energies

Article

Energy Efficiency of Transport Tasks Performed by the Air SAR System in the Baltic Sea: Case Study

Jerzy Fiuk [1], Norbert Chamier-Gliszczynski [2], Marianna Jacyna [1] and Mariusz Izdebski [1,*]

[1] Faculty of Transport, Warsaw University of Technology, 00662 Warsaw, Poland; jerzyfiuk@op.pl (J.F.); marianna.jacyna@pw.edu.pl (M.J.)
[2] Faculty of Mechanical Engineering, Koszalin University of Technology, 75453 Koszalin, Poland; norbert.chamier-gliszczynski@tu.koszalin.pl
* Correspondence: mariusz.izdebski@pw.edu.pl

Abstract: The issues discussed in this article concern the energy efficiency of transport tasks carried out by the air SAR system in the Baltic Sea. Search and rescue (SAR) are rescue operations consisting of finding people in danger, providing them with help, and delivering them to a safe place. The transport task is an element of the rescue operations carried out in the open water area. It is carried out by a given type of helicopter from a strictly defined rescue base. The aim of the article is to develop a method of selecting the base and means of transport for the transport task carried out by the air SAR system, based on the assessment of energy efficiency of a given transport task. The article proposes a selection model; parameterization of the model was carried out, indicators of energy efficiency evaluation were determined, and limitations were indicated. In practical terms, the authors' model of selection is presented on the example of transport tasks carried out by the air SAR system in the Polish zone of responsibility in the Baltic Sea.

Keywords: search and rescue (SAR); air SAR system; energy efficiency; helicopters

Citation: Fiuk, J.; Chamier-Gliszczynski, N.; Jacyna, M.; Izdebski, M. Energy Efficiency of Transport Tasks Performed by the Air SAR System in the Baltic Sea: Case Study. *Energies* **2022**, *15*, 643. https://doi.org/10.3390/en15020643

Academic Editor: Tomáš Skrúcaný

Received: 9 December 2021
Accepted: 13 January 2022
Published: 17 January 2022

1. Introduction

Ensuring safety in the Polish zone of SAR (Search and Rescue) responsibility generates significant costs, one of which involves transport tasks [1] carried out as part of rescue operations. Therefore, an important action in this area is to minimize these costs. One of the solutions involves search for an algorithm for the implementation of the rescue action to ensure the highest energy efficiency of the action. Energy efficiency in these activities is interpreted as the minimization of the necessary energy consumption required to meet a given transport task goal. The source of energy in the analyzed task is aviation fuel, which is used to power individual aircrafts and devices supporting the implementation of the transport task and, thus, the rescue operation carried out by the air SAR system. The aviation SAR system is a component of the maritime search and rescue service MSAR, which is a component of the SAR in the Baltic Sea.

By analyzing the reports/studies found in the literature of multiple individual rescue operations in the Polish responsibility zone in the Baltic Sea, one will notice a shortage of energy-efficient based tools and methods, aircraft-based selections and resource allocation regarding the implementation of transport tasks [2]. Therefore, the aim of this article was to develop a tool in the form of a selection method of the base and means of transport for the implementation of a transport task, based on the quality assessment index of the solution, in the form of energy efficiency. The considered transport task is a component of the rescue operation carried out by the aviation SAR system in a designated area, which, in this case, is the Polish zone of responsibility in the Baltic Sea. The transport vehicle is a helicopter of a given type. The helicopter starting point is identified as a base in the system.

The proposed method evaluates transport tasks that were already completed and conducts simulation studies to improve and expand the SAR system functionality.

This paper, considering the complexity of the issue, is divided into four sections:

- Section 1: a literature review.
- Section 2: a presentation of our own model for the selection of the base and transport vehicles, for the transport task carried out by the air SAR system in the Polish zone of responsibility in the Baltic Sea, based on energy efficiency criteria.
- Section 3: validation of the model,
- Section 4: a simulation study of the expansion of the air SAR system, with a new base or the purchase of new means of transport in which the developed model will be used.

2. Literature Analysis

The issue of energy efficiency in the transport sector is an important element of modern scientific research. In the literature, this issue is often taken up, and there is a plethora of research in this area. These studies refer to individual forms of transport, i.e., land transport (rail, road), water (sea, inland navigation) and air. The division into freight and passenger transport is also taken into account, as well as the area in which it occurs, for example, urban transport. In order to systematize the studies in the analyzed area, it was decided to specify individual scopes of literature research:

- Scope 1: the issue of energy efficiency in rail transport;
- Scope 2: the issue of energy efficiency in car transport;
- Scope 3: the issue of energy efficiency in water transport;
- Scope 4: the issue of energy efficiency in urban transport;
- Scope 5: energy efficiency issues in air transport.

It should be noted that these are only selected items of literature from the analyzed area of knowledge (Table 1).

The study of energy efficiency in rail transport concerns rail traffic on a given railway line, as well as all lines in a given country. In the case of rail traffic, means of transport are also important elements, the energy efficiency of which plays an important element in this research area. The issues of selection of the transport vehicle, its energy consumption, and modernization are identified. An important issue is the optimization of train timetables, in terms of energy efficiency of rail transport.

On the other hand, the study of energy efficiency in car transport concerns an evaluation process, determination of evaluation indicators, and calculation methods of energy consumption, in particular areas of road transport. Currently, an important element of research in this area is the energy efficiency of electric vehicles. This applies in particular to urban areas where passenger and freight trams, trolleybuses, and electric buses are operated, and their energy efficiency plays a significant role in the functioning of the urban transport system.

The study of energy efficiency in water transport concerns watercrafts, devices that are equipped with these units, and port terminals. Moreover, in air transport, the study of energy efficiency is aimed at improving the energy efficiency of air traffic and air means of transport.

Based on the analysis of the literature, on individual forms of transport, it should be concluded that energy efficiency research is an important element of research in the field of transport. The research is focused on examining the energy efficiency of individual forms of transport, means of transport, and methods of transport organization.

Analysis showed that the aspect of energy efficiency in the selection of the base and transport vehicle for transport tasks carried out by the air system operating under the established search and rescue (SAR) service has not been thoroughly researched, especially in relation to transport tasks performed by the air SAR system in the Polish responsibility zone in the Baltic Sea. Analyzing the publications in this area, in the field of efficiency, research is carried out only in relation to helicopters, with an indication of electric helicopters. Other studies are focused on, among others, developing an efficient algorithm for planning and implementing a rescue operation, in which the time of the action itself is an important aspect. Detailed research areas in this area are presented in Table 2.

Table 1. Energy efficiency in transport; literature analysis.

Research Area	Year of Publication	Source
Scope 1: rail transport		
Railway traffic energy efficiency	2018, 2018	[3,4]
Optimization of passenger train timetables with similar traction characteristics, energy recovery criterion at the stage of starting and braking	2016, 2019	[5,6]
Energy efficiency of rail transport, including rail means of transport	2014, 2020	[7,8]
Modernization of the railway transport system in terms of energy efficiency	2019, 2005	[9,10]
The problem of the selection of rolling stock (wagons, locomotives) for transport, in terms of energy efficiency assessment	2021	[11]
Energy consumption for the three types of railway vehicles	2021	[12]
The issue of energy efficiency in rail transport	2020	[13]
Scope 2: car transport		
Indicative assessment of the energy efficiency of road transport	2021	[14]
Developing criteria for assessing the energy efficiency of refrigerators used in supply chains	2021	[15]
Shaping the calculation method to determine energy consumption by forklifts in logistic centers	2022	[16]
Indicative evaluation of the energy efficiency of the warehouse in the transport chain	2016	[17]
Shaping the range of electric vehicles	2019	[18]
Scope 3: water transport		
Assessment of the impact of measures and incentives aimed at energy efficiency in maritime transport	2020	[19]
Improving fuel efficiency and the energy efficiency of the watercraft	2020	[20]
Assessment of energy efficiency in relation to the theoretical and actual energy consumption of inland navigation	2021	[21]
Shaping energy-saving technology in application to refrigerated containers in port terminals and on ships	2019	[22]
Scope 4: urban transport		
Assessment of energy efficiency on the example of a freight tram	2021	[23,24]
Energy recovery and energy efficiency of urban electric transport	2021	[25,26]
Life cycle of urban transport and energy efficiency	2020	[27]
Energy storage and the energy efficiency of urban transport	2020	[28]
Assessment of energy efficiency of various bus transport subsystems in public transport	2015	[29]
Economical evaluation of power supply in electric buses	2018	[30]
Scope 5: air transport		
Improving energy efficiency in air traffic	2017	[31]
Assessment of energy efficiency of hydrogen-powered transport aircraft	2015	[32]
Energy management in hybrid electric planes	2018	[33]
Assessment of the reliability of the drive system used in an electric helicopter	2017	[34]

Table 2. Energy efficiency in the area of the SAR system; literature analysis.

Research Area	Year of Publication	Source
Testing the drive system of an electric helicopter for rescue operations	2022	[35]
Testing the effectiveness of operating helicopters	2019	[36]
Study of an efficient route planning algorithm during the implementation of a rescue operation	2019	[37]
Analysis of medical rescue services in the North Sea and the Baltic Sea	2021	[38]
Planning of the search area, based on K-means clustering	2021	[39]
Development of a methodology to quantify the impact of helicopter operating conditions on the environment during the implementation of actions under the SAR system	2018	[40]
Development of an optimization model with the criteria of minimizing the time of rescue operations by helicopters in the MSAR system	2021	[41]
Analysis of the Search and Rescue Optimal Planning System (SAROPS)	2011	[42]
Development of an algorithm to optimize activities in the MSAR system	2020	[43]
Analysis of the decision-making algorithm in sea rescue	2019	[44]

The authors of the article do not question the assumption that, in the case of carrying out rescue operations, the most important thing is saving human lives. The rescue potential, being defined as a likelihood of finding and rescuing a person, is mostly affected by time—time of which is a sum of the duration of multiple sub-tasks carried out by the system. The research on selecting base locations based on the assessment of energy efficiency is important in the overall aspect of SAR service performance. It can save time in accessing disaster sites and cost of operation, especially during extreme weather conditions.

3. Methodology

3.1. Mathematical Model of the Problem

The research problem in the article involves the selection of the base and transport vehicle for the transport task [45,46] carried out by the air SAR system in the Polish zone of responsibility in the Baltic Sea. This selection is based on an assessment of the energy efficiency of the solution obtained. In order to correctly select the base and the means of transport, and considering the complexity of rescue operations carried out in open waters, it is necessary to determine the relevant data, which are presented in Table 3.

Table 3. Data identification for a mathematical model.

Name	Notation
Location of the SAR system air bases	***LB***
Rescue flight target location	***LC***
Location of intermediate points	***LM***
Parameters of the transport task	***TZ***
Aircraft parameters	***PS***
Costs of the transport task	***KT***
Energy efficiency of the transport task	***ET***

Referring to the data in Table 3, the ***MEESAR*** model for the selection of the base and means of transport for the transport task carried out by the air SAR system can be presented in the form of an ordered seven:

$$\boldsymbol{MEESAR} = \boldsymbol{<LB, LC, LM, PT, PS, KT, ET>} \tag{1}$$

The model is an application model and can be applied in any selected SAR responsibility zone in which aircrafts operate. The model is related to the implementation of rescue operations in the Polish zone of responsibility in the Baltic Sea.

The model of selecting the base and means of transport for the transport task carried out by the air SAR system should meet the following assumptions:

- The transport task is part of the rescue operation carried out by the air SAR system.
- The implementation of the transport task takes place within the adopted SAR responsibility zone (e.g., the Polish SAR responsibility zone in the Baltic Sea).
- The implementation of a given transport task complies with the applicable procedures for conducting rescue operations by the SAR system.
- The transport task is performed by the aircraft of the SAR system.
- Transport tasks begin and end at the bases of the air SAR system.

The analyzed transport tasks, which are the executive elements of the rescue operation, are carried out in accordance with the procedures adopted by the SAR system. On this basis, in each task, activities essential for the implementation of the transport task and the rescue operation itself should be distinguished:

- Helicopter take-off from the air base of the SAR system.
- Flight to the search site.
- Searching for and picking up the survivors.
- Flight to a location where the survivors are provided further aid (e.g., medical points).
- Return flight to the base.
- Landing at the base of the SAR system.

The algorithm for the implementation of the transport task performed by the air SAR system is shown in Figure 1.

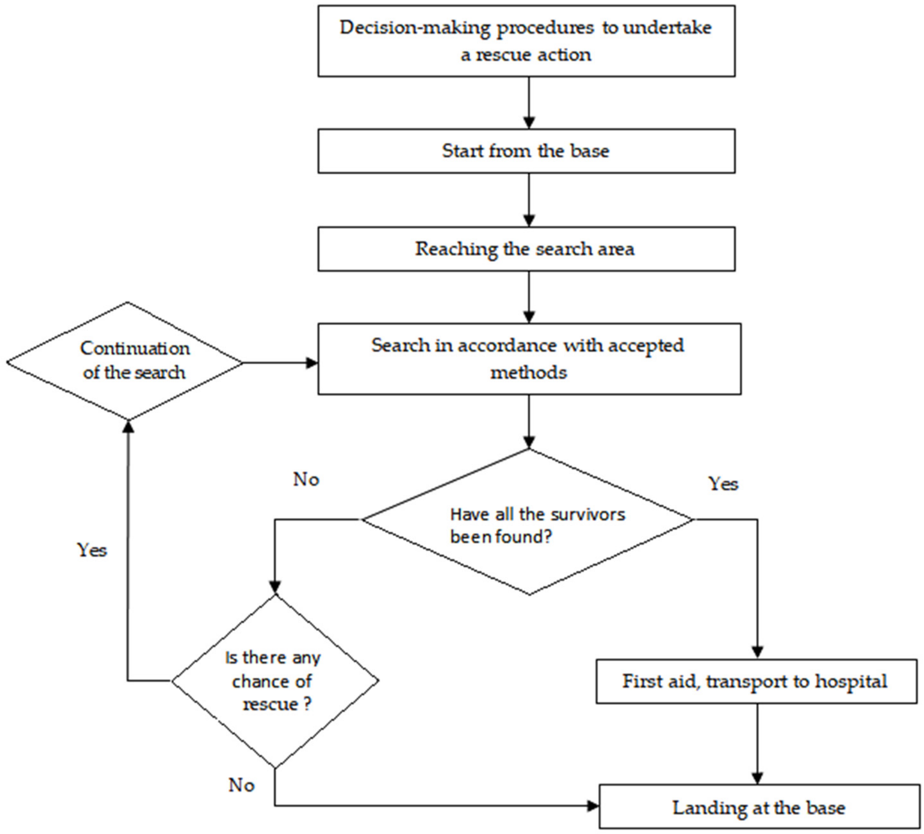

Figure 1. Algorithm for the implementation of the transport task.

3.2. Model Parameters

The problem of selecting the base and transport vehicle for the transport task carried out by the air SAR system, based on the assessment of energy efficiency of a given transport task, is solved, taking into account specific parameters and decision variables. The model defines the following values:

- *sb*(*lb*,*tz*)—a binary variable with the interpretation of the start from a given base for the implementation of the transport task, stored in the matrix $\boldsymbol{A}_1(tz)$.
- *cr*(*lc*,*tz*)—binary variable about rescue flight target assignment interpretation, stored in the matrix $\boldsymbol{A}_2(tz)$.
- *mp*(*lm*,*tz*)—binary variable about the interpretation of the assignment of the handover place of the injured person (s), recorded in the matrix $\boldsymbol{A}_3(tz)$.
- *sp*(*he*,*tz*)—binary variable about the interpretation of the assignment of the aircraft to the transport task, stored in the matrix $\boldsymbol{A}_4(tz)$.

Parameterization of the model is best started by parameterizing the transport task, which, for the purposes of research, is described by the following parameters:

- *ou*(*tz*,*pe*)—the transported elements are the people saved, taken from the set ***PE***.
- *bt*(*tz*,*bs*)—the transport task with the *tz* number starts in the base with the *bs* number of the air SAR system.
- *pt*(*tz*,*ct*)—the purpose of the transport task with the number *tz* is the search point (target of the rescue flight) with the number *ct*.
- *mt*(*tz*,*mmt*)—the transport task with the number *tz* has a point with the number *mmt*, i.e., the place of handing over the injured.
- *et*(*tz*,*bs*)—the transport task with the *tz* number ends in the base with the *bs* number of the aviation SAR system.

- *vpo*(*he*,*tz*)—search speed carried out by the *he* helicopter as part of the transport task with the number *tz*.
- *vp*(*he*,*tz*)—flight speed of the helicopter *he* as part of the transport task with the number *tz*.
- *rp*(*he*,*tz*)—search radius by the helicopter *he* as part of the transport task with the number *tz*.
- *tt*(*tz*)—duration of the transport task with the number *tz*.

On the basis of the adopted parameterization, it is assumed that each transport task carried out by the air SAR system will be described by the ***TZ*** parameter vector:

$$\boldsymbol{TZ} = [tz,\ ou(tz, pe),\ bt(tz, bs),\ pt(tz, ct),\ mt(tz, ct),\ et(tz, bs),\ vpo(he, tz),\ vp(he, tz),\ rp(he, tz),\ tt(tz)] \quad (2)$$

The time of carrying out the transport task is a complex time, in which we distinguish a number of partial times important for the implementation of the rescue operation:

- *tlo*(*tz*,*tt*)—flight time to the search (activity) area; the flight is carried out as part of the transport task *tz*.
- *tpr*(*tz*,*tt*)—working time in the search area; the work is carried out as part of the transport task *tz*.
- *tld*(*tz*,*tt*)—flight time to the place of casualty transfer; the flight is carried out as part of the transport task *tz*.
- *tpb*(*tz*,*tt*)—time of return to base; the flight is carried out as part of the transport task *tz*.

In the parameterization process, it is assumed that the time of carrying out the transport task carried out by the air SAR system will be described by the ***TT*** vector of parameters:

$$\boldsymbol{TT} = [tlo(tz, tt),\ tpr(tz, tt),\ tld(tz, tt),\ tpb(tz, tt)] \quad (3)$$

Another element that is parameterized is the means of transport involved in the rescue operation. In the aviation SAR system, the means of transport is the aircraft in the form of an ***HE*** helicopter. For the purpose of this research, the following parameters of helicopters were adopted, which are important for the considered transport task:

- *ty*(*he*)—helicopter type, *vm*(*he*)—the maximum speed of the helicopter; *vp*(*he*)—the cruising speed of the helicopter; *ve*(*he*)—economic speed of the helicopter; *vn*(*he*)—the minimum speed of the helicopter; *dl*(*he*)—helicopter flight length with basic fuel supply; *lsn*(*he*)—number of engines; *jzp*(*he*)—specific fuel consumption.

We assume that each aircraft will be described by the ***PS*** vector with the following parameters:

$$\boldsymbol{PS} = [ty(he),\ vm(he),\ vp(he),\ ve(he),\ vn(he),\ dl(he),\ lsn(he),\ jzp(he)] \quad (4)$$

The implementation of the transport task, taking into account the specificity of rescue operations, is influenced by the weather conditions in which the task is carried out. For the purpose of this research, the following weather parameters were adopted, i.e.:

- *dw*(*tz*)—wind direction during the implementation of the transport task; *sw*(*tz*)—wind force during the implementation of the transport task; *we*(*tz*)—the type of weather during the implementation of the transport task; *vis*(*tz*)—visibility during the implementation of the transport task; *ss*(*tz*)—the state of the sea during the implementation of the transport task.

We assume that the weather conditions during which the transport task is carried out will be described by the ***WP*** vector with the following parameters:

$$\boldsymbol{WP} = [dw(tz),\ sw(tz),\ we(tz),\ vis(tz),\ ss(tz)] \quad (5)$$

Wind parameters were calculated randomly, based on Weibull distribution taken from time approximated trends, gathered experimentally from western parts of the Baltic Sea. It is assumed that wind is uniformly distributed in magnitude and direction over the entire zone. Every simulation is repeated for a few hundred stochastic wind samples. The data are then treated with statistical analysis tools.

The following parameters were calculated in each simulation.

Ground speed $\vec{v_g}$ and return trip ground speed $\vec{v_{gr}}$ was a vector sum of rescue unit airspeed $\vec{v_a}$ and wind speed $\vec{v_w}$:

$$\vec{v_g} = \vec{v_a} + \vec{v_w} \tag{6}$$

In case of a return trip:

$$\vec{v_{gr}} = -\vec{v_a} + \vec{v_w} \tag{7}$$

where the magnitude of the rescue unit (RU) airspeed is equal to RU cruise speed $\left|\vec{v_a}\right| = v_c$. Knowing the velocities and distance d between the base and target, travel time t_{tr} could be calculated as a sum of travel time from the base to target location t_t and the time required for a return trip t_r:

$$t_{tr} = t_t + t_r = \frac{d}{\left|\vec{v_g}\right|} + \frac{d}{\left|\vec{v_{gr}}\right|} \tag{8}$$

When identifying the costs of implementing a transport task, it is necessary to determine the following parameters: aviation fuel costs incurred for the implementation of the transport task $kpl(tz)$, technical costs $kte(tz)$, and personnel costs $kos(tz)$.

We assume that each cost of the transport task will be described by a vector with the following parameters:

$$\boldsymbol{KT} = [kpl(tz),\ kte(tz),\ kos(tz)] \tag{9}$$

In turn, taking into account the energy efficiency of the transport task, it is necessary to determine what amount of energy $en(tz, he, wp)$ is necessary for implementation of the transport task. The energy demand in a given transport task depends on the type of aircraft and weather conditions.

3.3. Assessment Indicators for the Selection of the Base and Means of Transport

The selection of the base and transport vehicle for the transport task carried out by the air SAR system, based on the assessment of energy efficiency of a given transport task, were carried out on the basis of the following criteria:

- minimizing the costs of implementing the transport task:

$$F1(kt(tz)) = \sum_{lb \in \boldsymbol{LB}} \sum_{he \in \boldsymbol{HE}} kt(tz) \cdot sb(lb, tz) \cdot sp(he, tz) \to min \tag{10}$$

- minimizing energy consumption for the implementation of the transport task (determining the effectiveness of a given transport task):

$$F2(\boldsymbol{A}_1(tz), \boldsymbol{A}_4(tz)) = \sum_{lb \in \boldsymbol{LB}} \sum_{he \in \boldsymbol{HE}} sb(lb, tz) \cdot sp(he, tz) \cdot en(tz, he, wp) \to min \tag{11}$$

- minimizing the time:

$$F3(tt(tz)) = \sum_{lb \in \boldsymbol{LB}} tlo(tz, tt) \cdot tpr(tz, tt) \cdot tld(tz, tt) \cdot tpb(tz, tt) \to min \tag{12}$$

3.4. Limitations in the Problem of Choosing the Base and Means of Transport

Solving the decision problem requires defining limitations. These concern the aircraft under consideration (e.g., maximum flight time of an aircraft), execution of a rescue operation (e.g., visibility limiting factors, factors preventing the execution of rescue action, available fuel quantity on the aircraft).

4. Case Study

4.1. Characteristics of the Aviation SAR System

The air SAR system operating in the Polish responsibility zone in the Baltic Sea (Figure 2) is an integral part of the global SAR system. The basic criteria for the capability of the air SAR system and the success of rescue operations involve the time to find survivors and rescue them. The degree of difficulty of rescue operations is influenced by a number of factors: weather conditions, time of day and year, sea state, health and psychophysical fitness of the survivors and their numbers, reliability and sophistication of the equipment, and information about the place of the rescue operation. These are factors that are subject to detailed analyses, almost always in the shortage of time for launching and conducting an ASAR operation.

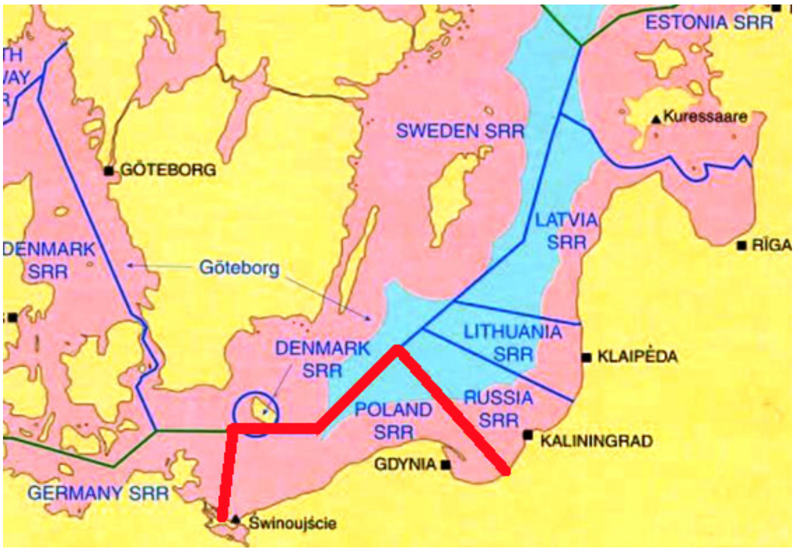

Figure 2. The Polish zone of maritime search and rescue responsibility in the Baltic Sea.

The airspace over the Baltic Sea in the Polish responsibility zone is secured by an aircraft detached from the structure of the Polish Navy. The basic search and rescue vehicles covering the entire zone are rescue helicopters Mi-14 PS (Figure 3a), W-3R Anakonda (Figure 3b), and AN-28 airplanes. The SAR aviation system is provided by military aircraft and crewmen. The Polish state decided to detach navy resources to provide search and rescue capabilities. International acts clearly allow such activities, and at the national level it is possible under aviation law and decrees of the Minister of National Defense. The system operates on the basis of the ASAR Plan (it was developed by the Chairman of the Polish Air Navigation Services Agency (PANSA)). The ordinance indicates the search and rescue unit (SRU) operating within the system; their deployment is to ensure the functioning of aeronautical search and rescue (ASAR) in the area of the responsibility of the search and rescue region (SRR), i.e., in our case, flight information region (FIR) Warsaw, 7 days a week, around the clock.

For the effective implementation of SAR service tasks, helicopters are ideal machines that can operate in various environments (over land, over water bodies). This was noticed by a constructor and helicopter pilot with a number one license, Igor Sikorski, who pointed to the differences between the plane and the helicopter, saying: “If a man is in need of rescue, an airplane can come in and drop flowers on him, and that’s just about all. But a direct lift aircraft could come in and save his life”.

(**a**) (**b**)

Figure 3. Types of helicopters equipped with the aviation SAR system: (**a**) Mi-14 PS, (**b**) W-3RM Anakonda.

Helicopters can be used to rescue survivors by lifting with elevators or landing on ships, if there are suitable locations. Water landing is possible when amphibious helicopters are used. Due to their unique flying abilities, they should be used whenever possible. They are particularly suitable for rescue at sea, in difficult conditions, or on land in hard-to-reach places, where other means of transport have limited options. However, there are specific limitations that the SAR mission co-operator (SMC) must be aware of:

- Actions performed by rescuers lifting the rescued persons onto the helicopter deck may be hampered by the noise of the rotors and air turbulence at the scene of the operation, caused by helicopters. To facilitate coordination between helicopters and lifesaving equipment, and to minimize the risk of collision associated with helicopters operating in confined spaces, operations should be coordinated by an agency communicating with them, preferably by an OSC.
- The number of survivors that the helicopter can take on board for a given transport task is limited. Therefore, it may be necessary to reduce its weight by removing irrelevant equipment or fuel. The amount of fuel at the scene of the incident can be reduced by using advanced bases with refueling capabilities.
- The helicopter route and the place where survivors are to disembark should be known to the SMC.
- Due to limited fuel reserves for helicopters and their susceptibility to icing in some locations, it may be advantageous to send the aircraft in advance to confirm the weather condition en-route and to ensure that the unit requiring assistance is adequately informed in advance of the procedures for lifting the rescued persons by helicopter.
- Conducting a rescue operation by landing a helicopter on board a ship or another facility creates additional concerns. Factors, such as turbulence, ground level, loose objects, altitude, landing, and take-off paths, must be taken into account when selecting a landing site. High altitude operations reduce the performance of the helicopter and seriously affect the hovering ability.
- A typical successful rescue operation is carried out by locating the survivors and taking them to the helicopter deck using a winch, rescue basket, rescue net, emergency chair, or emergency stretcher.

The Mi-14 PS helicopter (Figure 3a) is an amphibious helicopter designed for the search and rescue of people from the water or land, during day and night. The helicopter crew consists of two pilots, an on-board technician, a paramedic and, if necessary, a rescuer. The equipment of the Mi-14 PS helicopter makes it possible to search, locate, and provide help to survivors. Searching and locating can also be done in the difficult weather conditions (DWC) in the absence of visibility, with the use of the onboard radar station and the ARK-UD type radio finder. The ARK-UD radio compass is designed to drive search aircrafts to continuous and pulsed radio beacons in order to search and detect aircrafts and crews, and it is equipped with VHF and DCV radio beacons. In the ARK-UD radio compass, the operating beacons are indicated on the corresponding warning lamps and there is a built-in control system that provides an operative check of operability during the pre-flight check and checking the radio compass in the air. One Mi-14 PS helicopter can search a body of water measuring 90 × 45 km, visually, in 3.5 h and via instruments in 1 h.

The basic method of picking up survivors from the water (ship) is picking up from a hover using the ŁPG-300 type winch with a basket, with a capacity of 300 kg during the day and at night. When providing assistance to a larger group of survivors, the helicopter can land day and night and take 19 people on board, at sea levels up to 2°B and wind speeds up to 20 m/s during the day, and 15 m/s at night. The time the helicopter remains on the water surface with the engines working is up to 30 min.

To evacuate survivors from the endangered region of the sea (if it is not possible to land on water), the helicopter may drop 20 MEWA-6 life rafts for 120 survivors in the area of the accident. After connecting the rafts to each other with ropes, the Mi-14 PS can tow them from the hazard area to the shore or to a rescue ship (ship) with survivors inside.

The W-3 RM Anakonda helicopter (Figure 3b, Table 4) is adapted for use over the sea and land, it has the ability to fly during the day and at night, in normal and difficult weather conditions. The helicopter has special equipment on board that is safe and well prepared for the work of the crew during rescue operations. The most important part of the equipment is an electric lift, which is located outside the helicopter and is used to lift people or cargo up to 267 kg and up to a height of 50 m, at a speed of 0.75 m/s. A separate part of the equipment consists of devices that allow determining the location of the accident at sea. Safety during a rescue operation, in changing weather conditions and various configurations in flight over sea, is additionally ensured by navigation equipment that can determine the position of the aircraft from the position of the survivors or the shore facility or sea station.

Table 4. Basic tactical and technical data of the W-3RM Anaconda helicopter.

Tactical and Technical Data	
Maximum cargo mass inside the helicopter	2100 kg
Maximum flight speed	260 km/h
Maximum cruising speed	235 km/h
Maximum recommended cruising speed	222 km/h
Maximum range without additional fuel tanks at 222 km/h	734 km
Maximum flight endurance at 125 km/h	4.2 h

4.2. Analysis of Rescue Operations Carried out by the Air SAR System

An important element of the rescue operation carried out by the air SAR system is the limited time for the operation, because the probability of survival of the injured decreases with the passage of time [47]. The limited time during the search may require the involvement of a significant number of helicopters participating in the search of the area or lowering the probability of detection. This is reflected in the number of transport tasks carried out by the air SAR system.

Operational time of the performing search or rescue operations in the designated incident zone relies heavily on the transit time to and from the base location. Moreover, upon arrival, usually 15% of the remaining operational time has to be further spent on identifying objects in water (life rafts, people, and debris). Due to varying fuel consumption rates, at different flight speeds, the working time remaining is also dependent on the speed at which the search pattern is followed by a helicopter above the sea. In Figure 4, a relation among operational time, search speed, and search radius is presented. A detailed interpretation of the obtained results is presented in Tables 5 and 6. It can be seen that there is an optimal search speed that maximizes the time available to a helicopter rescue unit to operate at sea.

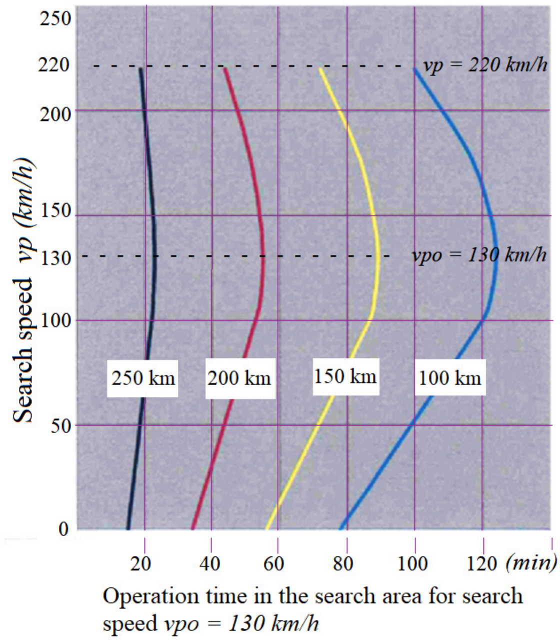

Figure 4. Dependence of the operation time in the search area depending on the search speed *vpo* achieved by the helicopter; optimal search speed is *vpo* = 130 km/h, constant cruising speed of the helicopter *vp* = 220 km/h and the set of search radius *rp* = (100, 150, 200, 250 km).

Table 5. Dependence of flight time and working time on cruise speed at search speed *vpo* = 130 km/h.

Radius *rp* (km)	**Cruising Speed** *vp* **= 220 km/h**		*vp* **= 200 km/h**		*vp* **= 180 km/h**		*vp* **= 130 km/h**	
	Time *tlo* (min)	**Time *tpr* (min)**	**Time *tlo* (min)**	**Time *tpr* (min)**	**Time *tlo* (min)**	**Time *tpr* (min)**	**Time *tlo* (min)**	**Time *tpr* (min)**
100	27	100	30	108	33	115	46	123
150	41	72	45	77	50	82	69	88
200	55	45	60	47	67	50	92	55
250	68	18	75	20	83	21	115	23

Table 6. Dependence of the maximum working time in the search area, depending on the search speed at a constant cruising speed *vp* = 220 km/h and the search radius *rp*.

Radius *rp* (km)	**250**				**200**				**150**				**100**			
Speed *vpo* (km/h)	220	180	130	110	220	180	130	110	220	180	130	110	220	180	130	110
Time *tpr* (min)	18.5	21	22.5	22	45.5	52.5	56	55	73	84	89.5	88.5	100	115	123	121

The data in Tables 5 and 6 were obtained on the basis of the analysis of reports on rescue flights performed by the Mi-14 PS and W-3 RM helicopters, which are presented in Figure 4. The graph shows the dependence of the operation time in the search area on the search speed *vpo* achieved by the helicopter, the optimal search speed is *vpo* = 130 km/h, the constant cruising speed of the helicopter is *vp* = 220 km/h, and the search radius set *rp* = (100, 150, 200, 250 km). Rescue flights were performed from the Gdynia bases (EPOK) and the Darłowo base (EPDA). The locations of the performed rescue missions are shown in Figure 5.

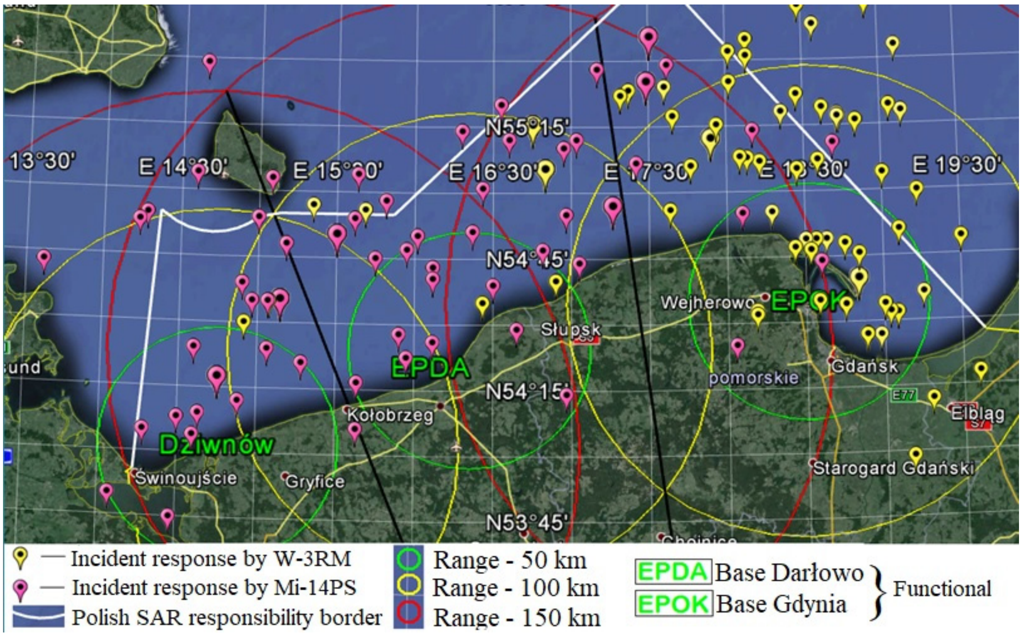

Figure 5. Range of operation of active SAR bases in Polish System (EPDA and EPOK) with provisionary base in Dziwnów.

Table 5 shows the dependence of the time of flight to the search area background on the speed of the flight from the base to this region *vp* and the effect of this time on the length of the search time *tp*. The data analysis shows that the further the search area is located from the base, and the faster the flight from the base to this area is made, the less time is available for the search and rescue operation itself, etc. The low energy efficiency of using the means of transport, which is the rescue helicopter, is noticeable. The action to improve energy efficiency was the constant search speed of *vpo* = 130 km/h.

Table 6 shows the dependence of the maximum operation time tpr in the search area rp on the changing search speed vpo at a constant flight speed from the base to the search area vp = 220 km/h. It can be seen that, at a shorter distance from the search area to the base, the speed of the flight from the base to the search area has a smaller impact on the time allocated to the search. The conclusion is that it would be advisable to increase the number of bases for rescue helicopters in order to minimize the time of arrival from the base to the areas of high traffic density. Communication routes for various purposes run along the Polish coast and shortening the arrival time to these routes will increase the level of navigation safety, and possible rescue operations will be carried out with greater energy efficiency of transport means. Bearing in mind the above conclusions, it is proposed to locate a new rescue base in Dziwnów, located in the western part of the Polish coast. The location is shown in Figure 5.

Figure 6 shows the distance from the base of rescue missions launched at the EPDA base in the years 1995–2001, with the use of Mi-14PS helicopters. Figure 6 shows the distance from the base of rescue missions launched in the EPOK base in the years 1995–2001, with the use of W3-RM helicopters.

Figure 7 shows a simulation of the course of rescue missions with the specifications of real missions from 1995–2001, but with the participation of the third base in Dziwnów. In Figure 8, those missions whose locations were within a radius of 150 km from the base were selected.

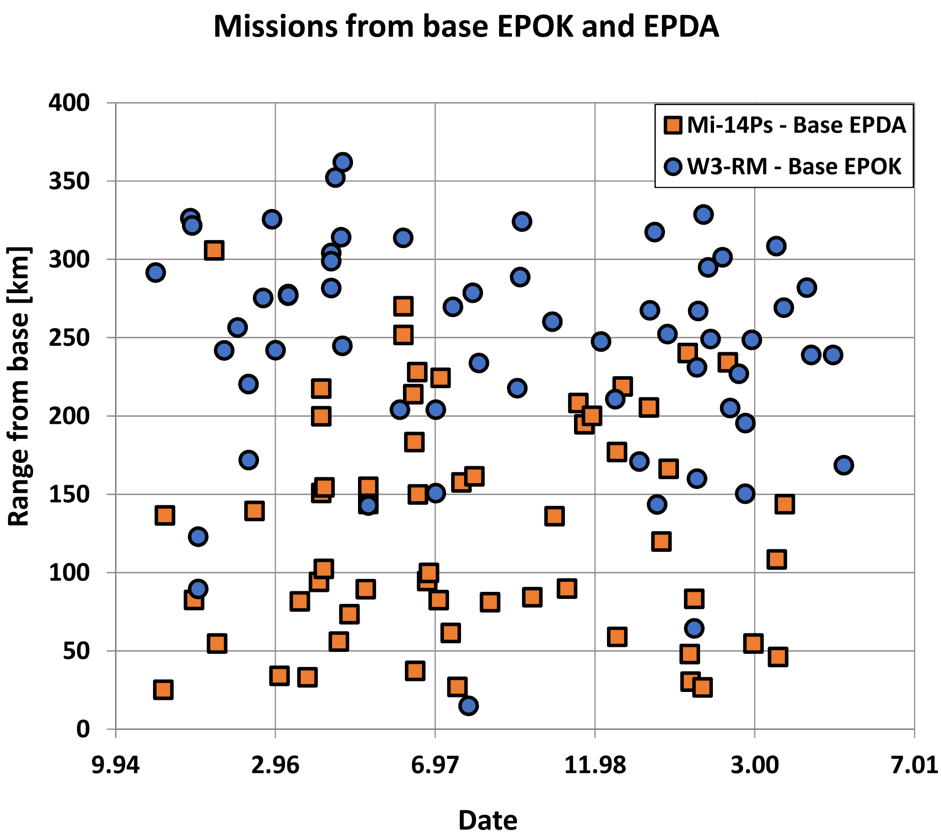

Figure 6. Rescue mission distance from base for missions which started from both EPDA and EPOK bases in years 1995–2001; Mi-14 PS and W3-RM helicopters were used.

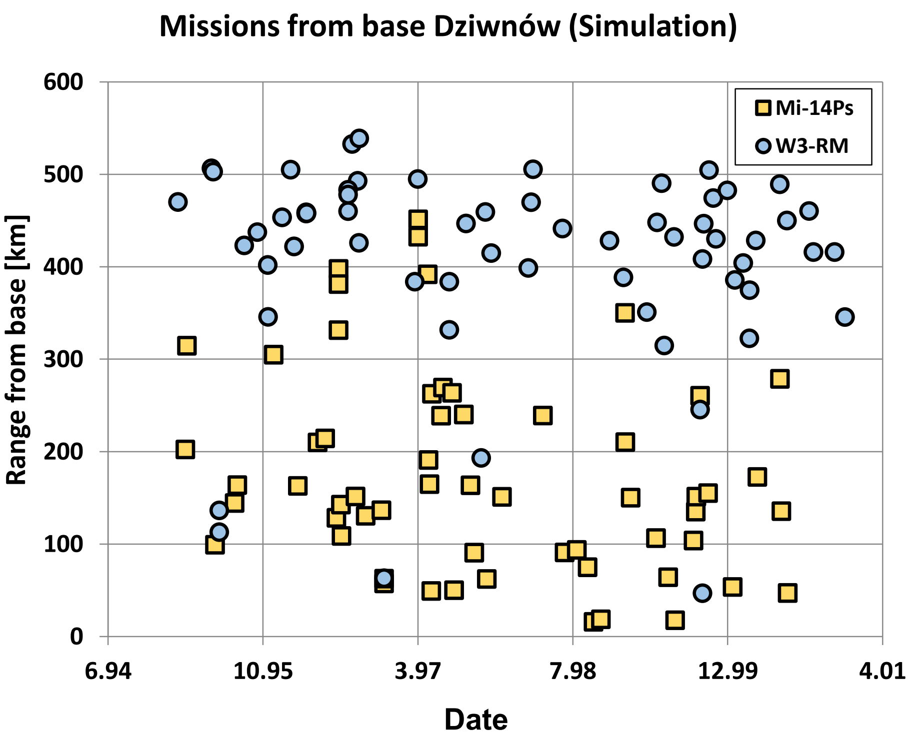

Figure 7. Range from base for simulated missions which started from Dziwnów base in years 1995–2001; W3-RM and Mi-13PS helicopters were used.

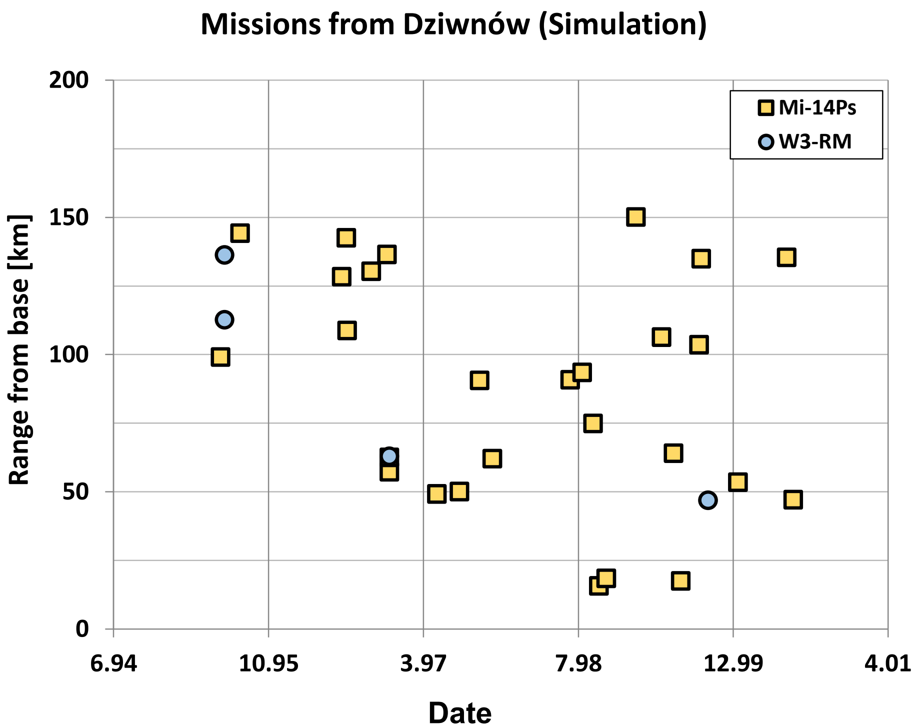

Figure 8. Range from base for simulated missions closer than 150 km which started from Dziwnów base in years 1995–2001; W3-RM and Mi-13PS helicopters were used.

Figure 9 shows the percentage distribution of missions depending on the distance from the starting base. It was observed that 40% of the missions launched at the EPDA base were carried out at a point more than 150 km from the base. It can be concluded that there is a location of a potential third base from which the distance to these points would be smaller. Figure 10 shows simulations of the distance distribution of the rescue flight target for missions starting at the base located in Dziwnów; 25% of the mission objective points are within the operating radius of 150 km.

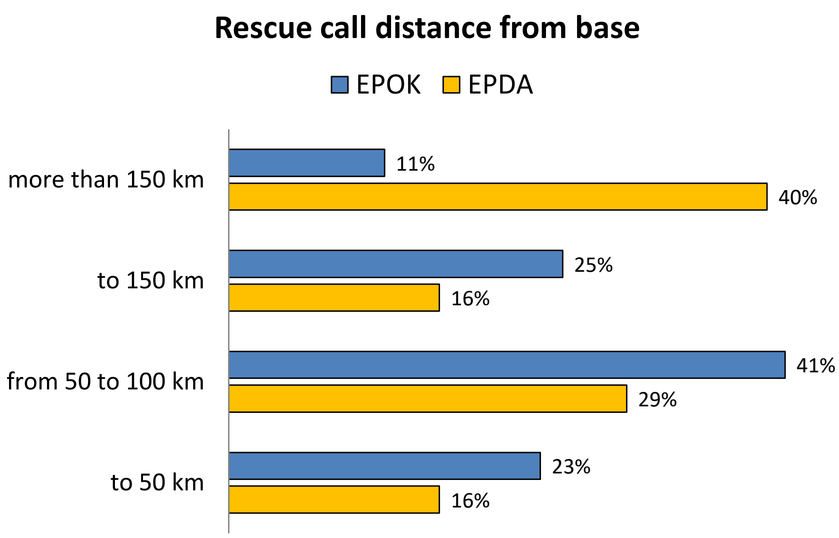

Figure 9. Distance distribution for missions that started from EPOK and EPDA bases in 1995–2001; W3-RM and Mi-13PS helicopters were used.

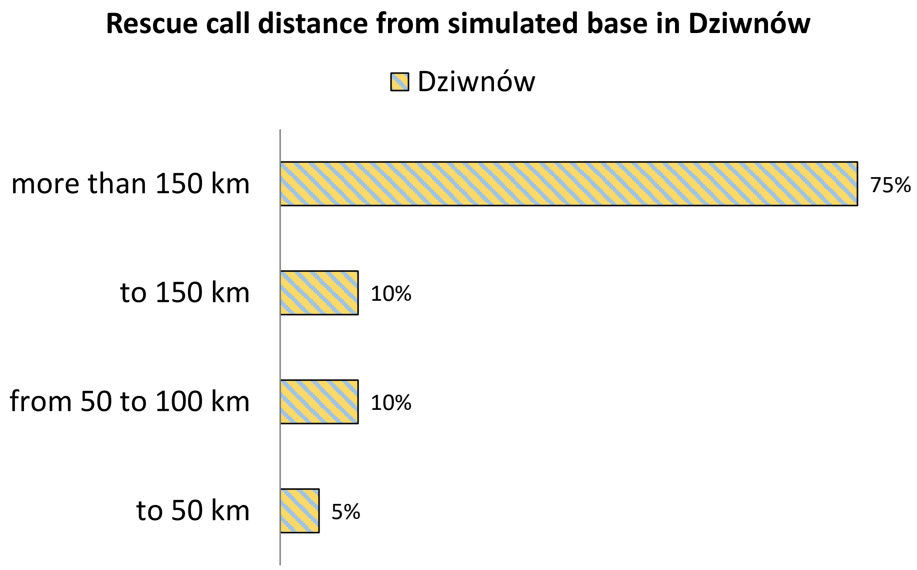

Figure 10. Distance distribution for simulated missions that started from Dziwnów base in 1995–2001; W3-RM and Mi-13PS helicopters were used.

5. Conclusions

Authors state that a complex system of providing search and rescue coverage over a part of the Baltic Sea can be mathematically modeled and simulated. The air SAR system model is based on the solution quality assessment index in the form of energy efficiency. It has been shown that, in the analyzed period, around 40% of rescue operations were carried out very far from the rescue unit staging base. This led to an increase in costs and energy consumption, negatively impacted the results. The two existing bases do not sufficiently cover the communication routes located in the area of the Polish SAR area of responsibility. The western regions of the Polish coast are located far away from the currently operating air bases. Helicopters Mi-14 PS and W-3 RM Anakonda are old and in need of replacement or thorough modernization. Propulsion systems in these aircrafts generate too-high operating costs due to outdated designs. Improving energy efficiency, i.e., more efficient use of the energy of the fuel taken aboard, is no longer enough. A holistic system-wise approach is needed. This could be done with proper resource allocation and via funding the creation of additional bases. A reduction in cost is not the only criterion used to evaluate the performance of the system. An optimized system would be characterized by wide area coverage of the rescue, potentially available in less than 30 min, with sufficient backup if possible. This work is a preliminary analysis of the influence of the base location and rescue unit parameters on the air SAR system, in regard to energy efficiency. More detailed studies are needed in the future that would address the uncertainty and stochastic character of the weather conditions, sea state, and drift motion of survivors. The authors believe that this work will prove useful to all parties interested in more rational and effective use of resources, to provide safety at sea.

Author Contributions: Conceptualization, J.F., N.C.-G., M.J. and M.I.; methodology, J.F., M.J., M.I. and N.C.-G.; software, J.F.; validation, J.F. and N.C.-G.; formal analysis, J.F., N.C.-G., M.J. and M.I.; resources, J.F. and N.C.-G.; data curation, J.F. and N.C.-G.; writing—original draft preparation, J.F., M.I. and N.C.-G.; writing—review and editing, J.F. and N.C.-G.; visualization, J.F.; supervision, M.J. and N.C.-G.; funding acquisition, M.J. All authors have read and agreed to the published version of the manuscript.

Funding: Funded by the Warsaw University of Technology, within the research grant for supporting scientific activities in discipline: Civil Engineering and Transport.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data available in a publicly accessible repository.

Acknowledgments: The authors would like to gratefully acknowledge the reviewers that provided helpful comments and insightful suggestions on a draft of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of the data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Cieśla, M.; Sobota, A.; Jacyna, M. Multi-Criteria decision making process in metropolitan transport means selection based on the sharing mobility idea. *Sustainability* **2020**, *12*, 7231. [CrossRef]
2. Jacyna, M.; Semenov, I. Models of vehicle service system supply under information uncertainty. *Eksploat. I Niezawodn.* **2020**, *22*, 694–704. [CrossRef]
3. De Martinis, V.; Corman, F. Data-driven perspectives for energy efficient operations in railway systems: Current practices and future opportunities. *Transp. Res. Part C Emerg. Technol.* **2018**, *95*, 679–697. [CrossRef]
4. Jacyna, M.; Szczepański, E.; Izdebski, M.; Jasiński, S.; Maciejewski, M. Characteristics of event recorders in Automatic train control systems. *Arch. Transp.* **2018**, *46*, 61–70. [CrossRef]
5. Jacyna, M.; Gołębiowski, P.; Urbaniak, M. Multi-option Model of Railway Traffic Organization Including the Energy Recuperation. In *Programmieren für Ingenieure und Naturwissenschaftler*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 199–210.
6. Urbaniak, M.; Kardas-Cinal, E.; Jacyna, M. Optimization of Energetic Train Cooperation. *Symmetry* **2019**, *11*, 1175. [CrossRef]
7. Ciccarelli, F.; DEL Pizzo, A.; Iannuzzi, D. Improvement of Energy Efficiency in Light Railway Vehicles Based on Power Management Control ofWayside Lithium-Ion Capacitor Storage. *IEEE Trans. Power Electron.* **2014**, *29*, 275–286. [CrossRef]
8. Szkoda, M.; Satora, M.; Konieczek, Z. Effectiveness assessment of diesel locomotives operation with the use of mobile maintenance points. *Arch. Transp.* **2020**, *54*, 7–19. [CrossRef]
9. Popescu, M.; Bitoleanu, A. A Review of the Energy Efficiency Improvement in DC Railway Systems. *Energies* **2019**, *12*, 1092. [CrossRef]
10. Gunselmann, W. Technologies for increased energy efficiency in railway systems. In Proceedings of the 2005 European Conference on Power Electronics and Applications, Dresden, Germany, 11–14 September 2005; p. 10.
11. Gołębiowki, P.; Jacyna, M.; Stańczak, A. The Assessment of Energy Efficiency versus Planning of Rail Freight Traffic: A Case Study on the Example of Poland. *Energies* **2021**, *14*, 5629. [CrossRef]
12. Ćwil, M.; Barnik, W.; Jastrzębowski, S. Railway vehicle energy efficiency as a key factor in creating sustainable transportation systems. *Energies* **2021**, *14*, 5211. [CrossRef]
13. Brenna, M.; Bucci, V.; Falvo, M.C.; Foiadelli, F.; Ruvio, A.; Sulligoi, G.; Vicenzutti, A. A review on energy efficiency in three transportation secotrs: Railways, electrical vehicles and marine. *Energies* **2020**, *13*, 2378. [CrossRef]
14. Sandoval-Garcia, E.; Matsumoto, Y.; Sanchez-Partida, D. Data and energy efficiency indicators of freight transport sector in Mexico. *Case Stud. Transp. Policy* **2021**, *9*, 1336–1343. [CrossRef]
15. Filin, S.; Filina-Dawidowicz, L. Improvement of Criteria for Assessing the Energy Efficiency of Thermoelectric Refrigerators Used in Supply Chains. *Energies* **2021**, *14*, 1620. [CrossRef]
16. Zajac, P.; Rozic, T. Energy consumption of forklift versus standards, effects of their use and expectations. *Energy* **2022**, *239*, D122187. [CrossRef]
17. Zajac, P. Indicators and Measures of Energy Efficiency the Warehouse. *Energy Comsumption Refrig. Wareh.* **2016**, *11*, 23–28. [CrossRef]
18. Dobrzycki, A.; Filipiak, M.; Jajczyk, J. Changes in the range of electric vehicles during operation. *Comput. Appl. Electr. Eng.* **2019**, *28*, 01009. [CrossRef]
19. Rehmatulla, N.; Smith, T. The impact of split incentives on energy efficiency technology investments in maritime transport. *Energy Policy* **2020**, *147*, 111721. [CrossRef]
20. Jayasinghe, S.; Lokuketagoda, G.; Enshaei, H.; Shagar, V.; Ranmuthugala, D. Electro-technologies for energy efficiency improvement and low carbon emission in martitime transport. In Proceedings of the 16th Annual General Assembly and Conference of the International Association of Maritime Universities, Rijeka, Croatia, 7–10 October 2015; pp. 119–123.
21. Bazaluk, O.; Havrysh, V.; Nitsenko, V. Energy Efficiency of Inland Waterways Transport for Agriculture: The Ukraine Case Study. *Appl. Sci.* **2021**, *11*, 8937. [CrossRef]
22. Filina-Dawidowicz, L.; Filin, S. Innovative energy-saving technology in refrigerated containers transportation. *Energy Effic.* **2019**, *12*, 1151–1165. [CrossRef]
23. Vajihi, M.; Ricci, S. Energy Efficiency Assessment of Rail Freight Transport: Freight Tram in Berlin. *Energies* **2021**, *14*, 3982. [CrossRef]
24. Ejdys, S. Model of a Sustainable Transport System on the Example of Olsztyn. *Rocz. Ochr. Srodowiska* **2021**, *23*, 811–822. [CrossRef]
25. Pavlov, G.; Sekulov, L. Study and Analysis of Efficiency of Recuperative Energy Utilization in Ground Urban Electric Transport. In Proceedings of the 17th Conference on Electrical Machines, Drives and Power Systems (ELMA), Sofia, Bulgaria, 1–4 July 2021. [CrossRef]

26. Izdebski, M.; Jacyna, M. An Efficient Hybrid Algorithm for Energy Expenditure Estimation for Electric Vehicles in Urban Service Enterprises. *Energies* **2021**, *14*, 2004. [CrossRef]
27. Kosai, S.; Yuasa, M.; Yamasue, E. Chronological transition of relationship between intracity lifecycle transport energy efficiency and population density. *Energies* **2020**, *13*, 2094. [CrossRef]
28. Krawczyk, G.; Wojciechowski, J. Improving chosen elements of energy efficiency in public transport through the use of supercapacitors. *Adv. Intell. Syst. Comput.* **2020**, *1083*, 131–142. [CrossRef]
29. Misanovic, S.M.; Zivanovic, Z.M.; Tica, S.M. Energy efficiency of different bus subsystems in Belgrade public transport. *Therm. Sci.* **2015**, *19*, 2233–2244. [CrossRef]
30. Filipiak, M.; Jajczyk, J. The economics of use wireless power supply in electric buses. *Comput. Appl. Electr. Eng.* **2018**, *19*, 01034. [CrossRef]
31. Cansino, J.M.; Roman, R. Energy efficiency improvements in air traffic: The case of Airbus A320 in Spain. *Energy Policy* **2017**, *101*, 109–122. [CrossRef]
32. Verstraete, D. On the energy efficiency of hydrogen-fuelled transport aircraft. *Int. J. Hydrog. Energy* **2015**, *40*, 7388–7394. [CrossRef]
33. Donateo, T.; Ficarella, A.; Spedicato, L. Applyng dynamic programming algorithms to the energy management of hybrid electric aircraft. In Proceedings of the Asme Turbo EXPO: Turbomachinery Technical Conference and Exposition, Lillestrom (Oslo), Norway, 11–15 June 2018; Volume 3.
34. Bolvashenkov, I.; Kammermann, J.; Herzog, H.G. Eliability assessment of a fault tolerant propulsion system for an electrical helicopter. In Proceedings of the 12th International Conference on Ecological Vehicles and Renewable Energies (EVER 2017), Monte-Carlo, Monaco, 11–13 April 2017; p. 7935864. [CrossRef]
35. Bolvashenkov, I.; Kammermann, J.; Rubinraut, A.; Herzog, H.; Frenkel, I. Design and Feasibility of Electrical Version of Search-and-Rescure Helicopter Based on Eurocopter. *SpringerBriefs Appl. Sci. Technol.* **2022**, *14*, 41–61. [CrossRef]
36. Xu, Y.; Niu, Y.J.; Fang, W.g.; Zhang, T.t. Research on the Efficiency and Application of Ship-Helicopter Cooperative Search. *Lect. Notes Comput. Sci.* **2019**, *11632*, 315–326. [CrossRef]
37. Shao, Q.; Xu, C.; Zhu, Y. Multi-Helicopter Search and Rescue Route Planning Based on Strategy Optimization Algorithm. *Int. J. Pattern Recognit. Artif. Intell.* **2019**, *33*, 1950002. [CrossRef]
38. Schemke, S.; Schwalbe, H.; Grunewald, L.; Maurer, H. Emergency medicine in the German Maritime Search and Rescue Service-Evaluation of medical emergencies in the North Sea and Baltic Sea over 2 years. *Anaesthesist* **2021**, *70*, 280–290. [CrossRef] [PubMed]
39. Xiong, P.; Liu, H.; Tian, Y.; Chen, Z.; Wang, B.; Yang, H. Helicopter maritime search area planning based on a minimum bounding rectangle and K-means clustering. *Chin. J. Aeronaut.* **2021**, *34*, 554–562. [CrossRef]
40. Ortiz-Carretero, J.; Pardo, A.C.; Goulos, I.; Pachidis, V. Impact of adverse environmental conditions on rotorcraft operational performance and pollutant emissions. *J. Eng. Gas Turbines Power* **2018**, *140*, 021201. [CrossRef]
41. Yu, Y. Discrete mission planning algorithm for air-sea integrated search model. *Sci. Rep.* **2021**, *11*, 16957. [CrossRef]
42. Kratzke, T.M.; Stone, L.D.; Frost, J.R. Search and Rescue Optimal Planning Sytem. *IEEE Xplore* **2011**, *10*, 11823426. [CrossRef]
43. Chen, Z.; Liu, H.; Tian, Y.; Wang, R.; Xiong, P.; Wu, G. A Particle Swarm Optimization Algorithm Based on Time-Space Weight for Helicopter Maritime Search and Rescue Decision-Making. *IEEE Access* **2020**, *8*, 81526–81541. [CrossRef]
44. Otote, D.A.; Li, B.; Ai, B.; Gao, S.; Xu, J.; Chen, X.; Lv, G. A Decision-Making Algoritm for Maritime Search and Rescue Plan. *Sustainability* **2019**, *11*, 2084. [CrossRef]
45. Rudyk, T.; Szczepański, E.; Jacyna, M. Safety factor in the sustainable fleet management model. *Arch. Transp.* **2019**, *49*, 103–114. [CrossRef]
46. Gołda, P.; Zawisza, T.; Izdebski, M. Evaluation of efficiency and reliability of airport processes using simulation tools. *Eksploat. Niezawodn.* **2021**, *23*, 659–669. [CrossRef]
47. Chistensen, R.E.; Ottosen, C.I.; Sonne, A.; Novernberg, B.; Juul, A.H.; Steinmetz, J.; Rasmussen, L.S. Search and rescue helicopters for emergency medical service assistance: A retrospective Study. *Air Med. J.* **2021**, *40*, 269–273. [CrossRef] [PubMed]