MS-E2177
Seminar on Case Studies in Operations Research
Assessment of Design Options for Border Control

Finnish Defence Research Agency - Project Group

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1 Introduction

1.1 Background

A major recent change in the security situation in Europe has been the Russian attack on Ukraine and the mobilization declared by Russia that started in February 2022 (Ministry of the Interior, 2022a). All EU member countries have condemned this attack since it is seen as unprovoked and unjustified military aggression. Due to this, the EU has adopted several sanctions against Russia. (European Council, 2022). The Finnish Government has since started to strongly restrict tourism from Russia since it could endanger Finland's international position and international relations. Also, in 2022, new proposed amendments were made to the Finnish Border Guard Act and the Emergency Powers Act. These amendments were made to prepare for hybrid influence activities that exploit migration. These activities include using illegal immigration as a tool of political pressure. These amendments would also allow restriction of being close to the border in emergencies and possibly building walls and fences to increase border safety (Ministry of the Interior, 2022b).

Our client for this project, The Finnish Defence Research Agency, is a multidisciplinary research and development organization that provides advanced research, development, testing, and evaluation services for defense. The Agency concentrates on strategy, military science, behavioral sciences, and various technologies. Our client contact in The Finnish Defence Research Agency is Dr. Esa Lappi. Dr. Lappi is a Chief Representative of Defence Technical personnel and has a Docent title at the Finnish National Defence University.

In this project, we assess design options for border control to increase border safety on the Russia-Finland border. The need for this project origins from Finland's desire to prepare for hybrid influence activities that exploit migration and increase border safety. The border between Finland and Russia is mainly forest without major population centers. Therefore, we focus on preventing illegal border crossing in these rural areas, where border control is scarce. In these areas, the options to increase border safety are, for example, fences, sensor systems, patrols with different vehicles, aircraft, and unmanned aerial vehicles (UAVs).

The base setting for our model comes from the Finnish geography near the Russian border. Figure 1 shows Highway 6 partly advances near the Russian border. This setting, where the highway is near the border, with no border crossing spots near, is the basic setting for our assessment. Moreover, we limit our model to include forest terrain solely.

Figure 1: Highway 6 in Finland.

1.2 Objectives

The project's main objective is to analyze the cost-effectiveness of different border control methods and suggest optimal portfolios for different budget levels. To achieve this, we simulate multiple border control scenarios with varying available resources and estimate expected efficiency with the simulation results. The focus is on managing resources for countering state-sponsored illegal border crossings of immigrants as a hybrid warfare tool.

2 Literature Review

2.1 Border Control

Previous literature on determining options for border control using mathematical models in a mathematical context has been made primarily in military academies like Naval Postgraduate School. No comprehensive simulation models found in the literature would be applied in practice. There is an ongoing modeling effort for border safety in the USA. U.S. Customs and Border Protection has contracted John Hopkins University to develop a new approach to model the border. They use a method that utilizes modeling and simulation of operational data and conditions and incorporates terrain and sensor models. (DHS, 2021).

In 2005, a Ph.D. thesis was made on optimizing border control in Arizona, USA. They introduced a mixed integer linear program to express the border control problem. The objective was to minimize the maximum escape probability for illegal border crossers. The two-sided idea included the possibility that illegal border crossers would know USA's border preparations and maximize their behavior. The measure of the effectiveness of their border options was set as the probability of capture. Using their model, they do a prescriptive analysis of different scenarios. This includes suggesting different strategies for different scenarios (for example, a surprise vehicle infiltration) (Pulat, 2005).

Another relevant thesis (Sözen, 2014) has been about using UAVs in border surveillance. This thesis focuses on UAV routes, altitudes, and speeds to maximize the probability of detecting illegal border crossers. The movement and behavior of both the border parts and UAVs are depicted mathematically. The thesis uses an analytical approach and simulation (Monte-Carlo) for optimization. They conclude that the most effective action would be to use several UAVs that work in a disjoint path, i.e., work together.

2.2 Circumstances

There are nine international border crossing points on the land border between Finland and Russia. In addition, there are also two temporary border crossing spots. Six of these border crossing points are where Highway Six is near the border: Vaalimaa, Vainikkala, Nuijamaa, Imatra, and Parikkala (South to North). These are depicted with red dots in Figure 2. (Finnish Border Guard, 2023).

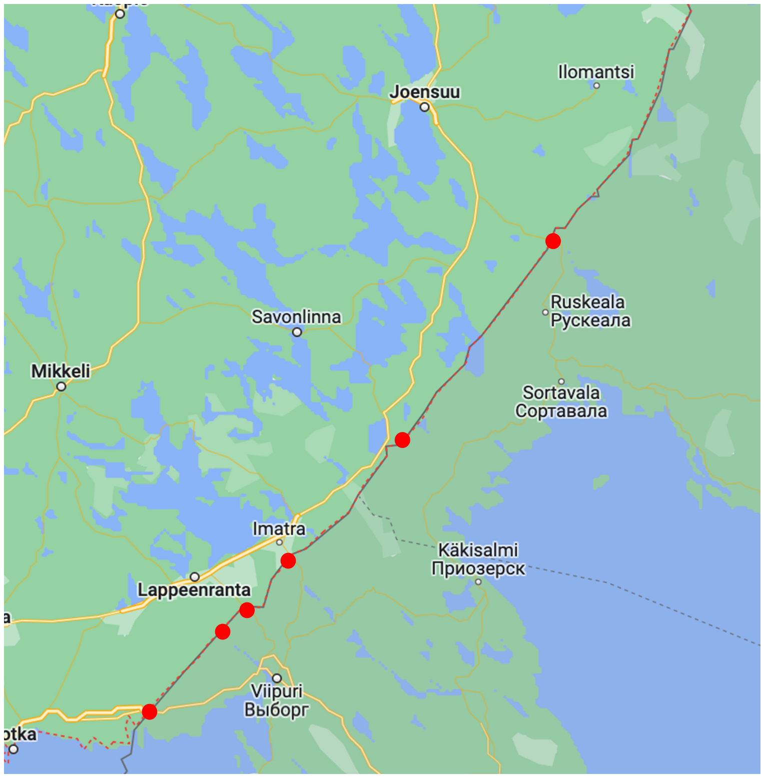

Figure 2: Border crossing points in the southern border of Finland and Russia.

Moreover, the closest cities to the border are Imatra in Finland and Enso in Russia. Their population counts are respectively 25,234 and 15,981. Also, they are located side by side near the Imatra border crossing point. In addition, there are many small municipalities along the border.

Figure 4 presents an example of the terrain in the border area. This satellite picture is 10 kilometers south of the Parikkala border crossing point. Also, this is where Highway 6 advances, closest to the border, only about 2 kilometers away. Notably, there is a 50-kilometer gap between the Imatra and Parikkala border crossing points. Most of the border area is similar to this example: low population density, mostly forest and crop fields. Also, the area has some small roads, mainly leading to houses and farms.

Figure 3: Satellite picture of the border area.

2.3 Equipment

The prices of border control-specific equipment are rarely discussed on manufacturer sources. This is due to the B2B nature of the trade. Also, most equipment had different versions, and custom add-ons were available. Therefore, the prices are determined individually for each customer case. In turn, specs and features of this equipment were usually available. The prices and specs on civilian-grade equipment were found more easily. The absence of exact prices and specs will not compromise our model since these parameters can be changed later.

The low-cost solution for cameras would be to use trail cameras. Customer trail cameras used for hunting start from around 100 euros. An example of these cameras is Zodiac Vision 2 trail camera (XLL Sports, 2023). This camera uses an infrared sensor to detect moving objects and takes a still photo of them. The range in this camera is 20 meters, but this range drops when objects like trees are in the way.

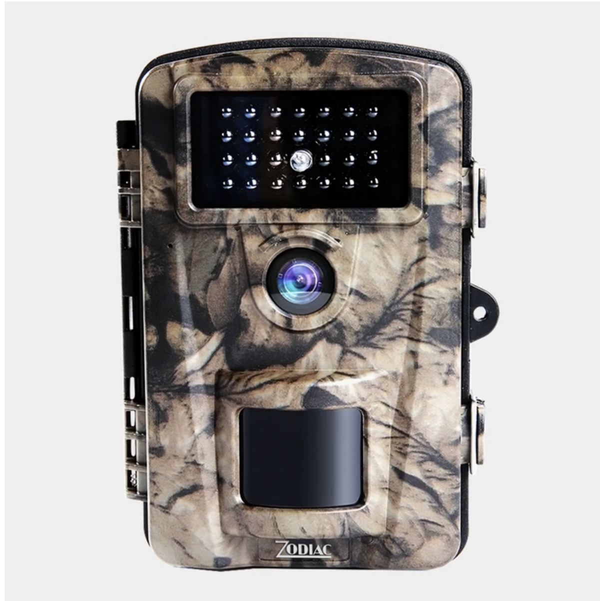

Figure 4: Zodiac Vision 2 trail camera.

For more advanced camera solutions, there are border surveillance-specific solutions available. For instance, TacFLIR® 380-HD - the camera has a 120x optical zoom and 360-degree rotation. This camera can also record full H.D. video and has a larger range. The price for this camera is unavailable, but we can speculate that it would be upwards of 10,000 euros. (Teledyne Flir, 2023).

Drones can be divided into two categories: multi-rotor and VTOL drones. Multi-rotor drones are more familiar to customers and look similar to helicopters. These drones are cheap; light customer versions start from around 300 euros. In turn, multi-rotor drones have lower ranges, and they tend to have less technology in them. VTOL drones are airplane-like drones that can take off and land vertically. The professional models of these VTOL drones cost between 3,000 and 300,000 dollars. Features like larger batteries and thermal capabilities increase this price. Compared to traditional multi-rotor drones, VTOL can achieve higher speeds (up to 350km/h) and a 200km range. These drones can also fly through wind, rain, and snow. An example product of VTOL drones is a JOUAV CW-007 (Figure 5). It is a base model from a drone manufacturer called JOUAV. That drone has a wingspan of 2.2 meters, and its cruising speed is 61.2 km/h. (JOUAV, 2023).

Figure 5: JOUAV CW-007 VTOL-drone

Fence specifications are based on the Finnish border guard's active pilot of the eastern border barrier fence. The fence (Figure 6) will be approximately 200km long, and most of the fence will be located at the southeast border, which is similar to our examined area. The fence includes a technical survey system. The fence aims to detect, prevent and slow down people at the border (Finnish Border Guard, 2022). The price of the fence is estimated to be 380 million (Reuters, 2023). This equals the price to be 1900 € per meter.

Figure 6: Illustrative image of the border fence

3 Data and Methods

3.1 Methodological Basis

To arrive at the optimal portfolio of border equipment, we take a simulation approach utilizing Monte Carlo to calculate effectiveness. The reason for using Monte Carlo is that the portfolio optimization problem is insoluble: we would need the effectiveness measures for each type of equipment to optimize. However, these effectiveness measures are unknown and can only be estimated via simulation. Therefore, we begin by constructing a specific subset of equipment portfolios. A portfolio consists of the set of border control equipment used and the locations for this equipment. Next, we run our border control simulation, described more thoroughly in Section 3.3. We repeat the same run multiple times, arriving at a Monte Carlo estimate of the effectiveness of the simulated portfolio. Finally, we combine the simulations' results, arriving at decision recommendations of which defense equipment portfolio is best to implement. As the complexity of a perfect simulation is very high, we need to, in each phase, make heuristic simplifications to ensure a runnable simulation. To summarize, our methodology is as follows. Here, M is the set of all possible border equipment portfolios, and $\overline{M}$ is the heuristically constructed subset of possibly optimal subsets.

1. Heuristically construct a subset of possible border control equipment portfolios, $m \in \overline{M} \subset M$
2. For each $m \in \overline{M}$, run n iterations of the simulation
3. Combine the results of step 2 to arrive at an effectiveness measure for each portfolio
4. Compare these effectiveness measures to decide on the best border control strategy

The software is created with Python and uses an object-oriented programming approach. The architecture of this software is presented in Figure 7. The software is divided into two parts: main and core. Main takes care of everything except simulation. The simulation is done in the core.

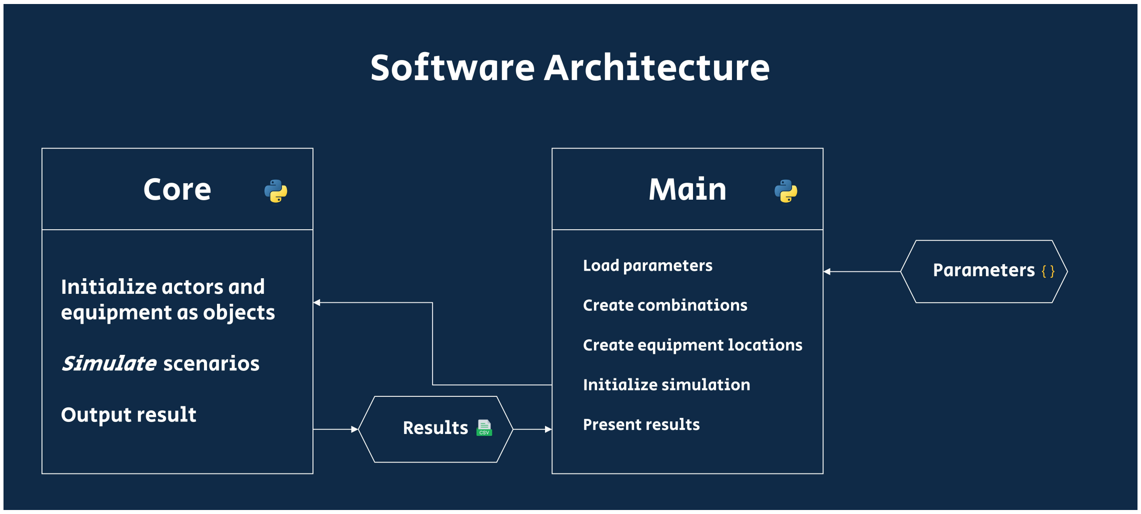

Figure 7: Architerure of the simulation software

The main first loads a JSON file containing the simulation's parameters; these include the number of immigrants, the number of border officers, prices for the different border equipment, the budget, and other parameters that affect the simulation. After loading the parameters, the code creates different combinations of border equipment that comply with the budget constraint. When the different combinations of border equipment are created, the Main creates different scenarios using this data. These different scenarios place the border equipment in different locations.

After creating the scenarios, main calls the core to run the simulations. The core consists of actual simulation and logic of equipment, actors, and movement area. Core first initializes the different actors and border equipment by creating them as objects to the simulation. After creating the objects based on scenario data, core runs the simulation until it is complete, which means that all immigrant groups have either been caught or have reached the edge of the area. After the simulation, the results are returned to Main, where results are output as a CSV file for interpretation.

3.2 Data

As the nature of our project is that of a simulation, the data we need is mainly parametric. We have two types of data: data based on literature and public sources and data based on assumptions. The description of the data gathering from the literature can be found in sections 2.2 and 2.3. The former class includes drone speed, camera cost, and the size of the simulation area, while the latter includes the immigrants' and border patrols' speed, among others. Tables 1 and 2 show the data used in our project

Data	Value
Camera observation range	20 m
Camera cost	100 €
Drone speed	17 m/s
Drone observation range	(100 m)
Drone cost	50 000 €
Fence cost	1900 € / m

Table 1: Data based on public sources

Data	Value
Number of immigrant groups	10
Immigrant group size	1-10
Immigrant speed	0.56 m/s
Number of border patrol groups	3
Border patrol speed	1.67 m/s

Table 2: Data based on assumptions

belonging to the previously mentioned two data classes, respectively.

The data in Table 2 was decided heuristically. The basis for this was that an amateur (immigrant) moving in the forest has roughly a speed of 2 km/h, while a more experienced person (border patrol) has a speed of 6 km/h. The number of immigrant groups multiplied by their sizes corresponds roughly to a busload of immigrants. In contrast, the number of border patrol groups is an assumption of how many groups the Finnish Border Guard can mobilize with short notice.

3.3 Simulation

Here is a detailed simulation description as introduced in section 3.1.

3.3.1 Landscape

The landscape of our simulation consists of three main areas: the border, the road, and the terrain. The immigrants start from the border and aim to move as quickly as possible to the road. If they do achieve the road, they have escaped. Using equipment to detect the immigrants' movement, the border patrol aims to detain as many immigrants as possible.

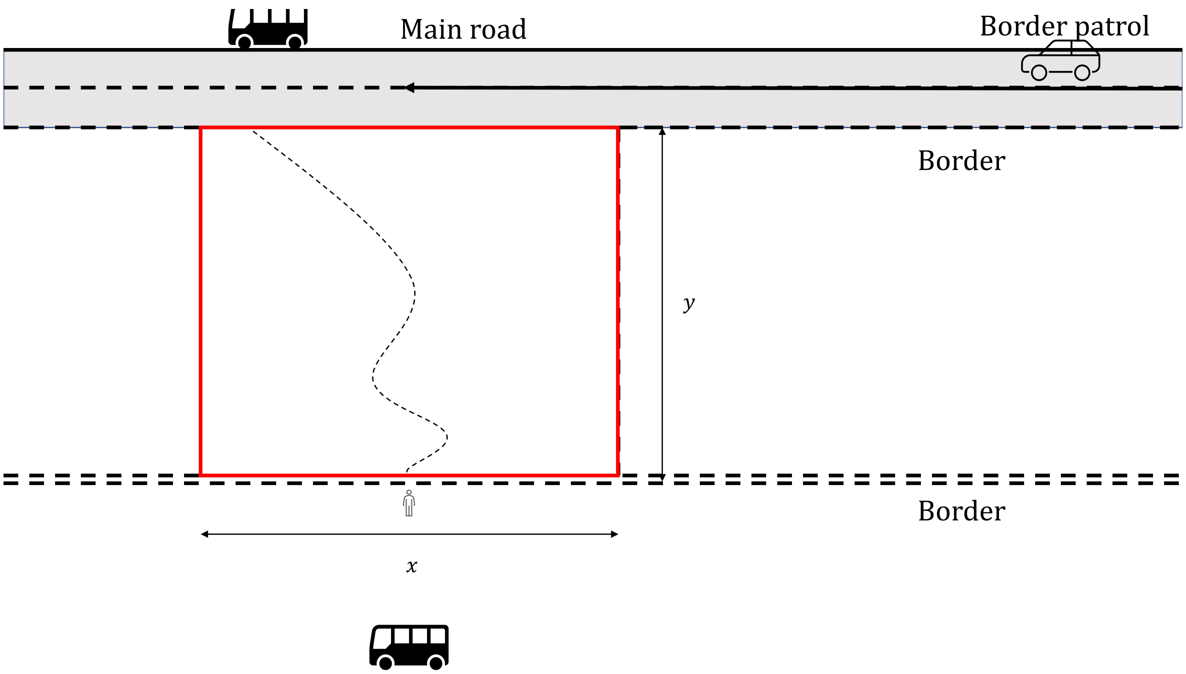

Figure 8: A simplified illustration of the base scenario that will be simulated and analyzed.

Figure 8 illustrates the landscape as described. The border and main road are the lower and upper border of the simulation area, respectively. The distance between these is denoted by y, while the width of the simulation area is x. In our simulation, $y = 10000m$ and $x = 20000m$. Our terrain is solely a forest terrain; we simplify our simulation by disregarding other types of terrain, such as fields and roads.

3.3.2 Equipment

Our simulation has three different kinds of equipment: fences, cameras, and drones. A fence is a barrier in the terrain that hinders the immigrants' movement for a set amount of time, and also has detection equipment detecting the immigrants as they arrive at the fence. Cameras are simple detection equipment which is stationary in the terrain and notifies the border control if they detect human movement in their detection area.

Finally, drones are more sophisticated detection equipment, which can move at high speed, scan the terrain for possible human movement, and follow a detected immigrant group to ensure up-to-date information on their location.

3.3.3 Portfolio Candidates

Next, we create the subset of possibly optimal portfolio candidates to run our simulation. In making this subset smaller, we use heuristics on two occasions. First, we decrease the number of different locations for the equipment, as this starts from practically infinite. Second, we decrease the number of combinations of different equipment, as this is also a combinatorially huge number.

Regarding the first point, we can approximate where the equipment should be placed. First, the fence should be placed horizontally in the same direction as the border to decrease costs. Second, the fence should be continuous and not have any gaps placement-wise. Third, the fence should also be placed relatively close to the border to maximize effectiveness. Finally, the fence should not be placed before all detection equipment; in this case, its hindrance effects do not contribute anything meaningful.

We also make several heuristic choices concerning the camera placement. These heuristics mainly rely on the fact that we assume our simulation environment to be symmetric; therefore, there is nothing gained by unsymmetrically placing cameras. Thus, we place all of our cameras in a single horizontal line with regular intervals, as this intuitively maximizes the expected value of immigrants caught as they spawn randomly on the border. However, the optimal vertical placement of this horizontal row of cameras is not intuitively clear, and different options are thus simulated to arrive at an approximate optimum placement.

As the drone is a moving piece of equipment, we need not worry about its placement. In our simulation, it starts from the road without delay, approximating its high deployment and movement speed.

Regarding the second point, we have two different heuristics two decrease the number of equipment combinations. First, we use the concept of Pareto-optimality. As we aim to maximize the number of immigrants detected and detained, a portfolio that has room to buy more equipment is strictly dominated, in the first-degree sense, by another portfolio that has allocated all of its budgets (taking naturally into account the discrete nature of costs). Second, we choose portfolios that have a noticeable difference between them, disregarding close combinations as their differences will not be significant.

With these two combination-reducing heuristics, we randomly create optimal candidate portfolios from the subset reduced via these heuristics. These candidate portfolios are then iterated through within the simulation.

3.3.4 Immigrants' Movement

The immigrants in the simulation walk in a random walk. They start from a randomized location from the border, and at each point, they move with the same speed and an angle θ, which is randomized from a normal distribution. The angle theta is in relation to the previous direction vector of that immigrant, i.e., θ shows the change in movement direction at each point. The normal distribution is centrally located at $\theta = 0$, as each immigrant aims to move directly from the border onto the road. However, there is random variation resulting from two phenomena. First, they move in forest terrain, which means they move according to the terrain, e.g., having to walk around cliffs and lakes. Furthermore, the immigrants are not perfect orienteerers and will likely deviate from their designated route due to orienteering errors. To account for these phenomena, we used $\sigma = 0.1$ as the standard deviation. The new movement direction is calculated every 10 seconds. As the immigrants start from the border, their start direction is randomized with a standard deviation of $\sigma = \pi/2$.

3.3.5 Border Patrols' Movement

The border patrol's goal is to catch as many immigrants as possible before they reach the road and have thus escaped. We have, heuristically, decided on one possible way for the border patrol to achieve this goal. This is, however, just an assumption, as we do not have information on the true motivation and strategies of the Finnish Border Patrol, as this information cannot be for security reasons found from public sources.

This goal is attained in two distinct phases: prioritization and route calculation. First, prioritization refers to choosing an immigrant group to chase after; as several groups might be detected by observation equipment in the terrain, it is crucial to choose a good order to catch these groups. Second, after the border patrol has chosen a group to go after, they must calculate their route. This calculation takes into account both the speed of the immigrants, as well as the randomness of their movement.

The prioritization is done vie calculating a prioritization score for each immigrant group.

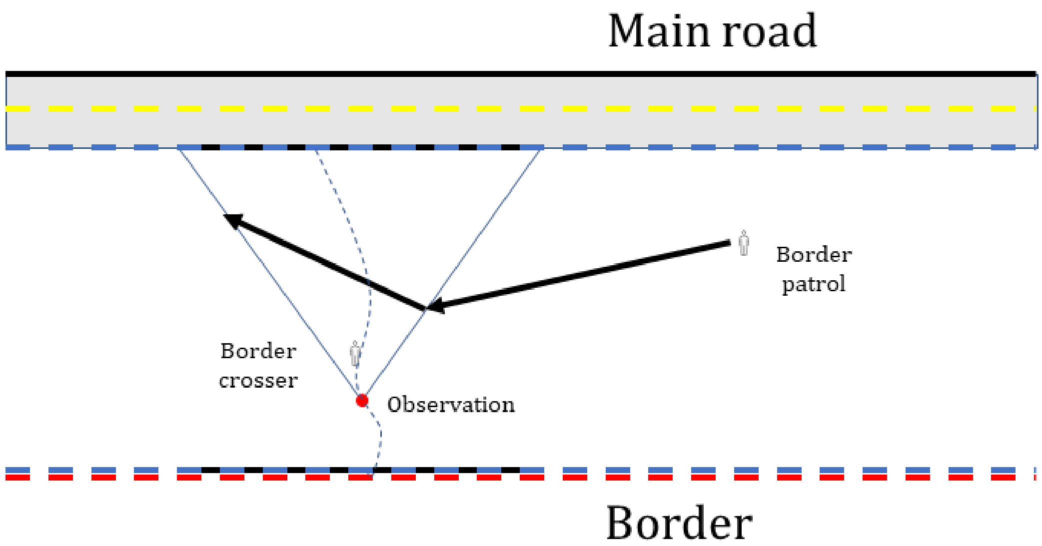

Figure 9: Border Control Movement

This is done via the formula

$$P_i = S_i \cdot d_i^{-1} \cdot r_i^{-1} \cdot t_i^{-1},$$

where P_i is the prioritization score of an immigrant group i, S_i its size (in people), d_i the distance from the immigrant group from the road, r_i the distance of the immigrant group from the border patrol, and t_i the time elapsed from the last observation made on the group. This list thus prioritizes large groups of immigrants who are close to escaping but can also be caught quickly, as they are close to the border patrol with recent and thus reliable observations. Each border control patrol calculates these prioritization scores for each immigrant group, choosing the group with the highest score as their next target, given that any other patrol is not yet chasing it.

After the target is chosen, the border patrol starts chasing this target. Figure 9 illustrates the situation. Here, the red dot is the latest observation of the immigrant group. The blue cone shows the possible locations the immigrant can be found in, illustrating the divergent nature of the random walks. The dotted line shows one possible route for the immigrant, while the black arrows show the movement of the border patrol. First, the patrol takes the fastest (straight line) route to the side of the cone closest to them, calculating the route such that they arrive at the side at the same time as an immigrant group, walking in a straight line along the edge of the cone, would. Second, the patrol's route cuts through the cone into the other edge, going upwards to consider the immigrant group's speed. If the border control catches the immigrant group at any point during this route, it recalculates its priority scores and chooses the next group to go after. This is also done if arriving at the endpoint and not catching the targeted immigrant group.

This route choice strategy maximizes the chances of catching this single immigrant group. Theoretically, given that the group's random movement does not deviate significantly from the expected, this should lead to a 100% capture rate.

3.3.6 Drone's movement

The border patrol may also utilize a drone to help detect immigrants. When a camera detects an immigrant group, a drone is deployed from a base location and travels toward this observation of an immigrant group. After it reaches the observation location, the drone starts to follow the observed immigrant group, which can always be approximated to be successful as the drone's speed is much higher than the immigrants', and its observation radius is reasonably high. The drone used in our simulation has a maximum flight distance of 200 kilometers, which is high enough not to restrict its usage for our purposes. While following this group, it updates the border patrols about the group's placement, decreasing the time the border patrol takes to catch an immigrant group. Simultaneously, it tries to observe other groups and notifies the border patrol of these groups as well. After the immigrant group the drone initially followed has been caught, it chooses another group from the set of observations the cameras have made and starts following this group.

3.3.7 Calculating Results

We simulate a suitable number of iterations for each equipment portfolio as described to get a convergent result on the Monte Carlo approach. Over these simulations, we calculate some key performance indicators (KPIs) of the performance of that border equipment portfolio. First, we calculate the percentage of immigrants caught, which is the primary indicator of successful patrol performance. Second, we use the percentage of immigrants detected, as it is beneficial to avoid so-called "unknown-unknowns"; immigrants escaping without the border patrol knowing they escaped.

As we have made several simplifying assumptions, used many heuristics, and used partly uncertain and even incorrect public data when constructing our simulation, the absolute

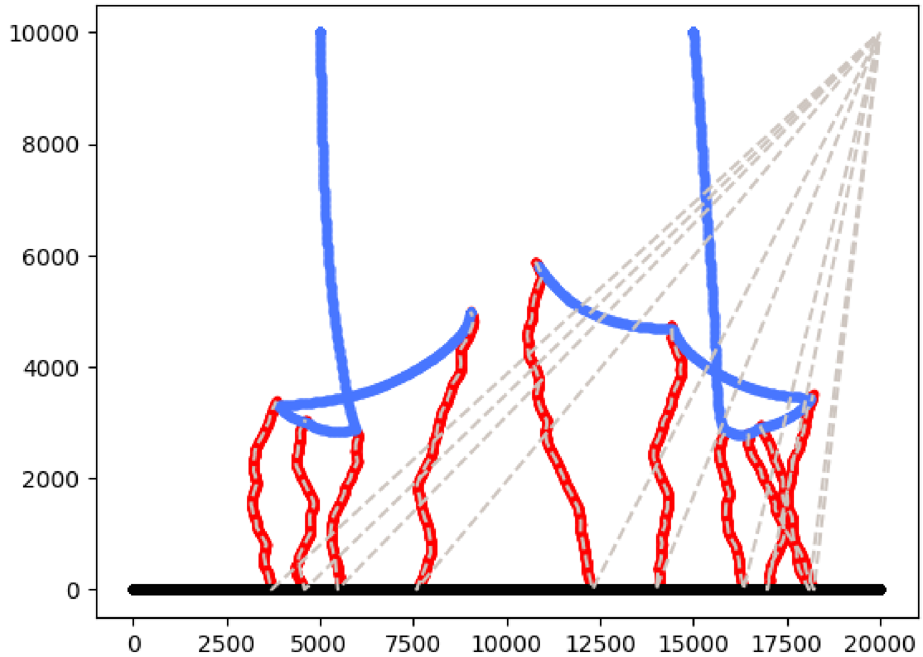

Figure 10: Example run of the simulation

values of the above metrics are probably incorrect. Therefore, in the next section, we mainly focus on the trends shown in the simulations: which equipment seems to fare better than others and would therefore be a wiser investment choice.

Figure 10 shows an example run of the simulation. Here, black dots represent cameras, red lines the immigrants' movement, blue lines border patrols' movement, and the gray dotted lines the drones' movement.

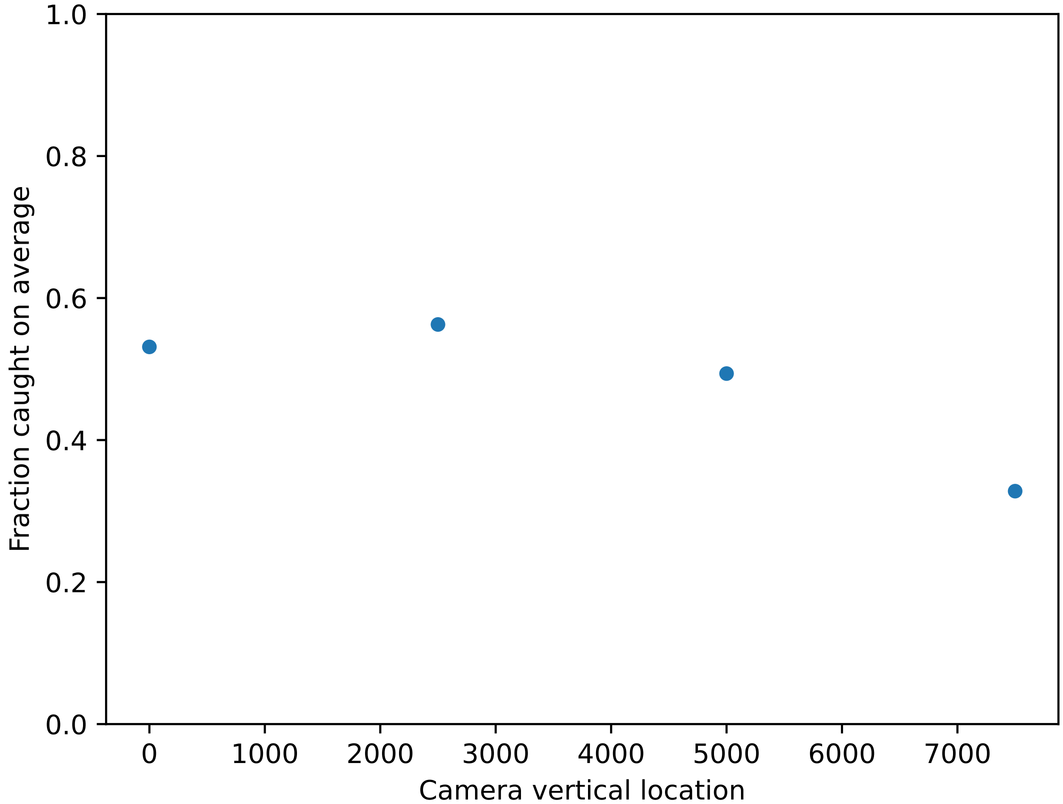

Figure 11: Average fraction of immigrants caught

4 Results

We initially constructed 50 combinations of border equipment, leading to 950 possible optimal portfolios, considering the different placement of cameras and fences. Then, for each of these 950 possibly optimal portfolios, we ran 100 iterations of Monte Carlo simulation, taking the average of these 100 to arrive at more precise estimations of KPIs.

As can be seen from Figure 11 above, the cameras' optimal placement is somewhere in the half nearer the border of the simulation area. These correspond to locations $y = 0$ and $y = 2500$, with y as meters from the border. Here, the coordinate $y = 0$ corresponds to the border, while $y = 10000$ corresponds to the road. Thus we discard the combinations with the other placements, as they are most likely not optimal, and focus the simulation on the aforementioned two camera placements.

In the previous simulation and the next one, we used a total budget of 2M€, with our simulation area being $20km$ along the border. This corresponds to roughly 100M€ total budget along the entirety of the Finnish border, which was the approximate amount

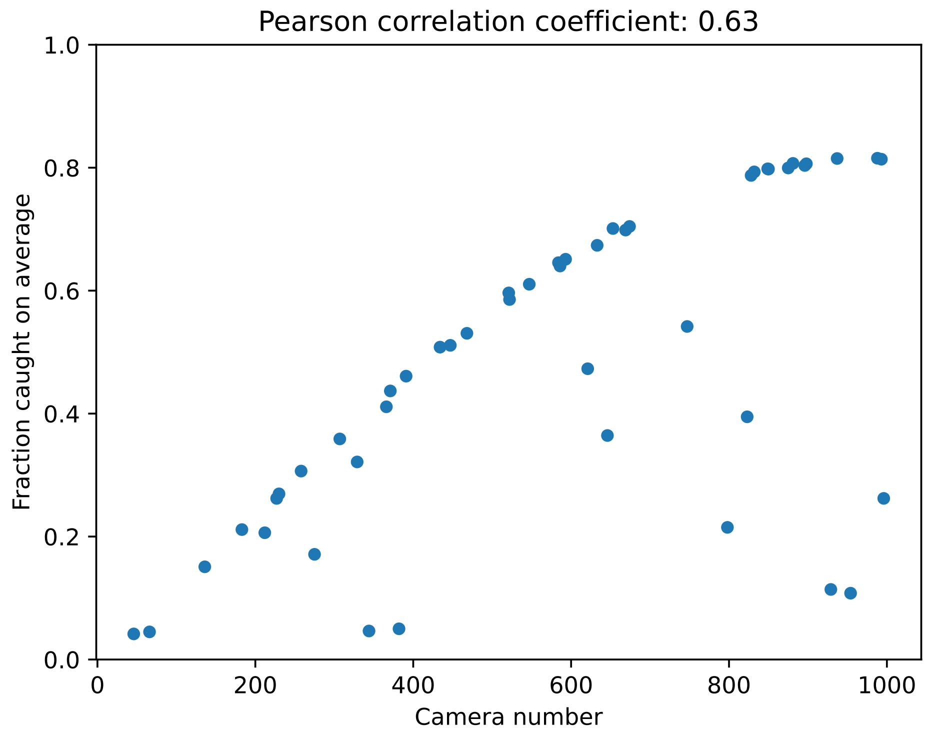

Figure 12: Fraction caught as a function of the number of cameras

we had for use.

Figures 12, 13, and 14 show the average fraction of immigrants caught as a function of the number of cameras, fence length, and the number of drones, respectively. These figures also show the Pearson correlation coefficients of these variables.

There are several observations made from these graphs. First, judging from the Pearson correlation coefficients, the camera seems to be the best investment of the three types of equipment. Second, trade-offs can explain the negative coefficient of the fence; the more fence is built, the less money there is to spend on cameras and drones.

Figure 12 has several outliers, which mainly result from the differences in amounts of other equipment - the less there are drones, the harder detainment is.

Furthermore, the fraction of immigrants caught rises approximately linearly until about 700 cameras, after which the growth steadies. The same is true for drones, with a limit of about ten drones.

Table 3 shows the best equipment combinations for budgets of 1, 2, and 3 M€. First, Table 3 shows that the budget has little effect on the overall capture rate as long as there are a sufficient number of cameras and drones. The length of the fence makes little

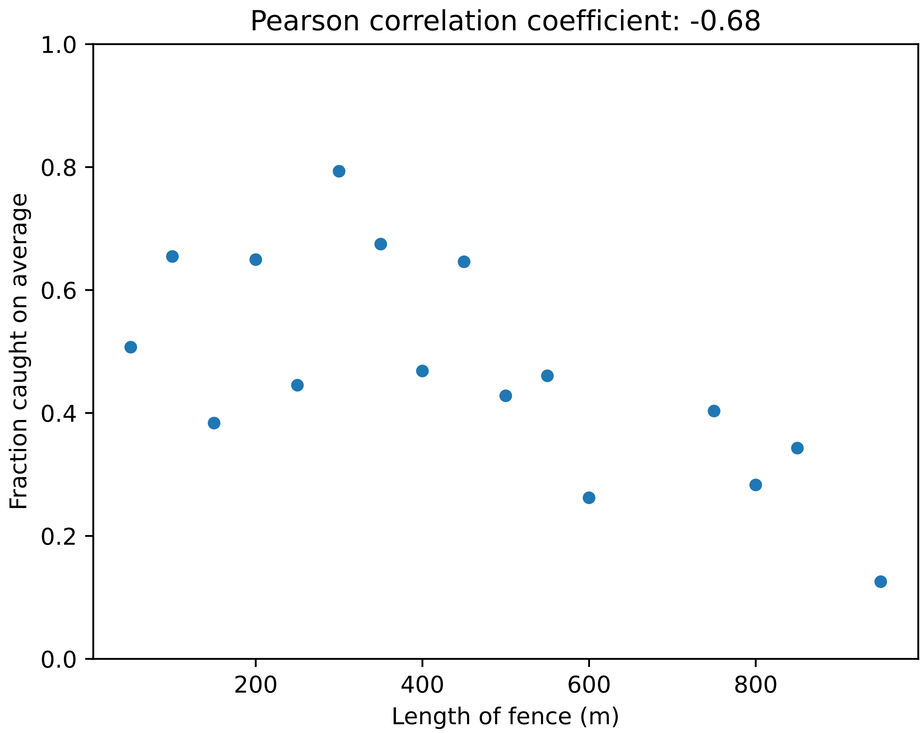

Figure 13: Fraction caught as a function of the fence length

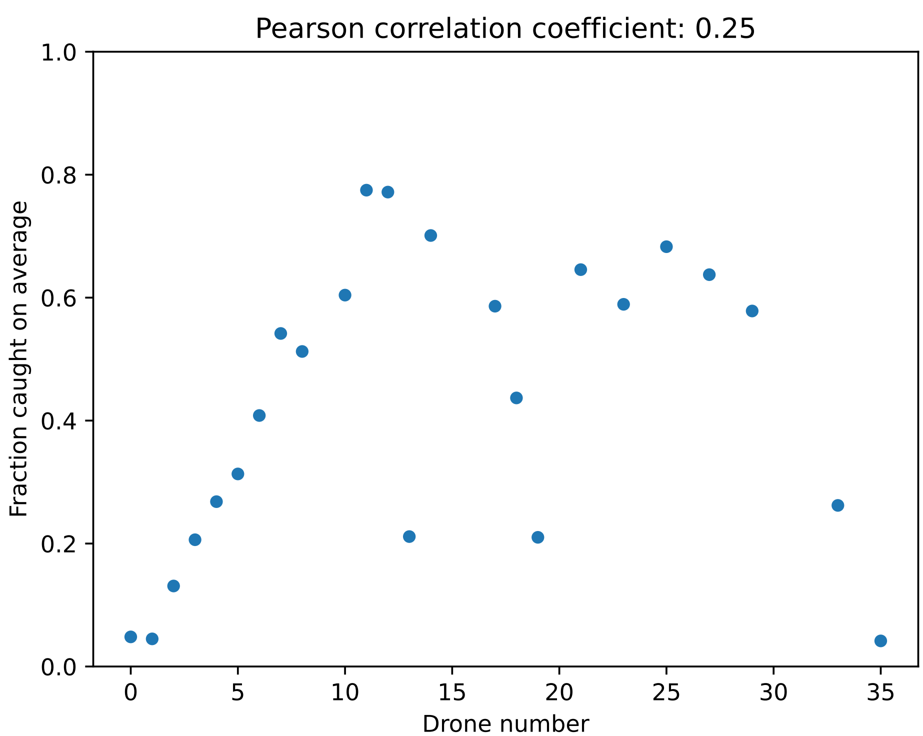

Figure 14: Fraction caught as a function of the number of drones

Budget	Fraction caught	Fraction observed	Number of cameras	Number of drones	Length of fence
3M€	0.980	0.987	987	15	850
2M€	0.983	0.998	993	27	200
1M€	0.978	0.997	982	14	0

Table 3: Best combinations for three different budgets

Number of border patrols	Fraction caught	Fraction observed
3	0.978	0.997
2	0.988	1.000
1	0.831	0.996

Table 4: Capture rates with different number of border patrols

difference in the effectiveness of the equipment combinations. Thus, it seems optimal to place approximately 1000 cameras per 20 kilometers, or one camera every 20 meters, and have at least 15 drones to follow the immigrant groups. Furthermore, placing the cameras relatively close to the border area is beneficial to maximize the time the border patrol has to detain the detected immigrant groups.

However, the standard deviation of these frequencies is in the range of $4 - 6\%$; there might thus be other optimal combinations, which are left out due to the random nature of the Monte Carlo simulation.

Table 4 shows the detection and capture rates, using the combination on the third row of Table 3, with varying numbers of border patrols. Two border patrols seem sufficient to capture ten groups of immigrants in our simulation environment, with a third patrol not statistically significantly different and one patrol significantly worse. Thus, we recommend at least one border patrol for every five immigrant groups detected crossing the border.

5 Discussion

Our project work has several inaccuracies and biases that need to be considered when interpreting the results given in the previous chapter.

First, even though we tried to do a thorough literature review on the possible equipment choices, we had to converge to only a few different pieces of equipment for our simulation to keep the computational complexity reasonable. Thus, the results might change, given different types of equipment. Furthermore, we only used equipment that could be found in the literature; this is a bias towards older and more tested equipment and might limit some types of equipment which cannot be readily found on the internet.

Second, we have used several heuristics and approximations when constructing our simulation, including those concerning how the observations are made, what the terrain is like, and how the actors move in the terrain. Because of their heuristics, the results we have achieved are not absolute. However, the trends these results show should be accurate as the bias in results is systematic and mostly independent of the simulated portfolio.

Most of the above inaccuracies and biases have a simple solution: advancing the simulation. Therefore, we purposefully designed the simulation and its code to be extended easily. This way, different types of equipment can be added, and the Finnish Defence Research Agency can specify more accurate parameters and models for, e.g., the border patrol movement based on their internal intelligence.

Further research should focus on incorporating a wider variety of border equipment, both more types of that equipment used here, as well as novel equipment not considered. Furthermore, the terrain can be specified, considering the changes in movement and observation with fields and roads, as well as the change of seasons, especially in winter. Finally, further research should focus on the adversarial nature of the problem. We made the simplifying assumption of treating the immigrants as non-strategic, considering only their own goal of reaching the main road. In reality, as the catching of immigrants has been going on for a while, the immigrants will start adapting their strategies to counter the detection and detainment techniques of the border patrol, which will influence the optimal solution given in the previous chapter. This can be done via, e.g., the Adversarial Risk Analysis framework (Rios Insua et al., 2009), or game theoretic treatments (Von Neumann and Morgenstern, 1947).

6 Conclusions

A recent change in the geopolitical environment and safety has led The Finnish Government to invest more resources in border safety. The main goal of these investments is to reduce the number of illegal immigrants successfully crossing the Russia-Finland border. Our project aims to provide decision support to the Finnish Defence Research Agency on what kind of border control equipment portfolio is best for attaining the abovementioned goal.

To provide decision support for this problem, we constructed a simulation environment, which created different border equipment combinations and tested their effectiveness using a Monte Carlo estimation approach. Our simulation considered cameras, fences, and drones as equipment helping the border patrol detect illegal immigrants and hindering their progress towards escaping.

Running these simulations, we found that the border equipment used can lead to a high capture rate of 99%, assuming a budget of 50 000 € per one kilometer of the border, ten groups of immigrants, and three border patrols. This high capture rate was achieved by a combination of border equipment where a horizontal, evenly placed line of cameras was placed less than 3 kilometers away from the border, such that the observation frequency of immigrants across this line is close to 100%. Furthermore, the combination should also include at least ten drones to follow the immigrant groups and thus reduce their capture time by the border patrol. Finally, we found that using a fence is not beneficial, as it takes resources away from more effective equipment.

Our results are directional, and the absolute values of capture rates presented in the previous chapters should be taken with a grain of salt. Further research should focus on making fewer assumptions and expanding the equipment portfolio and movement mechanics of the equipment and actors used in the simulation.

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8 Self-assessment

8.1 Succession of the project

Our project implementation followed reasonably closely our original project plan. We have implemented everything our project plan presented as mandatory - a working simulation environment, the most critical equipment, and a reasonable approximation of the real-life movement of immigrants and border patrol. The secondary objectives were not implemented, such as implementing lost people or smuggling goods via technology. We followed our original schedule closely, although our realized project stages overlapped quite a bit, even though our plan presented them separately. This is not necessarily a failure to adhere to the project plan and more of an on-the-fly optimization of our team's resource usage.

The project was successful in the regard of adhering to the project plan in broad strokes, as well as achieving all the necessary objectives. We also produced meaningful results, which we think will help our client determine the optimal portfolio of border equipment.

We would have liked more time on the project to implement more equipment. The project was also challenging as it had to rely only on public data, which led to us making several assumptions and heuristics. Because of these, we could not achieve meaningful results in the absolute sense and only have relative importance for the different types of equipment. However, our simulation can be further developed by our client and thus made more specific and accurate in its models and parameters.

8.2 Work flow

Regarding our workflow through this project, we held meetings 2-3 times a week. Roughly the first half of the project, we held meetings on campus, and in the latter part, we worked on the project remotely. Meetings requiring brainstorming worked the best on campus. Later, the coding part of our project worked better remotely. In every meeting, we wrote a to-do list and decided when to meet next time. While writing the code for the software, we held shorter meetings where we just updated the team on everyone's progress and wrote a to-do list. This puzzle-like way of working on the code has its risks, but we were able to complete the software fairly successfully. Notably, every new feature added increased the complexity of the model and increased the risk that different features would not work together.

Overall, the communication between the team was highly active. We were able to actively work on this project considering that our team members have jobs, hobbies, and other coursework. Also, team members had a good attitude towards this project, and there were no schisms between team members.

8.3 Schedule

In hindsight, we could have had a more strict schedule and meetings with our client. Furthermore, we could have spent more time on the literature review to understand better which equipment types are usually better and what kinds of assumptions are okay to make. In addition, we could have reserved a week for running simulations and refining the code. The simulation run times were around 4-6 hours for the whole code. This delayed the finishing of the software.

8.4 Documentation

The documentation of the project code could have been better. Documentation was based on comments in code and GitHub commit messages. Working together with the same code was possible through our frequent meetings where created code was explained and discussed. The creation of actual documentation would have given a better understanding of the code to all of the team members.