POLISH MARITIME RESEARCH 1 (117) 2023 Vol. 30; pp. 4-16
10.2478/pomr-2023-0053

COMPUTER-AIDED SYSTEM FOR LAYOUT OF FIRE HYDRANTS ON BOARDS DESIGNED VESSEL USING THE PARTICLE SWARM OPTIMIZATION ALGORITHM

Piotr Gomułka
[1] Damen Engineering Gdansk, Gdansk
[2] Gdansk University of Technology, Gdansk, Poland

* Corresponding author: *piotr.gomulka@pg.edu.pl (Piotr Gomułka)*

ABSTRACT

The functional layout of fire safety equipment in technical spaces of ships is a time-consuming process. When designing a ship fire protection system, the designer must manually position each system component in such a way as to meet the requirements of regulations arising from the technical specification, various legal regulations of maritime conventions and classification societies of the vessel to be designed. Layout of fire hydrants assisted by a computer that is based on pre-defined criteria and various constraints could significantly support the designer in working easier and faster. This paper presents a prototype computer-aided design system that enables optimal placement of fire hydrants using the metaheuristic Particle Swarm Optimization (PSO) algorithm. This algorithm was used in Rhinoceros 3D software with its Grasshopper plugin for visualizing the arrangement of fire safety equipment. Various solution arrangements compared with the fire hydrant placement in real ships are illustrated by a case study. Demonstrating how design work can be facilitated and what potential benefits can be achieved are presented as well.

Keywords: ship, fire hydrant, design, layout, particle swarm optimization

INTRODUCTION

The placement of fire protection equipment in ship technical rooms is an extremely important and time-consuming part of the ship design. One of the important components of this equipment is the fire hydrant, and its rational or optimal placement on board ships should reduce the degree of fire hazard. The proper placement of fire hydrants requires designers to conduct a preliminary analysis of the fire hazards that may occur on the ship's board. This should be preceded by familiarization with the applicable regulations, such as the SOLAS Convention[1], the FFS Resolution[2] , classification society rules, and standards that specify requirements for the designed fire protection installation, as well as the technical specification of the vessel. Then, based on legal and technical requirements and hazard analysis, the designer begins to layout hydrants on a ship's board, including determining their minimum number and location to ensure maximum effectiveness of the fire protection system. This takes into account factors such as the type of hydrants, water flow and pressure, and ease of access to hydrants. In existing ship design practice, the designer manually positions each fire hydrant to meet the imposed requirements based on his experience and knowledge, use a database of similar design solutions, and also follow the guidelines of installed equipment manufacturers. As a rule,

[1] The International Convention for the Safety of Life at Sea (SOLAS)– an international maritime treaty that sets minimum safety standards for ships, including requirements for design, construction, equipment, and operation.

[2] The Fire Safety Systems (FSS) Code – an international standard that provides guidelines for the design, installation, and maintenance of fire safety systems on board ships.

the manufacturers specify, for example, the necessary service or operator space, the location of connecting cooperating installations, or impose the order of their installation. The last step is calculations or simulations regarding the hydraulics of the system performed to ensure that each hydrant will have adequate water flow and pressure and that the entire fire protection system will work effectively in the event of a fire occurrence.

This paper presents a prototype computer-aided design system that enables optimal placement of fire hydrants using the metaheuristic Particle Swarm Optimization (PSO) algorithm. The PSO algorithm is embedded in Rhinoceros 3D software with its Grasshopper plugin for visualizing the arrangement of fire protection equipment. The Grasshopper program is a visual scripting environment for Rhinoceros 3D software that is very popular in ship design offices. Users can both build and use a library of existing parametric algorithms to modify, analyze, or create 3D models from scratch. They are also able to automate design processes without the need for writing software code.

Various solution arrangements compared with the fire hydrant placement in real ships are illustrated by a case study. Demonstrating how design work can be facilitated and what potential benefits can be achieved are presented as well.

LITERATURE REVIEW

In the subject literature, there are many concepts and solutions for object placement in any enclosed space. For example, in [1], the authors presented three approaches to automating the object placement process: rule-based, genetic algorithms, and artificial neural networks. They also discuss ways to improve the quality of automatic object placement by taking into account the specificities of space and user preferences. The authors of the article referenced in [2] described a new approach to automatic object positioning in three-dimensional spaces. The method described there is based on the use of constraints that allow for precise control of the object placement process in space. They present a mathematical model that allows for the formal definition of constraints and their application in the object positioning process. In the publication [3], the authors provide an overview of problems related to object location that have applications in various fields, including transport network planning, store location, warehouse, and medical centers. On the other hand, the possibilities of using tools based on various variants of *p-median* and *p-center* algorithms to solve transport network planning problems, store and distribution center location are described in [4]. The paper [5] employs uncertainty theory to address the location problem of emergency service facilities under uncertainty. Using the inverse uncertainty distribution, the uncertain location set covering model was transformed into an equivalent deterministic location model. This paper first studies the uncertainty distribution of the covered demand that is associated with the covering constraint confidence level α. In addition, the authors model the maximal covering location problem in an uncertain environment using different modeling ideas, namely, the (α, β)-maximal covering location model and the α-chance maximal covering location model. It is also proven that the (α, β)-maximal covering location model can be transformed into an equivalent deterministic location model, and then, it can be solved. They also point out that there exists an equivalence relation between the (α, β)-maximal covering location model and the α-chance maximal covering location model, which leads to a method for solving the α-chance maximal covering location model. Finally, the ideas of uncertain models are illustrated by a case study.

There are also a number of studies presenting solutions for facilitating the placement of equipment or installations in ship technical rooms. For example, criteria for evaluating the placement of equipment in the ship engine room and analysis methods that allow for choosing the best option in terms of safety, energy efficiency, and costs are presented in [6]. On the other hand, methods and technologies that improve access to equipment in the engine machinery room in terms of maintenance cost planning and effective maintenance strategy implementation are presented in [7]. The study [8] concerns the integration of computer-aided and knowledge base systems in designing ship machinery equipment and installations. The authors describe how integrating these two systems allows for better optimization and increases the efficiency of the design process that ensures greater device reliability or facilitating their operation. In [9], the authors focus on issues related to the design of ship pipeline systems. For example, they discuss pipeline layout design criteria, taking into account aspects related to the difficult working conditions, such as vibration or corrosion.

Despite the numerous articles on this topic, simple engineering decision support systems enabling the generation of alternative layouts of equipment, including the placement of fire safety equipment on board ships, have not been presented. This is confirmed, among others, by authors of [10], stating that this issue is not well researched in terms of general solutions. They propose to solve that problem using the a modified iterative-deepening search method. It is the iterative-exploration method that uses a classical greedy algorithm by means of it is possible to show the possibility of preliminary placement of fire safety equipment.

Our approach is based on developing a prototype computer-aided design system that enables optimal placement of fire hydrants using the metaheuristic Particle Swarm Optimization (PSO) algorithm.

CONCEPT OF COMPUTER-AIDED DESIGN SYSTEM THAT ENABLES OPTIMAL PLACEMENT OF FIRE HYDRANTS

PSO algorithm as a means of supporting the placement of fire hydrants on ship decks

To solve the problem of optimal layout of fire hydrants on the shipboard, one type of meta-heuristic algorithm, i.e., the PSO algorithm, was used in the developed computer-aided system. It has been found to be particularly effective in optimizing problems related to closed spaces because it can efficiently explore and exploit the search space. Closed spaces, such as those found structural optimization problems, often have complex constraints and interactions between variables that can make classical optimization methods difficult to apply [11]. However, the PSO algorithm is able to navigate these complex search spaces by simultaneously exploring the search space and exploring promising regions of the search space.

Additionally, the PSO algorithm is capable of handling non-linear and non-convex optimization problems, which are often encountered in closed-space optimization problems. By using a swarm of particles, the PSO can avoid getting stuck in local optima and instead converge to a global optimum solution. However, the effectiveness of the algorithm depends on various factors such as the complexity of the problem, the size of the space, and the number of design variables involved. Therefore, it is important to carefully evaluate the suitability of the PSO algorithm for a specific application related to closed spaces before implementation.

However, it should be noted that PSO, as a member of the metaheuristic methods family, only provides a way to create an appropriate heuristic algorithm. In turn, such an algorithm enables the obtainment of a solution for which it is possible to prove how close it is to the optimal solution, i.e., it is a quasi-optimal solution. From the point of view of engineering practice and ship design offices, such a solution is fully acceptable.

As previously mentioned, the PSO algorithm is built into the Grasshopper application and is an integral component of it. The useful features of the Grasshopper application were used to create a tool that assists designers in properly placing fire hydrants. By defining sets of design rules and constraints that determine the placement of these hydrants, an algorithm was chosen that is suitable for the complexity of the computational problem.

Meta-heuristic algorithms, while not guaranteeing the discovery of global optimal solutions, can provide results close to optimal in a reasonable amount of time. This seems to be a favorable solution for placing fire hydrants on a shipboard. Meta-heuristics are often inspired by natural processes, such as swarm interactions (particle swarm optimization, ant colony optimization), generational evolution (genetic algorithms, genetic programming, evolutionary programming), as well as physical phenomena (e.g., simulated annealing). Among the existing optimization tools in the Grasshopper environment, frequently used ones include Galapagos [12], [13], Goat [14], Silvereye [15], Opossum [16], Dodo [17], and Nelder Mead [18]. However, choosing the best one is a very difficult and ambiguous task. In the subject literature, both simulation studies have shown the superiority of individual algorithms [14], [15] and works that suggested that no single algorithm was dominant for the considered optimization problems [14]. Therefore, a clear assessment of the usefulness of the tool depends on the optimization problem and comparative methods that measure the efficiency of algorithms (e.g., convergence time, stability, resistance to getting stuck in local optima).

In this study, the goal is not to compare individual algorithms in terms of their speed or effectiveness but to demonstrate that the use of simple optimization tools in the placement of fire protection system components can bring noticeable benefits to the designer (reducing design time), shipyards (lowering installation costs), and ultimately ship-owners, who will be responsible for maintaining the selected installation components. Based on the criteria of ease of implementation with the system responsible for placing the fire protection system components, as well as the simplicity of its operation and use, the PSO algorithm was used, which works by using the “Silvereye” plugin.

At its core, the PSO involves a population of candidate solutions, called particles, moving around in a search space and adjusting their position based on their own best-known position and the best-known position of their neighbors. Mathematically, the position of each particle in the search space is represented by a vector x, and its velocity is represented by a vector v. The objective function that needs to be optimized is denoted as $f(x)$. The PSO algorithm iteratively updates the position and velocity of particles until a termination criterion is met, such as a maximum number of iterations or a target objective function value. The mathematical model of the PSO algorithm has been found in many studies, e.g., in [19], [20], and [21].

To develop a prototype computer-aided design system that enables optimal placement of fire hydrants on ship-boards, we should formulate an optimization problem. To formulate it using the PSO algorithm in Grasshopper, we can follow these two steps:

- define the problem by defining the constraints, the objective functions, and the design variables that can be adjusted to optimize the objective functions,
- use a PSO algorithm implementation in Grasshopper using the “Silvereye” plugin.

Constraints

To ensure optimal placement of hydrants on board a designed ship, a designer support system should take into account the following constraints:

- space constraints; the available space on the ship deck is limited by the size and shape of the ship,
- legal regulations; they dictate the minimum number and placement of hydrants on ship decks,
- significance of compartments; areas on the ship where fire is most likely or the risk is negligible.

Space constraints

The developed system that enables optimal placement of hydrants has to take into account the physical limitation of the vessel’s hull and the shape of the defined spaces. The shape of the hull can take on various forms, depending on the level of detail and complexity of the model. In Rhino Core software for design and modelling, it can be represented by:

– curves of various types, such as NURBS (Non-Uniform Rational B-Splines), Bezier, interpolating, spline,
– surface models, such as NURBS, which are one of the basic types of surfaces supported by Rhino Core, allowing for precise definition of the shape of the hull using control points and curves,
– mesh surface models,
– hybrid modeling,
– models imported from external CAD file formats, including IGES (Initial Graphics Exchange Specification), STEP (Standard for the Exchange of Product model data), SAT (Standard ACIS Text), and others; the hull can be designed in another program and imported into Rhino Core, where further work on the project can be carried out.

In the developed system, each of the ship rooms was created using closed curves (polylines), representing the outline of a particular space. The outlines assembled together form a flat projection on each of the analyzed vessel's decks, as shown in Figure 1. Such outlines can also be based, for example, on the general plan of the vessel made in a CAD program.

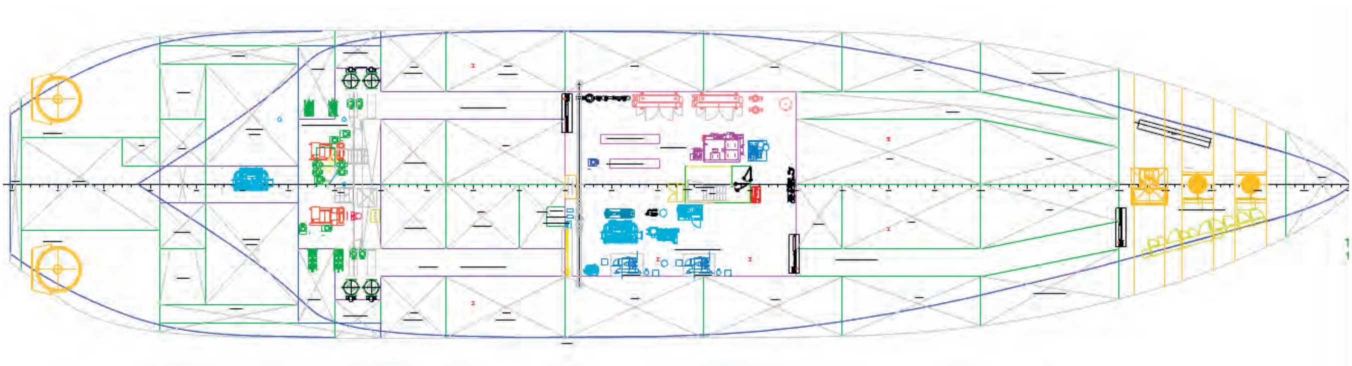

Fig. 1. Example top view projection of ship rooms created using closed curves

Fire hydrants should be located within the ship's geometrical representation, and any obstacles on the vessel (e.g., pillars, reinforcements) must be taken into account and should not create any collisions. In rooms, hydrants are usually located near walls, typically near communication routes or evacuation exits. In our approach, it was assumed that fire hydrants would be located on a closed curve, forming the outline of the selected room. Any point markers on the curve can represent the graphic representation of a hydrant. B-spline curves are used to interpolate a curve defined by knot points. They are a chain of Bezier curves. Any point on a polynomial curve in real coordinates is determined by the following equation:

$$p(t) = \frac{\sum_{i=0}^{n} w_i \cdot p_i \cdot B_i^n(t)}{\sum_{i=0}^{n} w_i \cdot B_i^n(t)} \quad for\ t \in (0,1) \tag{1}$$

where:
p_i is the i-th control point,
W_i is the weight coefficient of the i-th control point, determining the influence of each of the control points on the curve,
B_i^n is the i-th degree Bernstein polynomial expressed by the formula:

$$B_i^n(t) = \begin{cases} \binom{n}{i} t^i (1-t)^{n-i} & for\ i = 0, \dots, n \\ 0 & for\ i < 0, i > n \end{cases} \tag{2}$$

Legal regulations

According to the SOLAS convention, the number and placement of hydrants should be such that at least two water streams, not originating from the same hydrant, one of which should be supplied by a single length of hose, can reach any part of the ship accessible to passengers or crew during ship navigation. Fire hoses should be long enough to cover any compartment by a water stream where their use may be required. Fire hoses should be at least 10 meters long, but no more than: 15 meters in engine rooms, 20 meters in other compartments and on open decks, and 25 meters on open decks of ships with a maximum width exceeding 30 meters.

In the developed system, the range of the fire hose creates a circle with a radius equal to the length of the hose defined in the SOLAS convention. It should be noted that this is a certain simplification, as the actual range of the fire hose may be slightly smaller in the case of complicated compartment configuration and the need for its bends. In the developed system, the hose length can be easily defined and adjusted to any additional constraints or requirements, e.g., imposed by state authority regulations, which is illustrated in Figure 2.

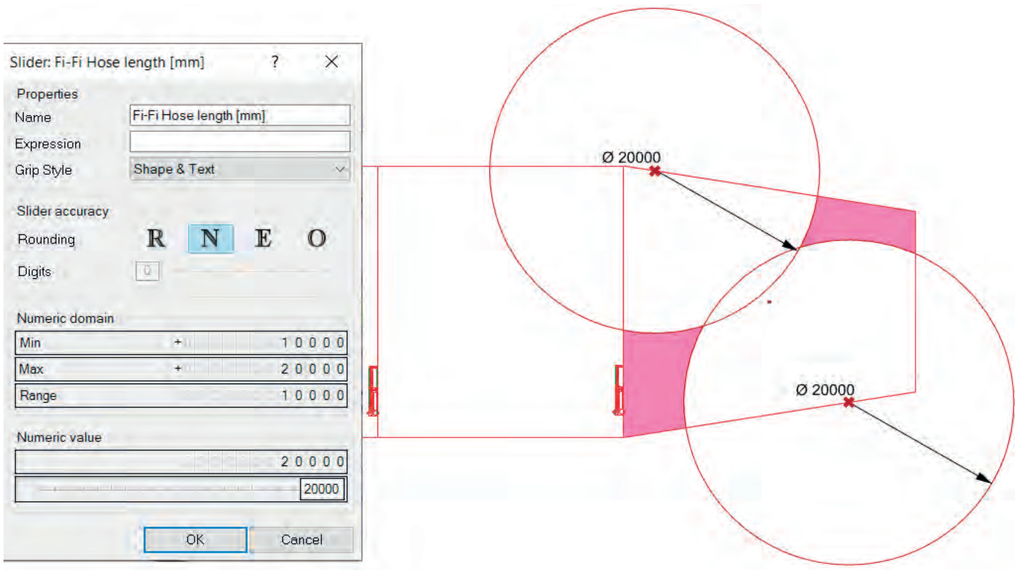

Fig. 2. Possible parameterization options for the length of a fire hose according to the SOLAS convention

Significance of compartments

The SOLAS Convention has distinguished different classes of bulkheads based on their ability to withstand fire and smoke on the endangered side. These bulkheads are classified as A, B, and C classes and create thermal and structural boundaries on the vessel. Spaces are separated by the appropriate class of bulkhead (either bulkheads or decks) depending on the level of fire risk. Details specifying the fire sealing standards to be applied to specific bulkheads between neighboring compartments can be found in SOLAS II-2 Part C. The following types of spaces are most relevant in terms of fire hydrant distribution:

- machinery space category A, which is classically considered the area with the highest fire risk and requires the highest safety standards – fire hoses with a length of not less than 10 [m] and not more than 15 [m] must be used,
- machinery spaces, which include both the previously mentioned machinery space category A and other spaces containing propulsion machinery, boilers, fuel units, steam and internal combustion engines, generators, and main electrical equipment, etc. – fire hoses with a length of not less than 10 [m] and not more than 15 [m] must be used,
- areas on the ship where the probability of fire is slight are usually considered places where the risk of fire is small and negligible, usually with limited human such as voids, cofferdams, tanks, chain lockers, fixed gas fire-extinguishing system storage rooms, and others – in this given case, there is no need to install a fire hydrant,
- other spaces and open decks – fire hoses with a length of not less than 10 [m] and not more than 20 [m] must be used.

In the developed system, each type of space is assigned to a specific drawing layer (Fig. 3). The number of layers and their assigned properties can be changed as desired. For example, machinery spaces of category A can be assigned to layer 1, while other machinery spaces can be assigned to layer 2. Spaces with low fire risk, such as voids or cofferdams, can be assigned to layer 3. Other spaces and open decks, where fire hoses are required, can be assigned to layer 4. By using different layers, the design team can easily distinguish between different types of rooms and apply different design criteria or safety measures accordingly.

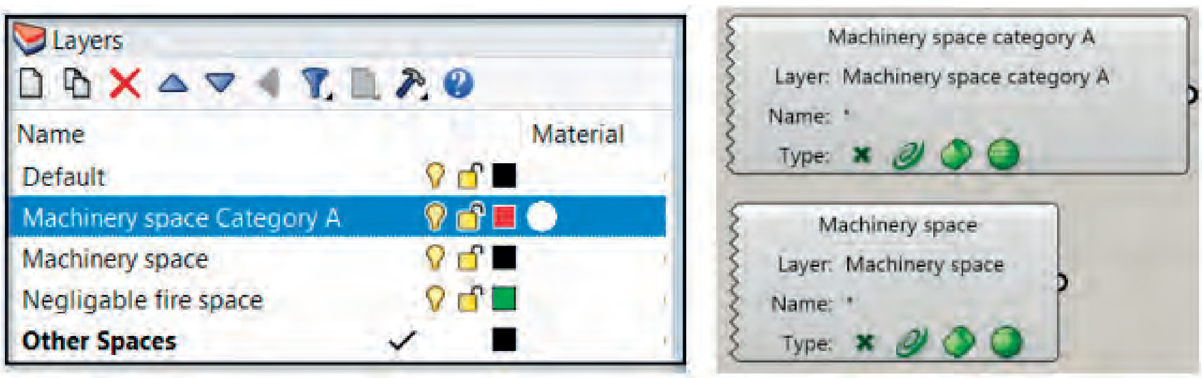

Fig. 3. Possible parameterization options for the length of a fire hose according to the SOLAS convention

Objective functions

In the case of optimizing the placement of fire hydrants, the objective function determines how well our system works from the perspective of the optimization criterion(s) chosen by the designers. They can prioritize each of these criteria, and then, the objective function will determine how well we meet these requirements. In the case of a few criteria selected, the objective function can be defined as a weighted sum of each criterion, where the weights are set by the designer.

In ship design practice, a number of alternative criteria for the rational placement of fire hydrants on shipboards can be found. Here are the most commonly encountered:

- maximization of the coverage of extinguished surfaces,
- minimization of power consumption to increase fire safety system efficiency,
- minimization of risk by optimal placement of hydrants in areas most vulnerable to fire,
- maximization of accessibility to hydrants,
- minimization of response time by optimal placement of hydrants that allow for fast and effective intervention,
- minimization of the number of hydrants to minimize costs and maintain system simplicity,
- minimization of response time, which assumes minimizing the time needed to reach the most fire-prone areas on the ship,
- minimization of the distance between hydrants to minimize costs.

It is obvious that the choice of criterion/criteria depends on many factors. The most important of these include the type of ship (cargo, passenger, etc.) and the size associated with it, as well as the preferences of the ship's owner or future ship operator.

In the developed system, the objective functions can be defined by four criteria, which are most preferred by the ship contractor, namely:

- the criterion of maximum coverage of the extinguished surface (or alternatively: minimizing the areas without reach of fire hoses),
- the criterion of minimal overlap of water streams,
- the criterion of minimum power demand for fire pump engines,
- the criterion of minimum distance from evacuation exits.

In all the cases of the objective function considered next, the design variables are the coordinates of the location of the hydrants *x* and *y*, which are distributed in the two-dimensional space determined by space conistraints, considering their position close to a closed curve forming the outline of the selected room. These coordinates are the centers of circles, whose radii are the lengths of fire hoses determined by the restrictions presented in the legal regulations and significance of compartments, respectively.

In addition, the designer arbitrarily determines the number of hydrants placed on each deck or room of the ship. At the current stage of system development, the determination of the number of hydrants is done iteratively, i.e., the designer takes any number of hydrants and then runs simulations looking for the best match. If a solution is found – the number and distribution of hydrants are stored. Then, another simulation is carried out reducing the number of hydrants in the next step (manually) until the *n-th* simulation finds a satisfactory solution.

In the case of the first criterion, which is the maximization of the coverage area of fire extinguishing, the area of such a zone depends on: the number of hydrants, the location of hydrants, the length of fire hoses connected to hydrants, and the configuration (shape) of the extinguished room. The measure of effectiveness in this case is to have a distribution of hydrants that ensures the most efficient fire protection. This can be expressed by the degree of coverage of the extinguished area, also defined as the area within the range of the fire hose. The larger the uncovered area, where there is no range of action of the fire hoses, the lower the effectiveness of the fire protection system.

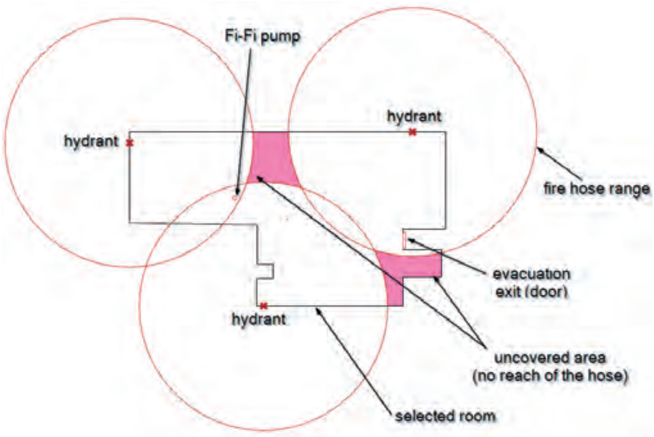

Fig. 4. Layout of hydrants with a demonstration of hose coverage in a selected room, taking into account the location of the fire pump, doors, and the area not covered by the installation

One possible way to present the distribution of hydrants and the coverage area of hoses in a selected room is to use a floor plan or a map of the room (Fig. 4). The hydrants can be marked with symbols or icons, and the coverage area of hoses can be presented as circles around each hydrant, showing the maximum distance the hoses can reach from each hydrant. The pump room and other important features such as doors and windows can also be marked on the floor plan. To illustrate the effectiveness of the fire protection system, the areas that are not covered by the hoses can be highlighted, indicating the potential areas where the fire could spread if the system is not sufficient. This can help to identify any potential weaknesses in the fire protection system and inform the decision-making process in optimizing the placement of hydrants and fire hoses for maximum coverage.

The developed system utilizes an algorithm that employs the region union and region difference functions to compare specified surfaces, calculate their difference, and determine their total area. The region union function is used to combine geometric regions represented as sets of points in two-dimensional space that can take different shapes, e.g., polygons. This function performs the operation of sum of sets, which can be mathematically described as:

$R_1 \cup R_2 \cup ... \cup R_n = \{x : x \in R_1 \ or \ x \in R_2 ... \text{ or } x \in R_n\}$. This means that the sum of the sets $R_1 \cup R \cup ... \cup R_n$ contains those elements x that belong to the set R_1 ($x \in R_1$) or belong to the set R_2 ($x \in R2$) ... or belong to the set R_n ($x \in R_n$). The set of points of the resultant area A is equal to the sum of the individual sets $R_1, R_2,...,R_n$ and $A = R_1 \cup R_2 \cup ... \cup R_n$ (n is the number of areas). Any point that belongs to at least one of these areas will also belong to the resultant area A. When the region union function runs, the program checks which areas intersect and then combines them to form a unified area. If the regions have common boundaries, these boundaries will be included in the resulting union region. The region difference function is used to calculate the difference between two geometric areas. It creates the resulting region, which is the result of subtracting one region from the other. The mathematical description of the function is as follows: $A = R_1 - R_2$. This means that the difference of the sets R_1 and R_2 consists of those elements x that belong to the set R_1 ($x \in R_1$) but do not belong to the set R_2 ($x \notin R2$). Mathematically, this means that the resulting area A is equal to the difference between the set of points R_1 and the set of points R_2. A point belonging to R_1 and not belonging to R_2 will also belong to the resulting area A. The goal of the algorithm is to find the smallest total area A_a of the zones not covered by the range of the hoses. Then, the objective function takes the following form:

$$f_1(x) = \sum_{a=1}^{n} A_a(x) \quad (3)$$

where:
$A_a(x)$ is the area of the region not covered by the reach of the fire hose.

Additionally, for better visualization, the custom preview function was used, which allows the user to quickly determine the areas not covered by the range of the fire protection system.

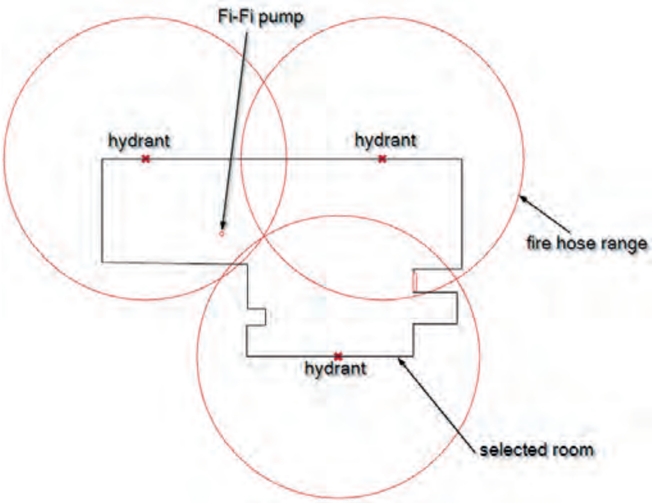

Fig. 5. Simulation results for criterion – maximization of the coverage area of extinguished surfaces

Figure 5 shows the results of a simulation in which the positions of three hydrants were changed. The algorithm placed the hydrants in such a way that the areas not covered by the hydrant range were as small as possible. In the case of the second criterion, which is the minimization of overlap of water streams, the algorithm works on the same principle as the one adopted in the first criterion. The difference, however, is that the areas protected by the fire hoses are compared, taking into account their common parts, i.e., overlapping areas B_a. In this criterion, the aim is to minimize the degree of mutual coverage of the hose ranges of their operation.

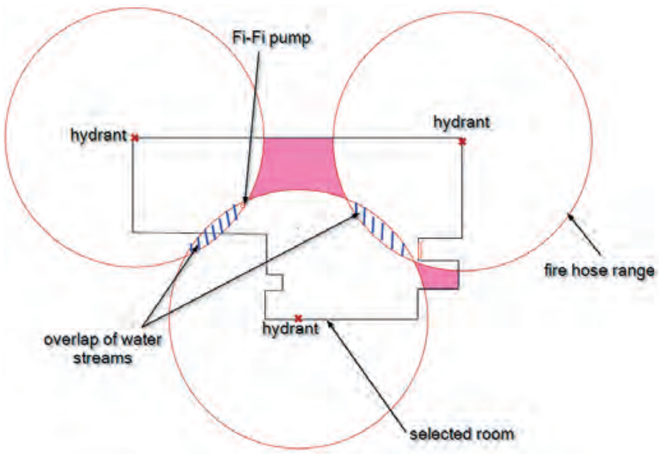

Fig. 6. Simulation results for criterion – minimization of overlap of water streams

In this case, the objective function takes the following form:

$$f_2(x) = \sum_{a=1}^{n} B_a(x) \quad (4)$$

where:
$B_a(x)$ is the area of the region of overlap of water streams.

Simulations were carried out by changing the positions of three hydrants. The algorithm placed the hydrants in such a way that the overlapping areas of the streams were as small as possible (Fig. 6).

The third criterion, which is the minimization of the power demand of the fire pump, depends on many factors, such as the length of the fire protection installation, the number of hydrants required for simultaneous supply, and the pressure of the fire extinguishing agent required in the fire protection installation. A longer pipeline contributes to greater pressure loss in the fire protection installation. This means that to achieve the required flow at the end point of the installation, the fire pump must generate higher pressure compared to a shorter pipeline. The pressure drop in the pipeline is proportional to the length of the pipeline and the flow velocity. The simplified mathematical equation of Darcy-Weisbach defines, among other things, the relationship between the length of the pipeline in a hydraulic system and the pressure drop in the system as follows [22]:

$$\Delta p = \lambda \frac{L}{D} \frac{\rho u^2}{2} \tag{5}$$

where:
Δp is the pressure drop [Pa],
λ is the resistance coefficient dependent, among others, on Reynolds number and relative roughness of the pipe [-],
L is the length of the pipeline [m],
D is the diameter of the pipeline [m],
ρ is the density of the fluid [kg/m^3],
u is the velocity of the fluid [m/s].

It should be noted that the power of the pump is directly proportional to the flow rate and pressure drop and inversely proportional to hydraulic efficiency. This means that there is a linear relationship between the length of the installation and the demand for the driving power of the fire pump. The power of the fire pump can be expressed by the following equation:

$$P = \frac{Q \cdot \Delta p}{(\eta \cdot \rho)} \tag{6}$$

where:
P is the power of the pump [W],
Q is the pump flow rate [m^3/s],
η is the hydraulic efficiency of the pump [-].

The solution to the proposed optimization criterion will, therefore, be to find the minimum of the objective function, which is the distance between each fire hydrant and the fire pump, with a previously defined location on the ship:

$$f_3(x) = \sum_{a=1}^{n} D_{a,p}(x) \tag{7}$$

and:
$D_{a,p} = \sqrt{|x_a - x_p|^2 + |y_a - y_p|^2}$ for a planar system (XY),
$D_{a,p} = \sqrt{|x_a - x_p|^2 + |y_a - y_p|^2 + |z_a - z_p|^2}$ for a spatial system (XYZ),

where:
x_a, x_p, y_a, y_p, z_a, z_p are the geometric coordinates of hydrant "a" and pump "p",
$D_{a,p}$ is the shortest distance between hydrant "*a*" and pump "*p*", *n* is the number of hydrants.

a) b)

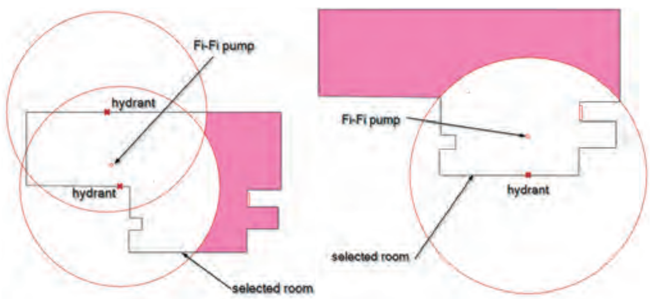

Fig. 7. Simulation results for criterion – minimization of the power demand of the fire pump: a) with two hydrants, b) with one hydrant

Figure 7 shows the results of a simulation that illustrates the power requirements for a given area depending on the number of hydrants installed.

In the case of the fourth criterion, i.e., the minimum distance from evacuation exits, the algorithm works in a similar way as described in criterion 3, with the difference that it takes into account the distance not from the fire pump, but from the evacuation exit. The objective function then takes the following form:

$$f_4(x) = \sum_{a=1}^{n} D_{a,we}(x) \tag{8}$$

and:
$D_{a,we} = \sqrt{|x_a - x_{we}|^2 + |y_a - y_{we}|^2}$ – for a planar system (XY),
$D_{a,we} = \sqrt{|x_a - x_{we}|^2 + |y_a - y_{we}|^2 + |z_a - z_{we}|^2}$ – for a spatial system (XYZ),

where:
x_a, x_{we}, y_a, y_{we}, z_a, z_{we}, are the geometric coordinates of hydrant "*a*" and evacuation exit "*we*",
$D_{a,we}$ is the shortest distance between hydrant "*a*" and evacuation exit "*we*".

a) b)

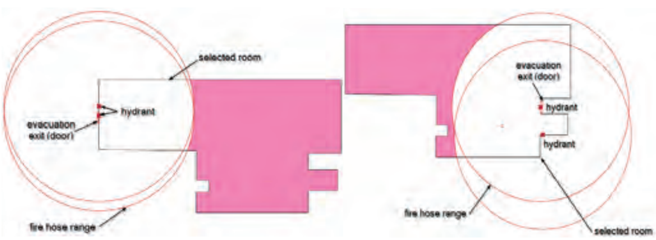

Fig. 8 Simulation results for criterion – minimum distance from evacuation exits: a) the evacuation exit is on the left side of the room, b) the evacuation exit is on the right side of the room

Two simulations were conducted, changing the location of the evacuation exits (Fig. 8). In Figure 8a, the evacuation exit is on the left side of the room, while in Figure 8b, it is on the right. The simulation parameters as well as the number of hydrants in both cases are the same. The algorithm placed the hydrants in the vicinity of the evacuation exits, which confirms the fulfilled assumption of placing the hydrants as close to them as possible.

It is obvious that the designer would like to take into account several of the mentioned optimization criteria simultaneously. In this case, these criteria should be merged into one representative objective function. There are many known methods for reducing classical multi-criteria optimization to single-criteria ones, such as the hierarchical optimization method, the method of constrained criteria, and the global criterion method.

In our approach, a relatively simple and often used weighted criteria method was applied. This method combines two criteria into a single objective function using a weighted sum. The substitute objective function would be a linear combination of the two criteria, where each criterion is multiplied by a weight factor that reflects its relative importance. The weights can be determined by the designer based on recognized priorities, for example, the type of a ship or ship-owner preference. In our approach, the total value of the substitute objective function, which represents the established criteria, should be minimized:

$$F_{sub}(x) = min \sum_{i=1}^{k} w_i \cdot f_i(x) \quad (9)$$

where:
k is the number of objective functions,
$f_i(x)$ is the value of the i-th objective function,
w_i are the weights of the objective function such that $w \in [0,1]$ and $\sum_{i=1}^{k} w_i = 1$.

As a rule, the substitute objective function can be subject to different criteria and may require normalization under certain circumstances. Normalization is the process of scaling or transforming data to bring it into a specific range or format. This is particularly important when dealing with multiple objectives or when the objective function has different units or magnitudes. This can be done using various techniques, but in this study, min-max normalization was applied. A detailed description of such a method utilized by the authors can be found in [23].

Weights are assigned to each of the objective functions, reflecting their relative importance to the overall evaluation of the solution. Various methods can be used to determine these weights, such as the analytical hierarchical process (AHP) method. Once the weights for each criterion have been determined, the weighted sum of the criteria for each solution was calculated, allowing the results to be compared on the basis of a single indicator and ultimately selecting the solution with the highest value.

The result of one such two-criteria simulation: maximizing the coverage of extinguished surfaces and minimizing the distance to evacuation exits is presented on Figure 9.

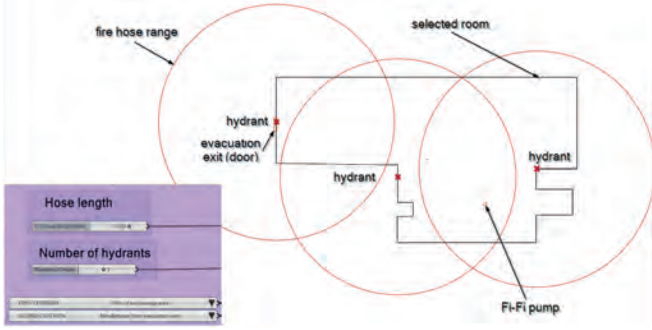

Fig. 9. Simulation results for two criteria – maximizing the coverage of extinguished surfaces and minimizing the distance to evacuation exits

It was assumed that the most relevant of the four criteria considered was the one that affects the degree of coverage of the room. The simulation showed that the extinguished surfaces were fully covered and the distance from the emergency exit also appeared to be optimal.

RESULTS AND DISCUSSION

As previously mentioned, the main goal of the developed system, i.e., the computer-aided system for the layout of fire hydrants on board designed vessels, is to reduce the designer's working time. It is difficult to estimate the working time of a designer who places hydrants on a ship's board using the classical method. On the one hand, the designer's working time depends on their knowledge, skills, and experience, for example expressing itself through routines, such as storing subject-specific regulations in his memory. On the other hand, this time depends on the type of ship and the constraints that exist in it, such as the scope of regulations that depend on the type of ship. In addition, designers may also be involved in other design work.

From the experience of one of the co-authors of this study as a lead engineer in a ship design office, the time required to complete the arrangement drawing is about 30 to 40 hours of design work. Assuming that nearly half of the time is taken up by the analysis of the placement of hydrants, and the rest is the pure drawing part, it is safe to say that potentially up to a dozen hours of work can be saved.

To evaluate the effectiveness of the developed system three different types of ships were considered. On board considered ships, hydrants were placed using the classical manual method and their layout was compared to the layout proposed by the developed system. These were ships of different types, namely:
- Fishery Researche Vessel (Fig. 10),
- Wind Platform Vessel (Fig. 11),
- Multi Role Auxiliay Vessel (Fig. 12).

It was assumed that the classical method of hydrant placement meets all the requirements (constraints) that were set before the designer. Figures 10, 11, and 12 show top view projections of selected rooms on the mentioned ships. In this case, specific details of the designed vessels were deliberately not provided to protect the intellectual property of ship-owners and the design office. Arrangements of individual technical rooms were modified, but the location and distribution of fire protection equipment remained unchanged. The placement of fire hydrants obtained using the classical method is marked using markers in the form of red circles, whereas the placement obtained using the developed system was overlaid on each projection using markers in the form of blue crosses.

In this case study, the values of individual weights of the objective function were determined based on one of the authors' experiences working in a ship design office, taking into account the type of vessel being designed. The example values of weights for individual partial objective functions have been presented in the captions of Figures 10, 11, and 12.

In particular, when formulating the substitute objective function, the following criteria were taken into account: maximizing the coverage of extinguished surfaces and minimizing the distance to evacuation exits for all considered vessels, i.e., the Fishery Research Vessel (Fig. 10), the Wind Platform Vessel (Fig. 11), and the Multi Role Auxiliary Vessel (Fig. 12).

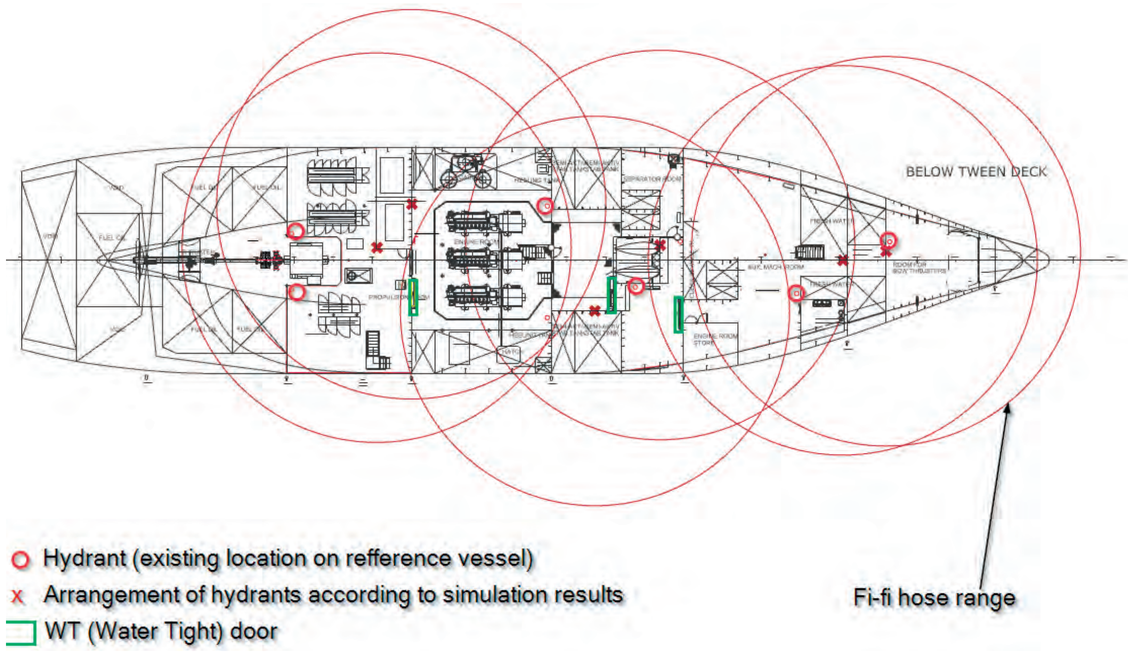

Fig. 10. Comparison of the actual arrangement of fire hydrants on a fishing vessel with their simulated distribution based on two selected criteria: maximizing the degree of coverage of extinguished areas and minimizing the distance from evacuation exits with weights w_1 = 0,6 and w_4 = 0,4 respectively

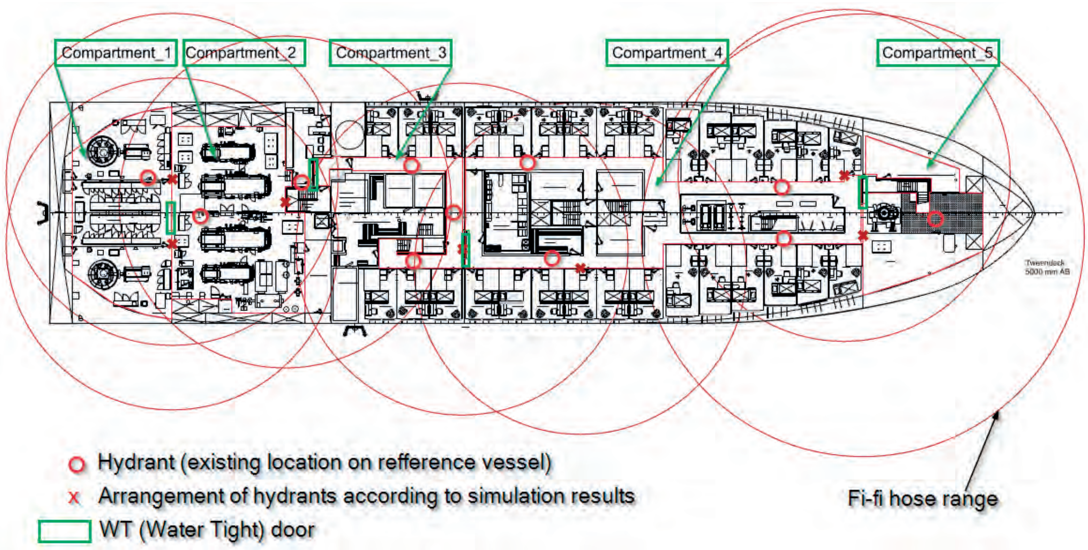

Fig. 11 Comparison of the actual arrangement of fire hydrants on a vessel servicing wind platforms with their simulated distribution based on two selected criteria: maximizing the degree of coverage of extinguished areas and minimizing the distance from evacuation exits with weights w_1 = 0,6 and w_4 = 0,4 respectively

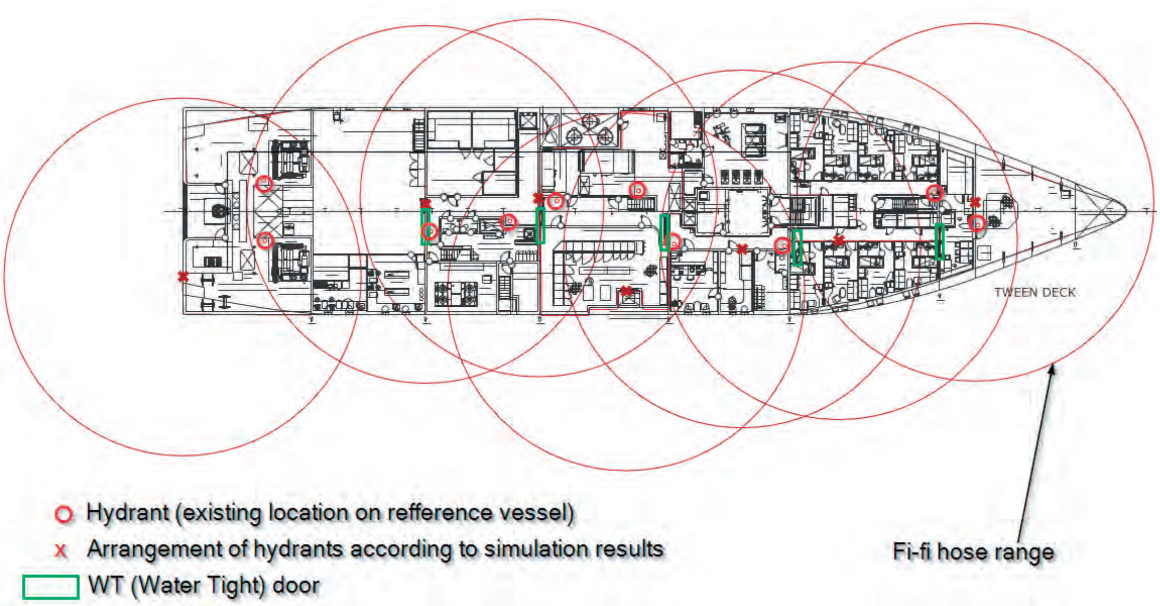

Fig. 12. Comparison of the actual arrangement of fire hydrants on a multi-purpose support vessel with their simulated distribution based on two selected criteria: maximizing the degree of coverage of extinguished areas and minimizing the distance from evacuation exits with weights w_1 = 0,6 and w_4 = 0,4 respectively

Based on the comparative analysis of the individual solutions regarding the arrangement of fire hydrants on the decks of various ships, the following can be concluded:

- both the layout of the fire hydrants obtained using the classical method and the one obtained using the developed system meet all the imposed requirements (constraints),
- the layout of the fire hydrants obtained using the developed system enables faster access by the firefighting team to the hydrants, thanks to the criterion of minimizing the distance from evacuation exits as a component of the substitute objective function, which significantly increases the level of protection against fire hazards on the ship.

Considering that the main goal of the developed system is to reduce the workload of the designer, the above-mentioned benefits are an additional but very significant element of the feasibility of the developed system. So, the basic question remains – how quickly can a solution related to the arrangement of fire hydrants be obtained using the developed system?

In order to answer the question above, a series of simulations were conducted using a computer with typical parameters for computers used in ship design offices. The results of the simulation duration for the Wind Platform Vessel are shown in Table 1. Similar simulations were conducted for the remaining three ships. Using the PSO algorithm, the number of iterations, speed, and number of particles (individuals) in the search space were varied. The type of analyzed vessel seemingly had an impact on the algorithm's speed, but this was solely due to the size of the graphic file that served as the source of the analyzed unit's general plan. The size of the graphic file depends on various factors, such as the number of graphic elements, resolution, number of layers, styles, and blocks contained in the file. The more graphic elements and details, the larger the file size, and consequently, the computer's computational power required for processing and displaying graphics in real-time becomes greater.

Tab. 1. Simulation duration for the Wind Platform Vessel, used for wind platform servicing, based on the criteria of maximizing the coverage degree of extinguished surfaces and minimizing the distance to evacuation exits

	number of hydrants					
	9	**12**	**15**	**18**	**25**	**50**
Max. speed = 0.1 Iterations: 20	11 [s]	11 [s]	11 [s]	12[s]	14 [s]	15 [s]
Max. speed = 0.2 Iterations: 20	11 [s]	11 [s]	11 [s]	12[s]	14 [s]	15 [s]
Max. speed =` 0.3 Iterations: 20	11 [s]	11 [s]	12 [s]	12[s]	14 [s]	15 [s]
Max. speed = 0.5 Iterations: 20	11 [s]	11 [s]	11 [s]	12[s]	13 [s]	15 [s]
Max. speed = 1 Iterations: 20	11 [s]	11 [s]	11 [s]	12[s]	14 [s]	15 [s]
Max. speed = 0.1 Iterations: 40	21 [s]	22 [s]	22 [s]	22 [s]	24 [s]	29 [s]
Max. speed = 0.2 Iterations: 40	21 [s]	21 [s]	22 [s]	23 [s]	24 [s]	28 [s]
Max. speed = 0.3 Iterations: 40	21 [s]	22 [s]	22 [s]	23 [s]	24 [s]	28 [s]
Max. speed = 0.5 Iterations: 40	21 [s]	21 [s]	22 [s]	22 [s]	24 [s]	29 [s]
Max. speed = 1 Iterations: 40	21 [s]	22 [s]	22 [s]	22 [s]	24 [s]	29 [s]

Changing the algorithm parameter of particle speed in the search space did not affect the algorithm's runtime. Increasing the number of hydrants used in the simulation (from 9 up to a maximum of 50) significantly increased the algorithm's runtime. The swarm size, determined by the number of particles (individuals) included in it, also had a significant impact on the algorithm's speed. In the extreme case, the time required to perform several dozen iterations was about 3 minutes, which compared to the time spent on placing hydrants in a classical way, seems to be an undeniable advantage of the applied method.

CONCLUSIONS

The proposed method is an attempt to support ship system designers using one of the methods of artificial intelligence, namely the PSO algorithm, which simulates the behavior of a particle swarm moving in a search space for the best solution to a problem, such as placement of fire hydrants on a ship's boards. The most important conclusions can be formulated as follows:

- the proposed method reduces the time-consuming process of firefighting equipment layout on a ship's boards while also easily implementing the general plan of the designed vessel in the Rhino environment,
- the use of metaheuristic optimization algorithms such as PSO can provide solutions in a relatively short time, ranging from a few seconds to several minutes, which is significantly shorter than the time required for manual design of hydrant placement, making the developed system much more efficient,
- as a result of optimal placement of fire hydrants based on selected criteria, additional benefits arise in the form of increased safety (faster access by firefighting teams to hydrants) and resource economy (reduced amount of water required to extinguish a fire or decreased electricity expenditure to power fire pumps).

Further research

The developed system is based on four different criteria for the optimal placement of fire hydrants; however, its further development seems reasonable. Directions for further research in the field of hydrant placement system using the PSO algorithm may include:

- optimization of the process of finding the minimum number of hydrants to reduce the cost of the ship's fire safety system while ensuring fire safety requirements,
- supplementing the developed system with additional optimization criteria depending on the specificity of the designed vessels, such as installation costs,
- using other metaheuristic optimization algorithms, such as genetic algorithms or ant colony algorithms, to compare the effectiveness of different algorithms in the context of hydrant placement.

REFERENCES

1. R. J. Cant and C. S. Langensiepen, "Methods for Automated Object Placement in Virtual Scenes," in *11th International Conference on Computer Modelling and Simulation, UKSim 2009*, 2009. doi: 10.1109/UKSIM.2009.69.

2. K. Xu, J. Stewart, and E. Fiume, "Constraint-based automatic placement for scene composition," in *Proceedings – Graphics Interface*, 2002.

3. R. Z. Farahani, N. Asgari, N. Heidari, M. Hosseininia, and M. Goh, "Covering problems in facility location: A review," *Computers and Industrial Engineering*, vol. 62, no. 1. 2012. doi: 10.1016/j.cie.2011.08.020.

4. S. Dantrakul, C. Likasiri, and R. Pongvuthithum, "Applied p-median and p-center algorithms for facility location problems," *Expert Syst Appl*, vol. 41, no. 8, 2014, doi: 10.1016/j.eswa.2013.11.046.

5. B. Zhang, J. Peng, and S. Li, "Covering location problem of emergency service facilities in an uncertain environment," *Appl Math Model*, vol. 51, 2017, doi: 10.1016/j.apm.2017.06.043.

6. S. Y. Kim, B. Y. Moon, and S. C. Shin, "Evaluation criterion of machinery arrangement design in a ship engine room," *Journal of Ship Production*, vol. 25, no. 3, 2009, doi: 10.5957/jsp.2009.25.3.117.

7. P. Gualeni, F. Perrera, M. Raimondo, and T. Vairo, "Accessibility for maintenance in the engine room: development and application of a prediction tool for operational costs estimation," *Ship Technology Research*, 2022, doi: 10.1080/09377255.2021.2020949.

8. J. K. Lee, K. H. Lee, N. S. Park, Y. U. Jang, J. Y. Bae, and H. S. Shim, "Integration of knowledge-base and CAD system for the machinery layout design of ships," in *Proceedings of the ASME Design Engineering Technical Conference*, 1996. doi: 10.1115/96-DETC/DAC-1070.

9. A. R. Chaudhuri and U. P. Thakur, "Design criteria of piping system for ships," *Journal of the Institution of Engineers (India), Part MR: Marine Engineering Division*, vol. 81, no. 1, 2000.

10. B. C. Lee, Y. Choi, and H. Chung, "Firefighting equipment arrangement optimization for an offshore platform considering travel distances," *J Mar Sci Eng*, vol. 9, no. 5, 2021, doi: 10.3390/jmse9050503.

11. X. Liu, B. Sun, Z. D. Xu, and X. Liu, "An adaptive Particle Swarm Optimization algorithm for fire source identification of the utility tunnel fire," *Fire Saf J*, vol. 126, 2021, doi: 10.1016/j.firesaf.2021.103486.

12. K. S. Lee, K. J. Han, and J. W. Lee, "Feasibility study on parametric optimization of daylighting in building shading design," *Sustainability (Switzerland)*, vol. 8, no. 12, 2016, doi: 10.3390/su8121220.

13. D. Rutten, "Galapagos: On the logic and limitations of generic solvers," *Architectural Design*, vol. 83, no. 2, 2013, doi: 10.1002/ad.1568.

14. C. Waibel, T. Wortmann, R. Evins, and J. Carmeliet, "Building energy optimization: An extensive benchmark of global search algorithms," *Energy Build*, vol. 187, 2019, doi: 10.1016/j.enbuild.2019.01.048.

15. J. M. Cichocka, A. Migalska, W. N. Browne, and E. Rodriguez, "SILVEREYE – The implementation of particle swarm optimization algorithm in a design optimization tool," in *Communications in Computer and Information Science*, 2017. doi: 10.1007/978-981-10-5197-5_9.

16. T. Wortmann, "Opossum – Introducing and Evaluating a Model-based Optimization Tool for Grasshopper," in *Proceedings of the 22nd Conference on Computer Aided Architectural Design Research in Asia (CAADRIA)*, 2022. doi: 10.52842/conf.caadria.2017.283.

17. I. Anton and D. TĂnase, "Informed Geometries. Parametric Modelling and Energy Analysis in Early Stages of Design," in *Energy Procedia*, 2016. doi: 10.1016/j.egypro.2015.12.269.

18. J. C. Lagarias, J. A. Reeds, M. H. Wright, and P. E. Wright, "Convergence properties of the Nelder-Mead simplex method in low dimensions," *SIAM Journal on Optimization*, vol. 9, no. 1, 1998, doi: 10.1137/S1052623496303470.

19. J. Kennedy and R. Eberhart, "Particle Swarm Optimization, Proceedings of IEEE International Conference on Neural Networks Vol. IV: 1942–1948.," Neural Networks.

20. L. M. Hiot *et al.*, *Handbook of Swarm Intelligence*, vol. 8. 2010.

21. S. Bhattacharyya and P. Dutta, *Handbook of research on swarm intelligence in engineering*. 2015. doi: 10.4018/978-1-4666-8291-7.

22. G. O. Brown, "The history of the Darcy-Weisbach equation for pipe flow resistance," in *Proceedings of the Environmental and Water Resources History*, 2002. doi: 10.1061/40650(2003)4.

23. K. Rudzki, P. Gomulka, and A. T. Hoang, "Optimization Model to Manage Ship Fuel Consumption and Navigation Time," *Polish Maritime Research*, vol. 29, no. 3, 2022, doi: 10.2478/pomr-2022-0034.