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Exploring the deployment of autonomous medical emergency vessels in island and coastal regions

An overview of the opportunities and challenges

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Contents

1. Abstract

Introduction: Emergency medical systems in island and coastal regions face challenges such as supply and staffing shortages and a dispersion of resources and people, which negatively affect the timely and efficient delivery of emergency medical services. This thesis explores the opportunities and challenges of using autonomous vessels in these systems to start a discussion, as current research in this area is very limited.

Applications of vessels in emergency medical systems: Currently, emergency vessels are primarily used to transfer patients to hospitals, doctors to emergency sites as well as equipment between islands. Floating hospitals ships generally combine these functions by enable comprehensive consultation, diagnosis, and treatment at the emergency sites. Additionally, rescue and search operations can also be counted among the tasks of emergency medical systems if one considers an extended range of tasks for these systems.

Method: The location of hub facilities, where autonomous vessels are stationed when not in operation, is one of the first decisions to be made when integrating those vessels into current emergency systems. Therefore, the model for solving the maximal covering location problem is applied and adjusted to cover a wider range of application of vessels in emergency medical systems. Simulations are conducted to identify opportunities to improve system performance when setting hub facilities for autonomous vessels.

Discussion: Hub facilities for autonomous vessels can be located at a greater number of locations, leading to better population coverage in some cases. Furthermore, the complexity of response routes can be decreased by the ability of autonomous vessels to transform current applications of vessels in emergency medical systems. Despite several other opportunities to reduce response times and use resources more efficiently, there are also challenges associated with the use of autonomous vessels. Some main challenges are to successfully integrate the new vessels into the existing system and to ensure their use by the population. Additionally, the costs of autonomous vessels are likely to exceed those of conventional vessels requiring in-depth cost-benefit considerations.

Conclusion: Autonomous vessels have a great potential to enhance the performance of emergency medical systems in island and coastal regions. Most of the challenges can be mitigated by carefully planning their operations and introduction of the vessels into the

existing system. However, in the context of scarce funding, higher costs compared to conventional vessels are likely to be the most significant challenge for the introduction of autonomous vessels.

2. Introduction

Emergency medical systems in island and coastal regions face distinctive challenges that have a significant impact on the timely and efficient delivery of medical services to those in need. These regions are characterized by shortages of "funding, supplies, and personnel" (Ratu Sage, 2005) necessitating the efficient utilization of limited resources. This issue is not limited to lower-income areas; even higher-income areas suffer from an unavailability of qualified medical professionals due to the migration of skilled workers to urban areas and other regions where better job opportunities are available (Duong, 2022; Negin, 2008). In addition, the geographical isolation and dispersion of available resources in these areas present a complex transportation problem that makes it difficult to efficiently allocate the limited resources to effectively respond to emergencies within reasonable response times. Ensuring a baseline service quality for emergency medical services is therefore often challenging, which significantly impacts the quality of life and the well-being of the population.

In recent years, autonomous vessels have garnered significant attention for their potential to transform the maritime sector, leading to an increasing number of publications in this field of research (Gu et al., 2022). While implementation projects have been carried out in commercial sectors such as container shipments (Yara, 2022) and passenger transport (Emir, 2023), the utilization of autonomous vessels in non-commercial areas has received relatively less attention, possibly due to the challenges of achieving profitability and breaking even on the invested amount.

This thesis aims to initiate a discussion on the utilization of autonomous vessels in emergency medical systems of island and coastal regions to overcome the difficulties that are hindering the successful provision of emergency medical services. Since the emergency medical systems in these areas often struggle to provide a base-level service quality, the focus will be on the potential of autonomous vessels to increase population coverage for a particular target response time and to decrease average response times, which are widely accepted performance indicators for emergency systems. Moreover, considering the shortages of critical resources and funding in these areas, the impact of autonomous vessels on resource consumption will also be taken into account.

Determining the optimal location for autonomous vessels, i.e., the locations at which they are stationed in between emergencies ready for immediate response, is an initial and crucial decision in the planning process of introducing autonomous vessels and integrating them into existing emergency systems. The mathematical maximal covering location model (MCLM) and its variants are valuable for modelling this decision and identifying improvements in response times and population coverage while considering resource constraints that are imposed by a limited number of hub locations that can be established (Daskin, 2008). Furthermore, the MCLM has been extensively applied in strategic network planning for optimizing facility locations and has also found usage in the context of healthcare and emergency services, confirming its usefulness in the chosen context of this thesis (Ahmadi-Javid et al., 2017; Garner & van der Berg, 2017).

The subsequent section describes the general applications of vessels in current emergency medical systems to understand their use in the provision of emergency medical services. Following that, the components of the original MCLM will be explained, and two adapted MCLM models will be developed which increase the covered scope of vessel applications in emergency medical systems of island and coastal regions. A simulation for each of the models will be conducted using a fictional geographical dataset to investigate the circumstances under which the usage of autonomous vessels leads to an increased performance solely based on the location of their hub facilities. Subsequently, an exploration of potential opportunities and challenges presented by autonomous vessels is provided. The discussion encompasses their influence on response time, population coverage, and resource consumption, while also taking into account the specific applications of vessels in emergency medical systems.

To the best of the authors' knowledge, this study represents the first comprehensive and consolidated examination of potential opportunities and challenges associated with the implementation of autonomous vessels in emergency medical systems tailored explicitly to island and coastal regions. Therefore, the discussion provided in this work offers a unique contribution to the existing literature. Additionally, the extensions made to the applied model contribute further novel insights to the field.

3. Application of vessels in emergency medical systems

Vessels have many different applications in emergency medical systems. Depending on the circumstances of a particular real-world scenario, vessels can have one or more of the applications described in the following.

The transfer of patients between islands (inter-island transfer) and between islands and the mainland is a critical responsibility of emergency vessels in island and coastal regions (Caliskan & Altintas, 2020; Jurban et al., 2018). The need for patient transfer rises due to the lack of medical professionals at each demand location, for example if a highly specialized doctor is needed for providing specific emergency medical services. Patient transfers are also essential when the treatment requires rare and expensive or immobile medical equipment. Furthermore, patient transfers are frequently utilized for less severe emergencies where time constraints are less critical as patients are not in life-or-death situations. Møller et al. (2021) emphasize the importance of island-coastland transfers in their article, reporting that "90.2% of island missions resulted in patient transport". However, those transfers were conducted via helicopter instead of vessels.

In addition to patient transfers, it is also possible to transport doctors to emergency sites, as seen in urban areas with emergency physicians. This approach is often adopted for life-threatening emergencies that demand an immediate response, such as strokes and heart attacks. It is also used when the patient's condition does not permit transportation to a hospital, for instance, when the patient is immobile or has other underlying conditions that could worsen during transportation.

Emergency vessels are also utilized for relocating essential supplies, including equipment and medicine, or for transporting them to emergency sites in situations where they are either unavailable or become depleted during the response process. This can involve picking up supplies from storage locations and transporting them to the emergency site or having the vessels stationed at a warehouse where they are pre-equipped with necessary supplies before directly driving from the warehouse to the emergency site.

Floating hospital ships are another application of vessels, combining the aforementioned functions of transporting doctors and equipment to emergency sites (Harris, 2012). They are able to provide more extensive consultation regarding medical topics, diagnosis of patients, and medical treatment at the emergency site than it is possible by an individual emergency physician with limited supplies. The utilization of floating hospital ships increases flexibility, consolidates resources in one location, and enables the relocation of the hospital. However, it also requires significant resource commitment to invest in such a vessel and coordinate its operations.

Depending on the definition of the tasks of emergency medical systems, rescue and search missions, such as flood rescue or natural disaster response, can also fall within their purview. In Germany, for instance, these missions “are almost always classified […] as emergency rescue in combination with (qualified) ambulance services” (Lechleuthner, 2021), according to state law. Considering the potential relevance of this broader scope to other regions, rescue and search missions will be regarded as a function of emergency medical systems in the following sections of this thesis.

4. Method

4.1 Models

The original model for solving the maximal covering location problem was proposed by Church and ReVelle (1974). In their paper, the authors did not explicitly distinguish between indices, parameters, and decision variables in the notation of the model components, a practice that persisted in various subsequent articles (e.g., Li et al., 2011; Daskin, 2008). To address this, the classification of the model components in this thesis follows the framework introduced by Ahmadi-Javid et al. (2017), who classified the components as sets (indices), input parameters, and decision variables.

The original model primarily focuses on direct routes from potential hub facilities, where the vessels are stationed and ready for deployment, to the emergency sites. This approach helps to model the total travel distance, i.e., the distance travelled until the provision of emergency medical services, of floating hospital ships, during rescue and search missions, and when delivering medicine from a central warehouse to the emergency site, as the vessels start from a hub location and directly drive to the emergency site in those applications. However, the model does not explicitly capture picking up patients, doctors, and equipment, which involves stopping at intermediate destinations. Therefore, adjustments are made to the original model to accommodate the process of picking up passengers. These adjustments involve incorporating potential intermediate destinations to consider the entire routes taken by the emergency vessels. As a result, two adjusted models are developed: one specifically designed for picking up medical professionals and equipment and the other for picking up patients. Thus, these adjusted models lead to a more comprehensive representation of the applications of vessels in emergency medical systems when solving the maximal covering location problem.

4.1.1 Original model

In the original model, a set of demand locations, denoted as I, needs to be covered by establishing hubs at potential candidate locations in set J. The set N_i is derived by combining two parameters: $d_{i,j}$, representing the distance between demand location i and hub location j, and S, which denotes the maximum allowable distance between a demand location and a hub location for the demand location to be considered as covered by the hub. By combining those two parameters, set N_i is derived, which, for each demand location i, contains only those potential hub locations that can cover the demand within the target distance, i.e., those "facility sites [that are] eligible to provide 'cover' to demand point i" (Church & ReVelle, 1974). The parameter a_i represents the population size of a demand point i, and p indicates the maximum number of hub locations the model can set. Finally, the model incorporates two binary decision variables: X_j indicates whether or not a hub is established at a potential hub location j, and Y_i indicates whether or not a demand point i is covered by at least one of the realized hub facilities.

Sets	
$i = 1, \ldots, I$	Set of demand locations
$j = 1, \ldots, J$	Set of potential hub locations
N_i	Set of hubs that cover demand point i, i.e. $\{j \in J \mid d_{i,j} \leq S\}$
Input parameters	
$d_{i,j}$	Distance from demand location i to hub location j
S	Maximum distance a route is allowed to have for a demand location to be considered as covered by a hub location
a_i	Population of demand location i
p	Maximum number of hub facilities that can be set
Decision variables	
X_j	1 if a hub is located at potential hub location j, 0 otherwise
Y_i	1 if demand location i is covered by at least one hub, 0 otherwise

Table 1: Components of the initial model by Church & ReVelle (1974)

The objective function (1) aims to maximize the population coverage. The first constraint (2) ensures that the number of facility sites set by the model equals the maximum number of hub facilities the model is permitted to set. For considering demand nodes as covered, at least one hub facility has to be located within the covering distance of that site. Therefore, constraints of type (3) ensure that hub facilities are set for demand to be fulfilled. Finally, the decision variables are both defined as binary by equation (4).

$$\max \sum_{i \in I} (Y_i * a_i) \tag{1}$$

$$\sum_{j \in J} X_j = p \tag{2}$$

$$\sum_{j \in N_i} X_j \geq Y_i \text{ for all } i \in I \tag{3}$$

$$X_j, Y_i \in (0,1) \text{ for all } i \in I, j \in J \tag{4}$$

4.1.2 Adjusted model 1

The first adjusted model focuses on the facility location decision in the context of picking up medical professionals (or medical supplies) and transferring them to emergency sites. The following explanations will outline the changes made and newly added components of the adjusted model compared to the initial model. Meanwhile, components that are not mentioned remain unchanged in their definition and usage.

To account for the collection of medical professionals, set *M* is introduced, which displays all locations at which the vessels can collect at least one medical professional. Therefore, the set consists of the potential pickup locations for medical professionals. Furthermore, the distance parameter is modified in the adjusted model(s). The total response distance travelled by the vessels from hub *j*, passing through the location of a medical professional *m*, and reaching the emergency site *I*, is now represented by the parameter $d_{i,m,j}$. This modification allows to consider the entire route taken by the vessel until emergency medical services are provided. When calculating N_i, which determines the potential hub locations covering demand location i, it is still ensured that the total travel distance from the hub through the locations of the medical professionals to the emergency sites is still less than or equal to the target distance for a demand location i to be considered as covered by a potential hub facility j. Thereby, it is sufficient that at least one medical professional can be collected and transferred to the emergency site within the target distance for a hub location to occur in the set of potential hub locations that cover demand location i.

Sets	
$i = 1, \ldots, I$	Set of demand locations
$j = 1, \ldots, J$	Set of potential hub locations
$m = 1, \ldots, M$	Set of locations of medical professionals
N_i	Set of hubs that cover demand point i, i.e. $\{j \in J \mid d_{i,m,j} \leq S\}$
Input parameters	
$d_{i,m,j}$	Distance from demand location i to the location of medical professional m to hub location j
S	Maximum distance a route is allowed to have for a demand location to be considered as covered by a hub location
a_i	Population of demand location i
p	Maximum number of hub facilities that can be set
Decision variables	
X_j	1 if a hub is located at potential hub location j, 0 otherwise
Y_i	1 if demand location i is covered by at least one hub, 0 otherwise

Table 2: Components of the first adjusted model

The objective function (5) and constraints (6) and (9) are kept similar to (1), (2), and (4) of the original model. Medical professionals can provide emergency medical services to the population of their location of residence without the need for transportation. Therefore, constraints of type (7) fulfil the demand at locations where doctors are available. As the demand fulfilment by constraint (7) is independent of the placement of hub locations, those islands have to be excluded from the set of demand locations considered in constraint (3), leading to the emergence of constraint (8). Thus, the added expression "if $i \in M$" in constraint (8) ensures that demand fulfilment by constraint (7) does not require hub locations to be set.

$$\max \sum_{i \in I} (Y_i * a_i) \tag{5}$$

$$\sum_{j \in J} X_j = p \tag{6}$$

$$Y_i = 1 \text{ for all } i \in M; \text{ if } i \in I \tag{7}$$

$$\sum_{j \in N_i} X_j \geq Y_i \text{ for all } i \in I; \text{ if } i \notin M \tag{8}$$

$$X_j, Y_i \in (0,1) \text{ for all } i \in I, j \in J \tag{9}$$

4.1.3 Adjusted model 2

The second adjusted model, which focuses on the pickup and delivery of patients to hospitals, incorporates similar logic and modifications as the first adjusted model. The new set H is introduced, which represents hospital locations to which patients can be transferred. The routes taken by the vessels, from the hub to the patients and from the patients/ emergency sites to the hospitals, are represented by the parameter $d_{h,i,j}$. This parameter and the maximum allowable distance S form the basis for calculating N_i. Similar to the former model, in the second adjusted model, it is sufficient that patients can be transferred to at least one hospital within the target distance for a demand point i to be considered as covered by a particular hub location j.

Sets	
$i = 1, \ldots, I$	Set of demand locations
$j = 1, \ldots, J$	Set of potential hub locations
$h = 1, \ldots, H$	Set of hospital locations
N_i	Set of hubs that cover demand point i, i.e. $\{j \in J \mid d_{h,i,j} \leq S\}$
Input parameters	
$d_{h,i,j}$	Distance from hospital location h to demand location i to hub location j
S	Maximum distance a route is allowed to have for a demand location to be considered as covered by a hub location
a_i	Population of demand location i
p	Maximum number of hub facilities that can be set
Decision variables	
X_j	1 if a hub is located at potential hub location j, 0 otherwise
Y_i	1 if demand location i is covered by at least one hub, 0 otherwise

Table 3: Components of the second adjusted model

The objective function (10) and constraints (11) and (14) are similar to the equivalent constraints of both of the other models. Meanwhile, constraint (12) ensures demand fulfilment for demand points at which a hospital is located, while constraint (13) represents the adjusted constraint (3), which now prevents hub locations to be set for demand fulfilment of constraint (12).

$$\max \sum_{i \in I} (Y_i * a_i) \tag{5}$$

$$\sum_{j \in J} X_j = p \tag{6}$$

$$Y_i = 1 \text{ for all } i \in H; \text{ if } i \in I \tag{7}$$

$$\sum_{j \in N_i} X_j \geq Y_i \text{ for all } i \in I; \text{ if } i \notin H \tag{8}$$

$$X_j, Y_i \in (0,1) \text{ for all } i \in I, j \in J \tag{9}$$

4.2 Assumptions

In the context of island and coastal regions, the locations in the models' sets are assumed to represent individual islands and points along the coastline of the mainland. The distances between these points are considered linear, as, typically, no obstacles need to be circumnavigated when traveling between two points by sea. In order to reinforce this assumption, islands are treated as massless points on the coordinate plane that do not hinder the course of the vessels.

The demand for emergency medical services is assumed to only occur on inhabited islands, as these services are primarily provided to individuals. Thereby, rescue missions and the provision of medical services on uninhabited islands and in the open sea, for example, on oil platforms, are disregarded due to their much lower frequency compared to missions in inhabited areas.

The response time, i.e., “the interval between the call reception and the arrival of the [vessel] at the scene of an emergency” (Colla et al., 2023), encompasses the waiting time when no vessel is immediately available, the preparation time of the vessel during which the crew gets on the vessel, and the travel time from the initial location to the emergency site. The distance-related parameters used in the models can be translated into time-related parameters in real-world scenarios, reflecting the actual time required to cover the travel distances. Hence, the distance parameters correspond to the travel time component of the response times, while the models’ target distance S is assumed to correspond to the response time targets, i.e., the service quality, set by authorities for providing emergency medical services for different types of emergencies in specific areas (NHS, 2023).

Hospitals, medical professionals, and hub facilities for commercial vessels are all located on inhabited islands, as they are connected and integrated into various communities. This arrangement avoids the inconvenience of having these facilities located on uninhabited islands, which would require commuting to other islands to participate in community activities.

The population of a demand location indicates the importance of that location relative to other demand locations due to the parameter’s usage in the objective functions of the models. The impact of the population on the optimal placement of hub facilities is neutralized by assuming the same population size at each demand location to understand the impact of the geographical formation of the island group on the benefits of autonomous vessels.

4.3 Data

The simulation is conducted for each of the three models using a fictional dataset of an island group comprising ten different islands, which is visualised in Figure 1 and shown in the Appendix under 8.1. The formation of the island group represents an arbitrary spread of islands which can often be found in real-world scenarios, with examples being the Galápagos Islands, Ecuador; Lakshadweep, India; the Cyclades, Greece; and the Society Islands, French Republic.

The distances can be derived from the locations of the different islands. The other inputs of the models, i.e., sets and input parameters, are varied in the course of the simulations to identify cases in which the usage of autonomous vessels leads to increased population coverage. A more detailed description of the value realizations can be found in the Appendix under 8.2.

Figure 1: Geographic visualization of the dataset used for the simulations

4.4 Simulation

The model is realized in Python version 3.8.8 and solved using the IBM Decision Optimization CPLEX Modeling for Python version 2.22.213 (IBM, 2023). In addition to this thesis, the commented code is provided to keep track of the implementation of the models, the simulation procedure, and the conducted analysis.

5. Discussion

In the following, the effects of autonomous vessels on emergency medical systems of island and coastal regions are discussed. The emphasis will be put on their impacts on response time, population coverage, and resources consumptions as commonly used performance indicators for the ability of emergency systems to provide base-level service quality. The effects are grouped into opportunities that can increase the performance of emergency medical systems and challenges that potentially impair the performance of these systems.

5.1 Opportunities

5.1.1 Facility location

The level of increasing autonomy ranges from remote-controlled vessels up to fully autonomous vessels that operate without any intervention from a human individual (Gu et al., 2022). Both levels of autonomy allow for a separation of the autonomous vessel's physical location and its captain’s location if there is even a human being in the loop. As a result, there are more places at which hub facilities of autonomous vessels, i.e., the locations where autonomous vessels are stationed and ready for deployment, can be potentially located.

Uninhabited islands. Many island groups incorporate uninhabited islands which can occur due to unfavourable environmental conditions, for example, the size of the islands, treacherous waters that surround the islands making navigation difficult, or an insufficient total population size to populate all islands. Traditional vessels cannot remain permanently stationed on uninhabited islands to wait for the occurrence of an emergency due to the need of the vessel captains to be connected to the local community. Meanwhile, autonomous vessels can be permanently stationed on uninhabited islands as they are not tied to the location of a captain.

The previously described ability of autonomous vessels can lead to an increased population coverage for all applications of vessels in emergency medical systems, as highlighted in Table 4, which contains the results of the conducted simulations of the different models for solving the maximal covering location problem. The numbers indicate that for each model there are specific cases in which locating a hub facility on an uninhabited island leads to increased population coverage for a given target response time. Accordingly, the population at the newly covered demand points has increased baseline service quality. Furthermore, target response times have to be increased or more resources for building additional hub facilities have to be invested in order for conventional vessels to achieve similar population coverage as autonomous vessels. However, the percentages of iterations that lead to increased population coverage is meagre when picking up and transferring medical professionals to the emergency sites (adjusted model 1), indicating a limited potential of autonomous vessels for this particular application of vessels in emergency medical systems.

For all models, advantages primarily arise if the uninhabited islands are located in the centre of the island formation, as shown in Table 5, since other islands are much faster to reach from central islands. Therefore, if there is a central uninhabited island in a real-world scenario, it may be beneficial to consider building a hub facility on that island to achieve benefits for all vessel applications described by the models.

Model	**# of iterations with advantages**	**Total # of iterations**	**Share of iterations with advantages**
Original model	9	220	4,1%
Adjusted model 1	38	28200	0,1%
Adjusted model 2	798	28200	2,8%

Table 4: Number and share of cases in which the utilization of autonomous vessels leads to an increased population coverage by model (the original model has fewer iterations as resource locations do not have to be iterated)

Island	Initial model	Adjusted model 1	Adjusted model 2
1			1
2			10
3			1
4			224
5			1
6	8	33	319
7		5	77
8			
9	1		182
10			

Table 5: Number of iterations in which the utilization of autonomous vessels leads to increased population coverage, broken down by the location of the uninhabited islands used as hub locations

The first adjusted model shows a low number of iterations with performance improvements when utilizing autonomous vessels as the model tries to save the distance from the hub facilities to the doctors by setting the hub facility at the location of a doctor. As doctors are always located on inhabited islands, hub facilities for conventional can be set at the same location as the facilities for autonomous vessels, leading to similar population coverage. Figure 2 illustrates one exemplary case where autonomous vessels lead to an increased population coverage compared to conventional vessels. For these benefits to arise, two groups of inhabited islands must be separated by a centrally located uninhabited area. Additionally, medical professionals need to be situated in both inhabited subgroups, preferably close to the uninhabited area. Then, supposing the hub facility is positioned in the uninhabited area, the autonomous vessels can efficiently transport the doctors to the outer islands of the inhabited subgroups while respecting the set target distances. Meanwhile, the hub facility for conventional vessels is set at one of the doctors' locations of the inhabited subgroups. This can prevent the conventional vessels from reaching the outer islands of the other subgroup within the target distance, resulting in a lower baseline quality of the emergency service for those islands.

The previously described scenario is rather unlikely to occur in real-world applications as it only emerges if highly specific conditions are met. Accordingly, the potential of autonomous vessels for covering additional islands when their hub facilities are set on uninhabited islands seems to be limited in this application.

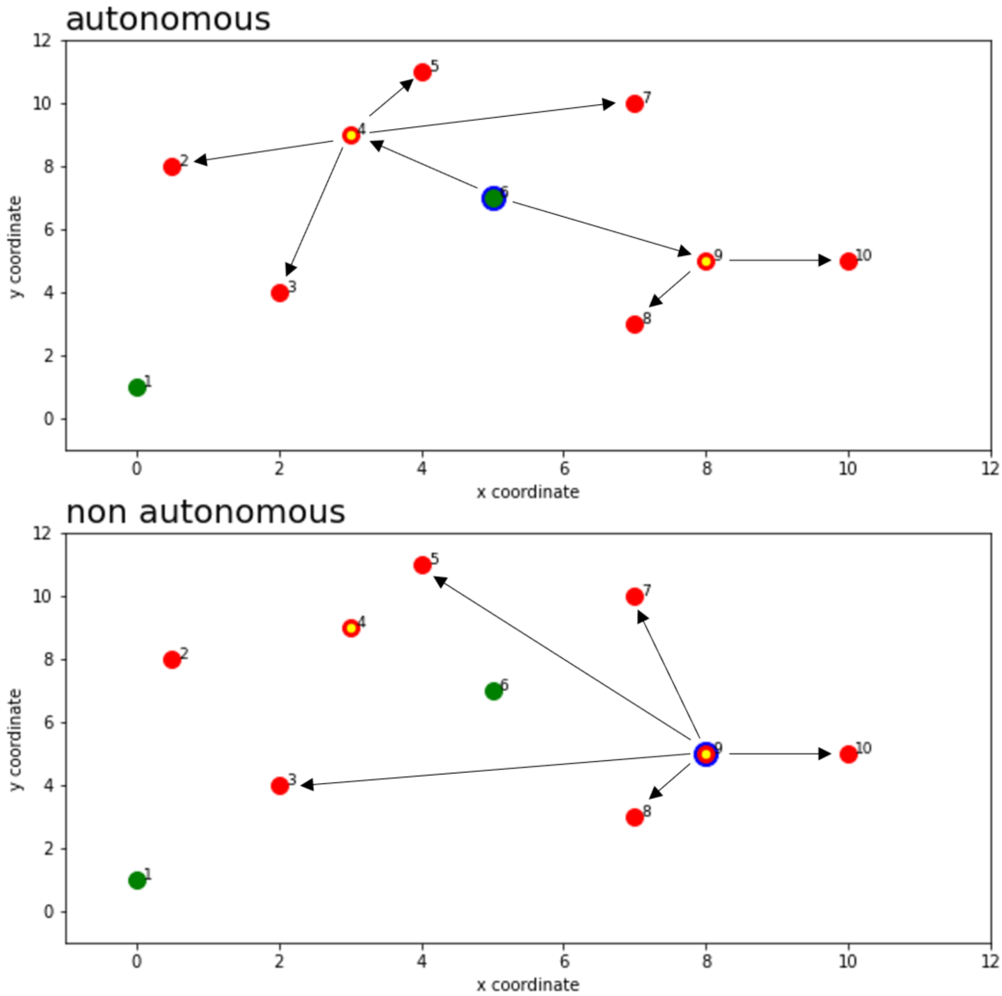

Figure 2: Exemplary case where autonomous vessels lead to increased population coverage in the first adjusted model, with inhabited (red), uninhabited (green), resource (yellow), and hub locations (blue) and routes taken by the vessels if emergencies occur (arrows)

Geographic scenarios. The dataset utilized for the simulations encompasses an arbitrary spread of islands, reflecting arguably the most common shape of island groups. However, it is essential to acknowledge that specific island formations, such as ring-shaped arrangements (e.g., Niau in the French Republic, Tetiaroa in the French Republic, or Manuae in the Cook Islands) and island chains (e.g., Hawaiian Islands in the United States of America, Mariana Islands in the United States of America, Fox Islands in the United States of America, and Kuril Islands shared by Russia and Japan), are also more frequently encountered in reality. Moreover, many islands are located close to coastal mainland areas (e.g., Lofoten in Norway, East Frisian Islands in Germany, Chiloé Archipelago in Chile, and Tuscan Archipelago in Italy), facilitating their integration into mainland emergency systems.

The presence of central uninhabited islands emerged as a driver for increased population coverage through the utilization of autonomous emergency vessels. Therefore, ring-shaped island groups are likely to have a limited potential for leveraging autonomous vessels due to the absence of central islands. Nevertheless, if an uninhabited area is located at the centre of a ring-shaped formation, the advantages of autonomous vessels can rapidly manifest across all models. Consequently, autonomous vessels can potentially reach a larger number of outer islands in both the original and the second adjusted models. Additionally, if doctors are located on opposite sides of the ring-shaped formation, autonomous vessels have the ability to collect the medical professionals from each side and transport them to the adjusted islands, potentially covering a greater number of islands in the first adjusted model.

Island chains inherently exhibit favourable conditions for the deployment of autonomous emergency vessels, as these formations naturally include islands positioned at the centre of the chain.

Finally, coastal areas and nearby islands can exhibit diverse shapes. Generally, coastlines can be compared to island chains as demand points one to eight could represent a linear coastline, while points nine to twelve represent adjacent islands in Subfigure 2.3. Bays, i.e., broad inlets of the sea where land curves inwards, on the other hand, are also a typical shape that coastlines can take. In both cases, hub facilities could be strategically placed in uninhabited central areas between inhabited towns to capitalize on the advantages offered by autonomous vessels. In addition, the potential benefits of autonomous vessels increase when the coastal environment or inadequate infrastructure inhibits efficient road transportation, resulting in extended response times and detours when utilizing ambulance vehicles.

Figure 2: Examples of the four discussed geographic scenarios – 2.1) ring-shaped islands, 2.2) island chain, 2.3) flat coastal area, and 2.4) coastal bay area

Locational preferences of vessel captains. The preceding findings were derived assuming that conventional vessels can be stationed on any inhabited island. Consequently, the presence of uninhabited islands becomes the sole determining factor for achieving increased population coverage by utilizing autonomous emergency vessels. However, it is crucial to recognize that individuals, such as vessel captains, generally have preferences regarding their location of residence, which further limits the number of potential facility sites for commercial vessels. The smaller the number of available captains, the more their preferences regarding their location of residence have to be taken into account. Therefore, the limited set of hub locations raises the possibility that an optimal hub facility location that the models suggested may not align with any captain's preference, which normally would result in the selection of a suboptimal hub location. This consideration becomes particularly significant when it comes to the transportation of medical professionals to emergency sites in the first adjusted model, as locating the hub facility at the doctors' location can lead to substantial time savings due to cutting the distance from the hub facility to the doctor's location.

However, in the case of fully autonomous vessels or vessels under remote control, with the latter being a more plausible scenario in the near future due to regulatory guidelines (Blindheim et al., 2020), the hub facilities can be situated at the optimal location irrespective of the captains' residential preferences. Moreover, by setting the hub facilities on inhabited islands, existing infrastructure such as harbours or service facilities can be utilized, thereby enhancing the value of the pre-existing infrastructure.

The previous discussion demonstrates that autonomous vessels can offer advantages for emergency medical systems, even in the absence of uninhabited islands, as the captains' preferences regarding their place of residence may hinder the realization of the optimal locations for hub facilities that were proposed by the models.

5.1.2 Transformation of current vessel application

The previous analysis of the facility location decision focused on the current applications of vessels in emergency medical systems. As autonomous vessels replace conventional vessels, they can not only improve performance in these areas, but also take on other functions that lead to new vessel applications.

In cases where equipment, medicine, and other medical supplies are scarce, autonomous floating supply ships can be utilized as floating warehouses. This application enables the vessels to travel from their current location directly to an emergency instead of having to travel back to a particular warehouse to receive supplies, which reduces the travel time of the vessels. Furthermore, when investigating the facility location decision, the pooling of resources aboard the autonomous supply vessels also allows the application of the original model for all equipment-related emergencies since the resources and supplies do not need to be picked up at specific locations anymore, unlike in the first adjusted model. However, the inability of autonomous vessels to transport their load past the shore of islands and coastal areas requires changing the transportation mode for the last-mile delivery of medical supplies to the exact location of the emergency, which generally limits the potential of vessels in emergency medical systems. The combination of autonomous vessels and drones, whose application in emergency medical systems has recently seen increasing attention for delivering medical supplies (Euchi, 2021), can create a valuable symbiosis in which the vessels drive the majority of the distance due to their greater speed and reach while the drones deliver the supplies to the exact demand location. The drones can take off from the vessels immediately when the vessels reach the shore; thus, there is no loss of time as a result of changing the means of transportation.

Another limiting factor of vessels in current emergency medical systems is the high degree of human involvement, as doctors must treat the patients, making the doctors a crucial resource in the response process. The introduction of autonomous vessels with diagnostic capabilities and robotic functions can increasingly relieve the burden on physicians in the future, allowing them to focus on emergencies where human assistance is still needed.

Diagnostic capabilities can help to categorize emergencies directly at the location of the patient and determine if a transfer to a hospital is necessary for a particular emergency by taking patient data like blood pressure and temperature. Transferring the data to a doctor via telemedicine and enabling doctor-patient communication can increase the applicability of the diagnosis. Besides potentially saving transportation capacities and capacities of the doctors by reducing unnecessary patient transfers to hospitals, early diagnosis also allows hospitals to prepare for a patient by setting up a treatment room and medical equipment before the arrival of the patient.

Robotic features that can take over some tasks of doctors, like changing bandages or providing vaccination, also decrease the number of transfers of patients to hospitals but it can also allow for faster initial emergency response for critical emergencies, as the vessels do not have to pick up a doctor before arriving at the emergency site since now the “doctor” is always on board of the vessels. The decreasing complexity of the routes taken by the vessels for emergency response enables the deployment of the original model for the facility location decision of autonomous vessels with robotic feature.

The last-mile delivery must also be considered for applications other than transporting medical supplies and equipment. The use of drones is difficult in the other applications of (autonomous) vessels in emergency systems, as drones can only carry light cargo. Autonomous amphibious vehicles can provide a seamless transition from sea to road and vice versa, reducing the complexity of the process and shortening transition times by not requiring a change of transport modes.

5.1.3 Inter-vessel communication and collaboration

The emergency response routes taken in the discussed models are very straightforward, involving at most a single intermediate destination before reaching the emergency site or hospital. In reality, however, there are situations where professionals and supplies must be gathered from multiple locations and transported to the emergency site. Such scenarios may arise during large-scale emergencies, such as natural disasters, where a large number of individuals is affected. They can further occur if doctors and essential supplies, that are required in the course of providing emergency medical services, are very scarce due to a high degree of required specialization or scattered across multiple islands. In these complex situations, autonomous vessels have the advantage of being able to communicate and collaborate with other vessels, allowing them to form collaborative networks capable of collectively addressing the tasks at hand.

The Internet of Things facilitates the connection of different autonomous vessels (Rose et al., 2015), enabling them to share timely situational data, including information about affected areas, ongoing rescue operations, and available resources. This enables the selection of the most suitable vessels based on various factors such as capacity, maximum reach, and current location, helping to optimise the allocation and consumption of resources for emergency response. This collaborative approach is particularly beneficial when multiple resources and personnel need to be transported to the emergency sites, and it also leads to a wider and more effective area coverage during search and rescue missions.

Moreover, inter-vessel communication also promotes information sharing, knowledge transfer, and learning within the emergency system (Du et al., 2020). Lessons learned, best practices, and situational awareness can be exchanged among vessels, facilitating continuous improvement and adaptation of emergency response strategies. As autonomous vessels must “learn” to dock successfully at a specific site before being able to repeat the docking process reliably in the future, the value of sharing the acquired knowledge among a fleet of autonomous vessels leads to economies of scale and improved efficiency.

5.1.4 Decreased preparation time

The previous discussions mainly centred around the travel time component of the response time. However, as mentioned when discussing the simulations' assumptions in section 4.2, the preparation time is another key driver of the response time (Yang et al., 2005). Emergency medical systems in urban areas constantly have teams waiting and readily available that respond to upcoming emergencies to minimize preparation time. Meanwhile, personnel and funding shortages as well as the infrequent occurrence of emergencies in sparsely populated island and coastal regions can hinder the constant availability of an emergency team for direct emergency response due to cost and capacity reasons.

During the preparation process of conventional vessels, the crew gets aboard the vessel and prepares for departure. Factors such as the experience of the crew members or the time the crew members are working together impact the length of the preparation time. In contrast, once stationed at the hub facility and readily available, fully autonomous vessels can directly leave their current position after their allocation to respond to a particular emergency, which abolishes the entire preparation process and reduces preparation times to zero. On the other hand, remote-controlled vessels still require some preparation from the human supervisor before the vessels can leave their location. Nevertheless, in both cases, the preparation time is less than for conventional vessels.

If the vessel has to collect a medical professional, the doctor has time to prepare while it drives to the doctor's location. However, hub facilities are generally located at the location of the medical professional to save the travel time from the hub to the doctor's location, as argued in section 5.1.1. Therefore, the preparation time of the doctor also influences the preparation time until commercial vessels are able to leave their hub facilities. If an emergency allows for the deployment of autonomous diagnosis or robotic vessels, the preparation time of the medical professionals can also be abolished.

5.1.5 Increased accessibility and safety

Autonomous vessels are capable of operating under a broader range of conditions; for example, they are more reliable in navigating through treacherous coastal waters and operating under adverse weather conditions. The ability to access those areas quickly and efficiently enables the timely provision of emergency medical services. This is primarily beneficial for search and rescue operations and delivering emergency services for critical emergencies.

The reliability of autonomous vessels decreases the risk and endangerment of the passenger during the transfer of medical personnel and patients, especially if the vessels have to navigate under hazardous conditions. Furthermore, the human supervisors who monitor and remote-control the vessels are not endangered during the operations as they are not located on board of the vessels which is different from the captains of conventional vessels.

However, rescue missions are often conducted under uncertain conditions. Fully autonomous vessels are less reliable in new environments since they have not yet been trained to operate in those environments. For example, floods change the landscape of coasts and islands, and driving to houses for collecting affected individuals requires docking at new locations, which can pose problems for autonomous vessels. Accordingly, the provision of human assistance or remote controlling the vessels from a control centre might be required under those circumstances.

5.1.6 Freeing up higher-quality human capacities

Autonomous vessels can alleviate the issue of personnel shortages in emergency medical systems by freeing up the capacities of the vessel captains and, if the vessels have built-in diagnosis and robotic technologies, some capacities of the doctors. Those capacities can be utilized to respond to emergencies that still require human involvement, such as operating conventional vessels in uncertain circumstances or complex medical conditions that require an experienced medical professional.

In addition to the increased availability of human capacities, the quality of human capacities is increased, as autonomous vessels can constantly operate at a high level of quality regardless the time of the day. Conventional emergency vessels often require captains to work night shifts, as highlighted in the study conducted by Caliskan and Altintas (2020), which found a significant number of emergency responses to be conducted during the night. Such working hours can be highly inconvenient, leading to interrupted sleep patterns, decreased quality of life, and an increased likelihood of errors resulting from human fatigue. This is especially problematic in emergency systems that suffer from staffing shortages as the personnel is less able to take rest periods and vacations. Therefore, the introduction of autonomous (diagnosis and robotic) vessels allows captains and, to some degree, doctors to have more convenient working hours, which prevent human fatigue and increases the quality of the work where human capacities must be deployed.

5.2 Challenges

5.2.1 Integration into the existing emergency medical system

The previous analysis of the facility location decision was conducted without considering existing processes and infrastructure in the considered regions. However, almost all regions of the world have some kind of emergency medical system and infrastructure in place to mitigate damage and provide emergency medical services to those in need. To unleash the full potential of autonomous emergency vessels, the successful integration into the existing emergency medical systems has to be ensured to avoid inefficiencies in emergency response and resource usage. Those inefficiencies can manifest in investing in too many resources for emergency response, for example, when sending a conventional as well as an autonomous vessel to the emergency site despite only one vessel being required. However, for critical emergencies, it is even worse if no vessel is sent to the emergency site, due to failures to properly integrate autonomous ships and assign responsibilities, as a delayed response can costs lives.

The integration of autonomous vessels involves mapping out the process of delivering emergency medical services with autonomous compared to conventional vessels and defining target processes to allocate the responsibilities of each actor in the system. Here, the emergency types for which autonomous vessels are utilized can be defined. Furthermore, it is vital to plan the interaction of autonomous vessels and other participants in the processes, like medical professionals and patients. This also includes defining the process steps that are conducted on the islands, as current vessels can only transfer their passengers to the shore of the islands and are less suited for assisting the last-mile delivery of their passengers to hospitals and the patients' door.

An exemplary split of responsibilities, based on the previous elaborations, is using conventional vessels in new and uncertain environments and during convenient times for the vessel captains, e.g., during the daytime. Meanwhile, autonomous vessels can be used in hazardous environments, for tasks with a high degree of repetitiveness, e.g., transfer of equipment and passengers, and larger scale emergencies that require a high degree of coordination. Thereby, humans and vessels can work in symbiosis and supplement each other, leading to increased system performance, service quality, and more efficient resource consumption.

5.2.2 Maintenance and refilling

Generally, existing infrastructure can be used for maintenance and refilling operations (service operations) when hub locations are located on inhabited islands. However, the results of the simulation indicated situations in which the introduction of autonomous vessels led to increased population coverage if the hub facilities for the vessels were set on uninhabited islands, as seen in section 5.1.1. Furthermore, optimal hub locations can also be situated on less populated islands without extensive service facilities. For the benefits of autonomous vessels to arise and a timely emergency response, the vessels stationed at the hub facilities have to be ready for deployment; more precisely, the vessels have to be equipped, their fuel has to be refilled/ their battery has to be recharged, consumed supplies have to be restocked, etc. Otherwise, the autonomous vessels might not be able to immediately respond to emergencies, or complications, such as insufficient inventory or running out of fuel, might arise in the process of providing emergency response. Therefore, the service process has to be changed to accommodate the hub facilities on uninhabited and less-fitted inhabited islands.

Authorities can mainly decide between building service capacities at the chosen hub locations/ sending service boats to the hub facilities and utilizing current service locations by letting the autonomous vessels take detours between responding to emergencies. The former incurs higher investments for building capacities at or transporting supplies to the location of the hub facilities, while allowing the vessels to stay at the optimal locations, that were chosen by the optimization models, for the majority of the time. Requiring the vessels to take detours to receive services increases the complexity of the process. However, it might also require fewer resources to be invested as detours can be strategically combined with the routes taken for emergency response. As previously elaborated in section 5.1.3, the Internet of Things can be utilized to check on the status of the vessels and determine the best-suited vessel for emergency response. This knowledge can be used further to factor in maintenance and refilling decisions to deploy vessels that need to receive services after the emergency response. Preventive maintenance can be applied to prevent unforeseen breakdowns and reduce the need to drive to inconvenient locations to fix vessels that have suddenly broken down.

The most important decision in the context of services for (autonomous) vessels is probably to ensure that batteries are fully charged/ fuel is completely refilled. When taking detours, driving back to the hub facility consumes a part of the vessels' energy source, reducing the maximal distance of the route the vessels can drive for emergency response. Currently, public attention is shifting away from fossil-fuelled to electricity-powered vessels. By building solar panels or wind turbines near the hub facilities, the batteries of the vessels can be charged without human assistance if the vessels dock at a charging port, even if the island is uninhabited.

5.2.3 Public perception

In addition to successfully integrating new technologies into the existing system, the effective utilization of these technologies also requires their acceptance and adoption by the population. Autonomous technologies in all fields of maritime transportation currently face concerns regarding their safety and the responsibility of final decision-making (Chan et al., 2023), which are increasing with an increasing level of autonomy (Goerlandt & Pulsifer, 2022). This results in remote-controlled vessels experiencing a higher degree of trust from the average individual than fully autonomous emergency vessels.

A lack of trust in autonomous vessels can harm their deployment. For example, suppose doctors and patients resist the usage of autonomous vessels and demand the transfer via conventional vessels. In that case, waiting times can increase if the whole fleet of conventional vessels is fully utilized despite autonomous vessels, that are suitable for a particular mission, idle. Meanwhile, forcing passengers to be transported by autonomous vessels by divesting from conventional and investing in autonomous vessels puts additional stress on doctors and patients during the transfer. This added stress could worsen the patients' conditions and divert the doctors' focus, potentially leading to mistakes during the treatment of the patient. The process of convincing patients and doctors to enter an autonomous vessel and waiting for a conventional vessel to arrive if the passengers strictly refuse to get on board the autonomous vessel also increases response times. Furthermore, resisting patients might call an ambulance as late as possible to postpone the transfer via autonomous vessels. This could worsen the situation of the patients and convert their situation from non-critical to life-threatening, which then requires the deployment of additional resources for a timely response.

Not being able to use conventional and autonomous vessels interchangeably for missions they are both suited for also increases the complexity of providing emergency medical services, potentially increasing the number of mistakes made during the response process. Furthermore, it hinders the integration of autonomous vessels into existing systems and prevents harnessing the full potential of autonomous vessels, because of the need to run an autonomous and a conventional medical response system in parallel, depending on the preferences of the passengers. In the worst case, the authorities deem autonomous vessels ineffective and stop considering the new technology for their emergency medical system.

Targeted measures can be implemented to foster trust in autonomous technologies, for instance, by first addressing the concerns of doctors, who represent a smaller group compared to all potential patients. Afterwards, the doctors can lead as role models for convincing patients to rely on autonomous technologies. Additionally, passengers should always be able to communicate with a human supervisor or the remote-controlling captain to ensure that they feel cared for and not abandoned during their journey. Age plays a significant role in adopting autonomous technologies, as older individuals resist their adoption more than younger individuals (Park et al., 2021). Unfortunately, older people are also more likely to have a medical emergency which poses a significant challenge to the usage of autonomous vessels by the population.

Regardless of the population's acceptance of autonomous vessels, they can still be effectively used to transport medical supplies and equipment to emergency sites, which is an essential application of emergency medical systems. Nevertheless, the sole use of autonomous vessels for transporting supplies represents rather limited potential concerning the considerable human involvement in emergency medical systems.

5.2.4 Technology

Despite the advancements in autonomous technologies, there remains a learning curve in optimizing autonomous vessels' algorithms, sensors, and decision-making capabilities, especially in currently less utilized areas such as their utilization in emergency medical systems. In these systems a timely response to occurring emergencies must be ensured to provide effective care in life-or-death situations. Therefore, preventing system failures, malfunctions, and unforeseen obstacles is an important priority to prevent disruptions of response operations as they can lead to delayed emergency response. Furthermore, if the response process is disrupted due to the failure of the responsible vessel, additional vessels and resources have to be deployed to ensure timely responses to ongoing emergencies. In the worst case, critical malfunctions can give rise to a second emergency where passengers have to be rescued from the affected vessels, which creates the need for deploying even more vessels and resources by sending a third vessel to rescue the passengers of the malfunctioning vessels.

Minimizing the number of technological failures is also crucial for retaining the population's trust in autonomous vessels. A single severe technological failure can have detrimental consequences for the overall acceptance and usage of autonomous vessels due to increased perceived uncertainty and risk associated with using autonomous vessels. This further highlights the importance of preventive maintenance and closely monitoring the status of the vessels to ensure smooth operations and mitigate potential problems before they arise.

Autonomous vessels rely heavily on data connectivity and communication infrastructure. Disruptions in network coverage and cyberattacks can therefore hinder the responsiveness of the emergency system, delay the provision of emergency services, and result in an inefficient allocation of resources. The vulnerability of autonomous vessels to system breakdowns and cyberattacks also poses a significant drawback compared to conventional vessels that can be operated independently from a central control system. Accordingly, protecting the infrastructure from breakdowns and attacks is also important to consider when setting up the network. The implementation of telehealth systems to assist the emergency medical systems of Pacific Island regions indicates poor conditions of the technological infrastructure in remote island regions (Higa et al., 2018). Accordingly, building infrastructure for successfully operating autonomous vessels is also likely to face severe challenges and require a sufficient development budget.

5.2.5 Costs

When evaluating the costs associated with conventional and autonomous vessels, it is crucial to consider a range of factors that influence the expenses associated with each vessel type. So far, cost estimates in commercial settings have been subject to significant uncertainties and are highly situational, making them reliable only within the specific studies they were conducted (Ziajka-Poznańska & Montewka, 2021). In the following, different cost components will be qualitatively assessed to find a tendency regarding the superior vessel type from a cost perspective.

One significant cost parameter is the initial investment required for purchasing autonomous vessels and establishing infrastructure to support their operation. The advanced technologies incorporated in autonomous technologies result in higher acquisition costs compared to acquiring additional conventional vessels to extend the existing fleet. However, fewer autonomous than conventional vessels may be needed to ensure a certain baseline service quality, as found in section 5.1.1. Therefore, the decreased number of vessels could offset the higher purchasing price of autonomous technologies, potentially resulting in lower overall purchasing costs. Conventional vessels usually do not require additional infrastructure investments, as similar vessels already operate within the existing emergency system. Autonomous vessels, on the other hand, need infrastructure for communication, monitoring, and remote control. Furthermore, as discussed in section 5.2.2, additional hub facilities and service locations must be built for autonomous vessels if the vessels are located on uninhabited or sparsely populated islands. Finally, upfront training costs incur for autonomous vessels to familiarize supervisors with the new technology and enable them to remote-control and monitor the vessels.

The operating costs of the vessels include labour costs which are dependent on salary and crew size. A single supervisor can take control of and monitor multiple autonomous vessels while each conventional vessel requires at least one captain, giving autonomous vessels an advantage regarding the crew size. Moreover, fully autonomous robotic diagnosis vessels could completely remove the need for paying a human salary, however, the deployment of such vessels will be in the far future. Meanwhile, the higher responsibility of supervisors and the novelty of the skills required are likely to lead their salaries to be greater than those of conventional vessels captains. The fuel type also plays a crucial role in the operating costs of the vessels. As the trend towards electric-powered vessels continues, autonomous and conventional vessels will likely have similar electricity costs. However, when comparing fuel-powered and electricity-powered vessels, cost advantages for one vessel type might arise depending on the prices for electricity and fossil fuels like diesel.

Emergency medical systems constantly have teams readily available to respond to emergencies in densely populated areas such as cities. However, in sparsely populated island groups, medical emergencies occur very infrequently. Accordingly, having constantly captains available for potential emergency response leads to long waiting periods and high idling costs. Fully autonomous vessels, on the other hand, have no variable costs if they are not in use. For remote-controlled vessels there are the idling costs of the supervisor. Accordingly, there is only a cost advantages for some levels of autonomy.

Maintenance costs are also in favour of conventional vessels as the more complex technologies built into autonomous vessels require more knowledgeable engineers and more expensive spare parts. Finally, the service process for autonomous vessels is also likely be more costly and resource intensive for autonomous than for commercial vessels, as argued in section 5.2.2.

The majority of aspects are for a cost advantage of conventional compared to autonomous vessels at least in the near future where autonomous technologies remain costly and supervisors are required to steer and monitor autonomous vessels. Therefore, it can be concluded that the increased flexibility and performance of autonomous vessels is very likely to come at an increased cost. As many cost components are very situational, in-depth cost-benefit analyses for particular regions have to be conducted to determine the size of the performance increases if autonomous vessels are utilized and cost difference between autonomous and conventional vessels to make a case for the implementation of autonomous vessels.

6. Conclusion

There are a variety of areas in which the utilization of autonomous vessels can lead to performance increases in emergency medical systems of island and coastal regions. This increases the baseline quality of emergency medical services delivered to the population. Those benefits can manifest in response time reductions, increased population coverage within response time targets, and more efficient resource consumption. Furthermore, autonomous vessels can transform current applications of vessels in emergency medical systems to decrease the operational complexity of the routes taken for emergency response.

Most of the challenges regarding autonomous vessels can be overcome by thoroughly planning the introduction and use of autonomous vessels to ensure a seamless integration, smooth operations, and successful adoption by the populations. However, the costs probably remain the most challenging aspect for utilizing autonomous vessels as the increased flexibility and performance come higher costs than those of conventional vessels.

As literature concerning the topic of this thesis is very scarce, and there is currently no real-world case in which autonomous vessels are utilized in emergency medical systems, future developments in this area will be very interesting to pursue for analysing the disruptive nature and actual application of the new technology. The different opportunities and challenges addressed in this thesis leave plenty of space for further investigations concerning the quantitative assessment of performance benefits and associate costs, the redesign of response operations, and the operational transformation of emergency medical systems in island and coastal regions.

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8. Appendix

8.1 Dataset

islands	loc_x	loc_y
1	0	1
2	0,5	8
3	2	4
4	3	9
5	4	11
6	5	7
7	7	10
8	7	3
9	8	5
10	10	5

Table 6: Geographical dataset used for the simulations

8.2 Simulation values

Component	**Values**	**Description**
S	4, 8	The coordinate plane is 12x12; therefore, 1/3 and 2/3 of this length are arbitrarily set as target distances
p	1, 2	Resource constraints prevent building a large number of hub facilities
a_i	1 for each *i*	According to the assumptions made
Uninhabited islands	Between 1 and 2 locations	Iteratively placed on different islands during the simulations
Set *I*	Between 8 and 9	Affected by the number of uninhabited islands according to the assumptions made
Set *J*	Between 8 and 9	Affected by the number of uninhabited islands

	for conventional vessels	according to the assumptions made for conventional vessels
	10 for autonomous vessels	Every island can serve as a hub location for autonomous vessels
Set *M* (only for adjusted model 1)	Between 1 and 3 locations	Iteratively placed on different inhabited islands during the simulations
Set *H* (only for adjusted model 2)	Between 1 and 3 locations	Iteratively placed on different inhabited islands during the simulations

Table 7: Values taken by sets and input parameters during the simulations