. This was surprising since it is clear in the results that the behaviour of the model differs for different number of islands. So it is probably the case that these effects cancel out in the global approach of the sensitivity analysis. The fact that in our model we fixed the speedboat price is a limitation of the research. The global sensitivity analysis showed that this parameter is quite influential on model output.

6.1 Future Work

To continue our experiment in the future, there are a few points worth examining which will give more insight into to the dynamics of the model and the behaviour of the agents. First and foremost, is examining the behaviour of every agent individually. This will tell us how the model dynamics influence the choices of the agents and it will show us the behaviour of the agent regarding their choice of transport. A second point is quantifying the cost and profit of the strategies in order to translate it to an applicable method for e.g. a government, if it were to be a efficient and worthy strategy to implement. A third would be to bring the system dynamics closer to reality. In our model a conjunction happens at certain density benchmarks, which influences travel times of both ferries and speedboats and affects the ratio of ferry and speedboat users. For such dynamics we need to try to mimic reality as close as possible in order to make our experiments more applicable.

7 Conclusion

For two islands, price is consistently the dominant factor influencing ferry use. As the number of islands increases, ferry density decreases, leading to different dynamics. Higher ferry prices lead to a decrease in ferry usage, especially for the two-island scenario. However, increasing ferry price in the three-to-five islands scenarios above that of the speedboat might lead to an increase in ferry usage. In terms of ferry capacity, increasing capacity from 250 to 500 passengers significantly reduces travel time for both ferries and speedboats.

References

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