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A review of joining methods of particle-reinforced aluminum metal matrix composites

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JEL Classification: L61, O14, O32, Y30

Abstract

Composite materials based on aluminum alloys are widely used in the automotive, aviation, and shipbuilding industries. The presence of the ceramic reinforcing phase significantly changes the mechanical properties of aluminum alloys. By appropriate selection of the components that make up the composite materials, it is possible to create mechanical properties that are not possible with unreinforced alloys. Structural elements made of these types of materials often require joining in welding processes. This article presents a general description of methods of joining composites based on aluminum alloys reinforced with ceramic particles, which have been divided into three groups: fusion welding method, solid state welding, and different methods. The individual methods highlighted how the presence of a reinforcing phase affects the welding process. Difficulties mainly arise from the disintegration of the ceramic phase by the concentrated heat source during welding processes, the formation of harmful surface products, and the lack of wettability of the ceramic particles through the metal matrix. The joints obtained vary in terms of structure, ceramic particle distribution, and mechanical properties with respect to the values characterizing the native material. From an analysis of the individual methods, it appears that solid-phase methods have the smallest effect on the degradation of ceramic particles, but have limitations in terms of the shape and size of the materials to be joined. In fusion welding methods, the degradation of the reinforcement phase by the concentrate heat source is greatest. To a certain extent, this can be compensated for by the choice of an additive material, which consists of elements that improve the wettability of the reinforcement phase through the metal matrix and form strengthening separations.

Introduction

Composite materials combine the properties of metals and non-metals. The undoubted advantage of these types of materials is the ability to create their individual mechanical properties. Through the appropriate selection of components included in the composite and control of its production process, structural elements are obtained with parameters impossible to achieve using traditional materials (Aghajanian et al., 1993; Sharma, Mahant & Upadhyay, 2020; Kumar et al., 2021).

Most often, alloys of aluminum, titanium, magnesium, copper, nickel, and steel are used as the matrix in metal-ceramic composites, and carbides (SiC, TaC, B_4C, and TiC), borides (TaB_2, ZrB_2, TiB_2, and WB), nitrides (TaN, ZrN, Si_3N_4, and TiN), and oxides (Al_2O_3, ZrO_2, ThO_2, and BeO) (Eagar, Baeslack & Kapoor, 1994; Kaczmar, Pietrzak & Włosiska, 2000) are used as reinforcement. Due to the advantages of aluminum alloys, they are widely used as a matrix in metal composite materials. These are mainly alloys intended for heat treatment from the 2000, 6000, 7000, and 8000 series and cast on an aluminum matrix reinforced with particles of Al_2O_3, SiC, or B_4C. Therefore, for composites based on aluminum alloys reinforced with a ceramic phase, there are no developed industry standards as there are for non-reinforced alloys. This is due to the fact that, in most cases, composites are produced using different processes and as unit series. In addition, the mechanical properties described in the literature for manufactured composites, with a similar chemical composition of the metal matrix and weight content of the ceramic phase, differ in values. It is not insignificant that these tests also differ in testing methods, sample size, and structural homogeneity of the composites (Parikh et al., 2023).

While the methods of producing metal composites are developing dynamically, in many cases, the use of these types of materials is limited by problems related to the lack of effective methods of combining them (Maurya, Kumar & Bajpai, 2018). Aluminum-ceramic composites are referred to as materials that are difficult to bond. When using traditional bonding methods, especially welding methods, in most cases, the mechanical properties of the joint are reduced, sometimes even to values characteristic of the matrix material. This is mainly due to two factors. Firstly, from the physical, mechanical, and chemical interaction of the metallic matrix and the ceramic reinforcing phase at elevated temperatures. Secondly, the use of additional materials that do not contain reinforcing particles during bonding. In many cases, especially in welding processes, there is significant degradation of the reinforcing phase or the formation of undesirable surface reaction products at the interface between the metal matrix and the ceramic reinforcing phase, which significantly affects the quality and mechanical properties of the obtained joint (Irving, 1991).

This article contains a summary and condensed review of attempts presented in the literature to join aluminum alloy matrix composites reinforced with ceramic particles using welding methods. The results of the studies on the influence of welding processes on the structure are presented, in particular on the change in the distribution of the ceramic reinforcing phase, the degree of its degradation, the tendency for surface reactions to occur at the metal matrix/ceramic reinforcing phase interface, and the influence of these factors on the mechanical properties of the joints obtained.

Joining methods of aluminum-based metal matrix composites

The Polish Standard PN-84/M-69001 divides joining methods that produce a connection with metallic continuity (bonding methods) into welding, pressure welding, and soldering. However, the systematics of methods for joining metal-ceramic composites presented in the world literature divides them into three basic groups: welding, pressure welding, and other methods. The latter are shown in Figure 1 (USA, Department of Defense, 1999).

Due to the small amount of available Polish literature on this subject, it was decided to present the problems of bonding composites based on aluminum alloys reinforced with ceramic particles according to the systematics presented in the literature, but considering the definitions contained in the cited Polish standard.

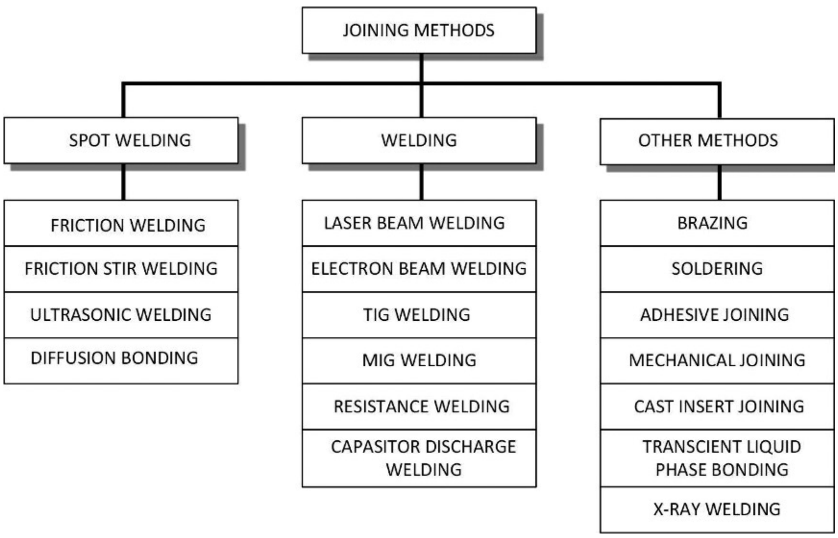

Figure 1. Classification of selected joining methods for metal matrix composites (performed on the basis of the Composite Materials Handbook, 1999)

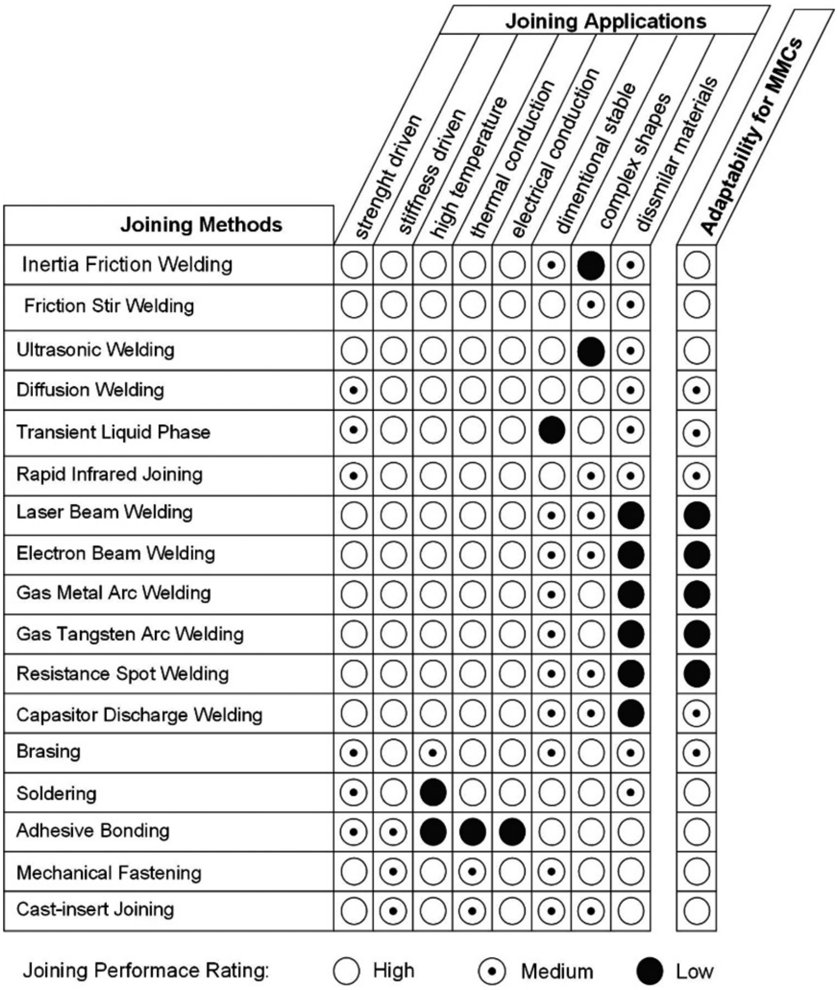

Figure 2. Qualitative rating for joining adaptability, applications, and selection (Chernyshov, Panichenko & Chernyshova, 2003)

As mentioned earlier, the mechanical properties of aluminum alloy matrix composites reinforced with ceramic particles can be created not only by the chemical composition of the matrix alloy, but also by the size, type, and weight content of the ceramic reinforcing particles. The manufacturing methods are also not fully standardized. As a result, the mechanical properties of composites with a particular matrix/reinforcement configuration can vary. Due to a wide variety of such composites, the results and effectiveness of the joining method described in the literature are usually related not to the standards included in the standards, but to the mechanical properties of the material being joined.

Different methods can be used to join metal composites with a matrix of aluminum alloys reinforced with ceramic particles. In assessing the adaptability of welding techniques for joining this type of material, the properties of the weld compared with the joining material, which includes strength retention, stiffness retention, dimensional stability, and characteristics such as thermal conductivity, electrical conductivity, and the ability to combine with other materials (Figure 2) (Chernyshov, Panichenko & Chernyshova, 2003), should be taken into account.

Fusion welding methods

The main problems that arise when joining elements made of aluminum-ceramic composites using welding methods include:

- the phenomenon of partial degradation of the ceramic phase used as reinforcement under the influence of high thermal energy of welding processes;
- the possibility of chemical surface reactions occurring between the reinforcement material and the matrix alloy;
- the tendency for the formation of agglomerates of reinforcing particles and areas without a reinforcing phase in the solidified weld metal;
- the problem of wettability of ceramic particles by the molten mixture of the matrix alloy and the additional material;

- the tendency to create gas porosity in the weld metal (Hashim, Looney & Hashmi, 1999; Lee, Li & Chandel, 1999; Ureña, Escalera & Gil, 2000).

Microstructural changes in the area of the welded joint depend, among others, on the energy of the heat source and the type of ceramic phase used as the reinforcement. The increase in the thermal energy of the welding process, on the one hand, contributes to the degradation of the ceramic phase particles and, on the other hand, it increases the amount of molten metal and extends the time of its contact with the ceramic phase. When SiC particles are used as reinforcement in composites based on aluminum alloys, the most significant problem is the formation of a chemical reaction, which can be described by the following chemical equation:

$$3SiC + 4Al = Al_4C_3 + 3Si \tag{1}$$

where Al_4C_3, as a product of the matrix-reinforcement surface reaction, is a brittle compound that reduces the mechanical properties of the joint and, in a humid environment, it significantly reduces corrosion resistance (Ellis, Gittos & Threadgill, 1994; Ureña et al., 2001).

The subsequent melting of the metal matrix of the welded composite, the introduction of unreinforced additional material, and the subsequent solidification of the weld metal cause it to have a different structure than the native material. This relates to the mutual relationship of the crystallization front of the matrix alloy mixture of the base material and the additional material with the reinforcing phase. Ceramic particles are mostly pushed out by growing dendrites and then confined to the interdendritic spaces. Agglomerates of reinforcing particles formed in this way make it difficult for gases to escape from the weld to the surface (Lienert, Brandon & Lippold, 1993; Lean, Gil & Ureña, 2003). This results in an increase in gas porosity and, with a significant concentration of gases (especially hydrogen), in the formation and spread of cracks in the welded joint (Famodinu et al., 2018).

The intensification of physico-chemical phenomena in the area of the welded joints largely depends on the different properties of the metal matrix and the ceramic reinforcing phase. The following are mentioned here:

- a large difference in melting temperature (> 2000 °C reinforcement and 660 °C pure aluminum);
- a large difference in thermal expansion coefficients (formation of internal stresses);
- a large difference in thermal conductivity coefficients (change in crystallization conditions);
- a difference in electrical conductivity values (Praveen & Yarlagadda, 2005).

TIG and MIG welding

The mentioned differences in physical properties are illustrated by tests of the TIG welding using only an electric arc without additional material of the 6061/SiC/15(p) composite (Figure 3) (Wang et al., 2009), where the formation of a layer of surface oxides made it impossible to achieve penetration or, as in the case of AlSi9/SiC/20(p), the energy of the electric arc can lead to the complete melting of the reinforcing phase (Figure 4) (own research).

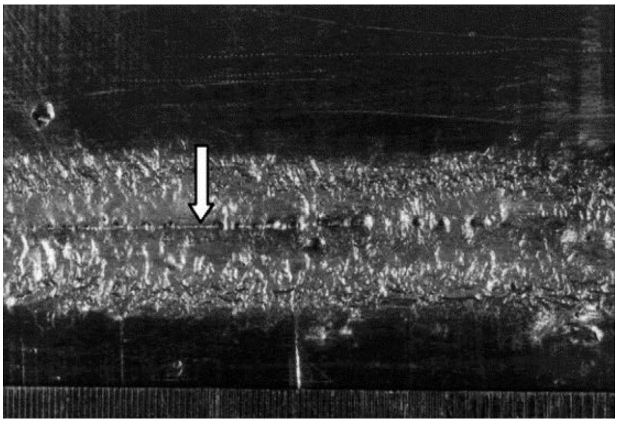

Figure 3. View of the 6061/SiC/15(p) weld without additional material (Wang et al., 2009)

Figure 4. View of the AlSi9/SiC/20(p) weld without additional material

Therefore, it is necessary to correlate welding parameters, such as the flow rate and type of shielding gas, welding speed, current intensity, and chemical composition of the additional material.

As mentioned earlier, the process of melting the base material, introducing the material, and the subsequent solidification process is associated with changes in the structure of the solidified weld metal

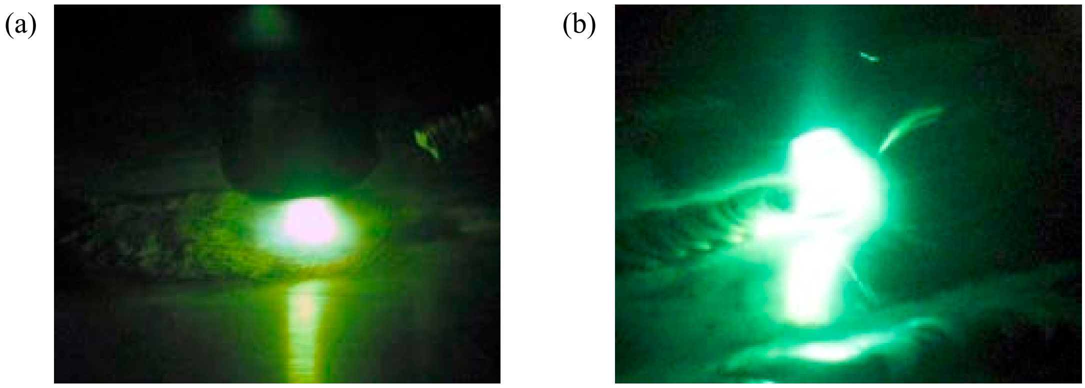

Figure 5. View of the weld pool: (a) composite AlSi9/SiC/20(p) and filling material AlMg5Sc0.61 and (b) alloy 6061 filling material ER5356 (Wysocki, 2009)

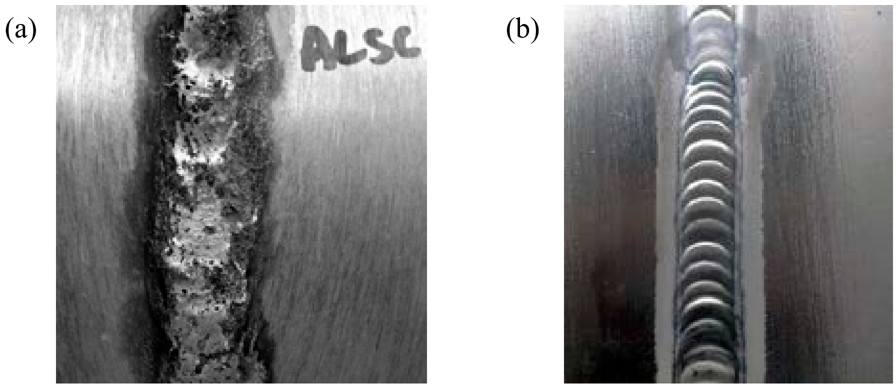

Figure 6. View of the weld face: (a) weld composites AlSi9/SiC/20(p) filling material AlMgSc0.61 and (b) alloy 6061 filling material ER5356

and the heat-affected zone. The high energy of the electric arc and the absorption of heat by the reinforcing particles cause the welded material to melt over a large area. Moreover, the weld pool is wide (Figure 5(a) and 5(b)), the weld metal solidifies more slowly, and the weld face looks different than in the case of welds of unreinforced aluminum alloys (Figure 6(a) and 6(b)).

In a welded joint made using the TIG or MIG method, four main zones of structural changes can be distinguished (Figures 7(a), 7(b), and 7(c)) (Irving, 1991): Zone (1) where the material is heated below the melt recovery temperature, i.e., the zone of the native material; Recovery zone (2) where the hardening deformations disappear, stresses are reduced, and the grain boundary structure of the matrix stabilizes; Recrystallization zone (3), due to the presence of reinforcement, there is a limited growth of the grain boundaries of the composite matrix, caused by the rapid process of diffusion and chemical interaction between the matrix and the reinforcement; Weld zone (4), in which three areas are distinguished as follows:

- 4', significant overheating of the molten composite and long contact time of the metal with the reinforcing particles may result in almost complete melting of the reinforcing phase. Traces of particles appear in the central part of the

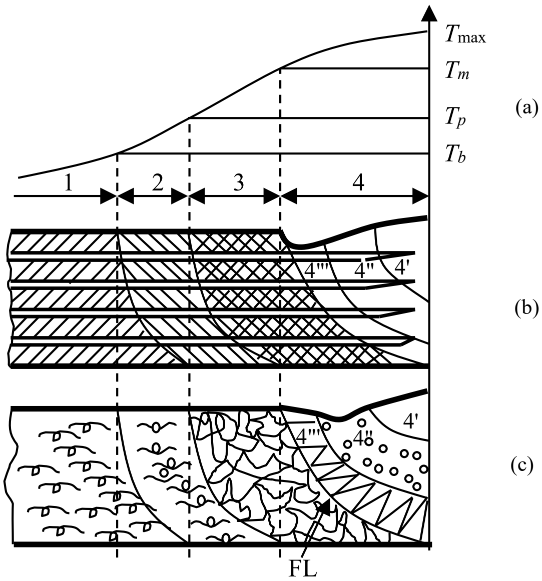

Figure 7. (a) Distribution of maximum temperatures in the weld zone in the cross-section to the welding direction, (b) structural changes in the composite reinforced with continuous fibers, and (c) structural changes in the composite reinforced with particles (Irving, 1991)

face surface as a result of gas absorption on the reinforcing particles, which facilitates their fluctuation.
- 4", a slightly lower temperature than in section 4', where the reinforcement is partially melted in the liquid matrix; the remaining part of the reinforcement is enclosed in the arms of growing columnar dendrites.
- 4'", formation of clusters of precipitates at the grain boundaries, free from reinforcing particles at the fusion line, where crystallization of the molten composite begins, and the growing dendrites move the particles toward the center of the weld.

The size of the area of changes and intensification of chemical processes can be influenced, to a limited extent, by the appropriate correlation of the welding process parameters and the selection of an additional material with a determined chemical composition. By lowering the current and increasing the welding speed, the thermal energy of the process is reduced. The portion of molten base material limited in this way and the shortened contact time of the liquid metal with the ceramic particles partially inhibit the occurrence of surface reactions at the matrix-reinforcement interface (Wysocki, 2009; Sivachidambaram & Balachandar, 2015).

The results of the tests combining composites based on aluminum alloys reinforced with SiC particles, e.g., 6061/15SiC(p) (Wang et al., 2009), 2014/SiCp (Uluköy, 2017), have shown that some positive results are achieved when using Al-Si additional material with increased silicon content, e.g., ER 4043 or ER 4047. Although the use of unreinforced, additional material causes the weld to have a much lower reinforcing phase content than the native material, the addition of silicon largely inhibits the formation of harmful surface reaction products, such as Al_3C_4. However, the increased share of silicon in the additional material contributes to the formation of low-melting Al-Si eutectics and precipitates of pure silicon, which surrounds the slower-cooling ceramic particles with a thin layer.

Favorable results are also obtained when using a binder with the composition AlMg5 (ER5356). Microstructural analysis of joints of welded composite elements 6092/SiC(p) (Lean, Gil & Urena, 2003) or 359/SiC(p) (Grabian, Wysocki & Gawdzińska, 2003) showed that magnesium introduced into the liquid weld pool in the additional material reacts with aluminum oxide on the SiC/Al surface, forming compounds MgO and $MgAl_2O_4$. This contributes to improving the wettability of the reinforcing phase by the liquid metal. Therefore, the additional material type AlMg5 is recommended for joining composites of Al/Al_2O_3 type (Gomez de Salazar & Barrena, 2003). Thanks to better wettability, an improved connection is achieved at the matrix-reinforcement interface and a more uniform distribution of ceramic phase particles in the metallic matrix that, in turn, to some extent, prevents the loss of mechanical properties of the joint in relation to the base material.

When joining cast composites AlSi/SiC(p), fairly good results are obtained when using an additional material with the chemical composition AlMgZr or AlMgSc. The introduction of scandium or zirconium into the weld pool changes the crystallization method from dendritic (Figure 8(a)) to fine-grained (Figure 8(b)). Al_3Sc precipitates form when the additional material, AlMgSc or Al_3Zr with the additional material AlMgZr, strengthens the weld, which improves the wettability of the reinforcing particles and does not tend to create harmful surface reaction products. Such welds are characterized by a slightly reduced tensile strength and a slight decrease in hardness in relation to the welded material (Wysocki, 2007a; 2007b).

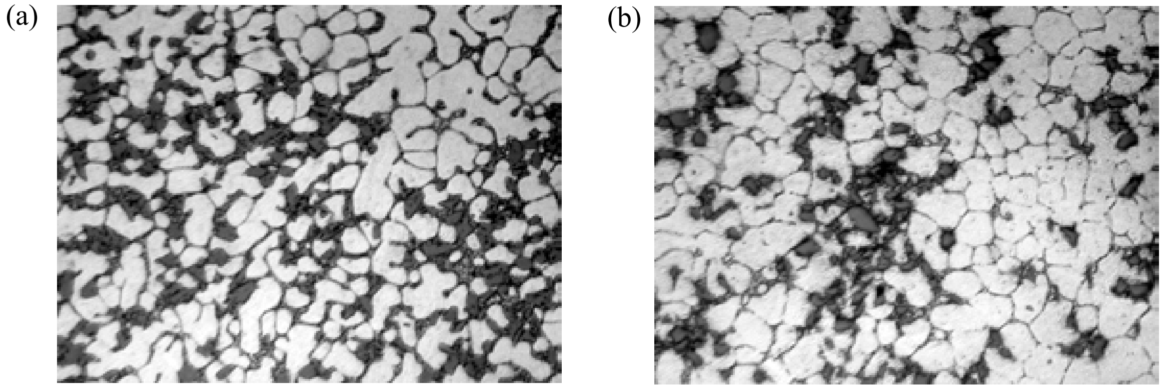

Figure 8. Weld microstructure AlSi9/20SiC9(p) using filling material: (a) AlMg5 and (b) AlMg5Sc0,61 (Wysocki, 2009)

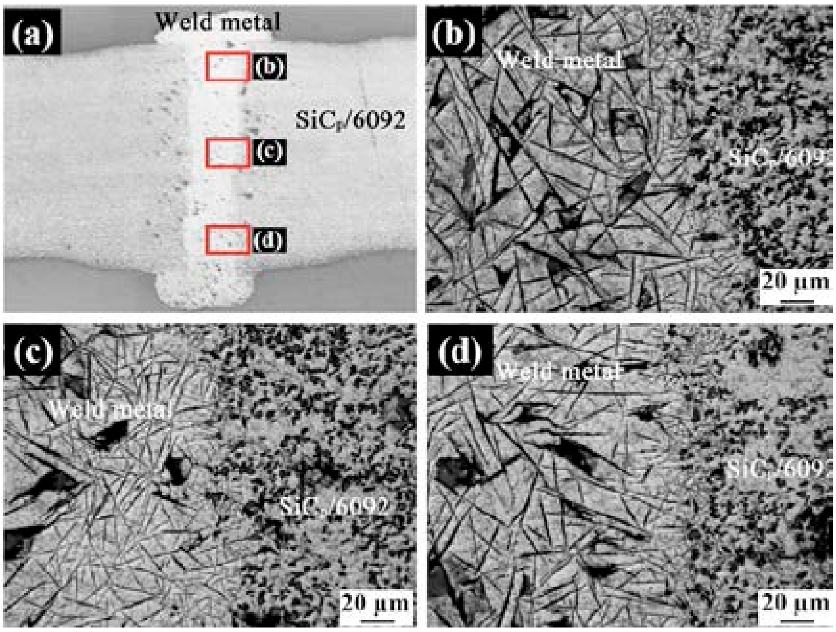

Figure 9. Microstructure of weld at 1700 W and 25 mm/s: (a) overall weld morphology, (b) top of the weld, (c) middle of the weld, and (d) bottom of the weld (Zeyu et al., 2023)

Laser beam welding

Laser welding has several positive features compared with arc welding. The basic advantages include high energy concentration, a small weld pool, and a very narrow heat-affected zone (Atabaki et al., 2016). One of the basic problems that occurs during laser welding is the uneven absorption of the laser beam by the components of the aluminum-ceramic composite. Since ceramics are a greater absorber of the laser beam than the matrix metal, there is a risk that the reinforcing particles will be completely dissolved in the liquid weld pool or that the intensity of harmful surface reactions will significantly increase, as shown by bonding tests of A356/SiC/20(p) (Bassani et al., 2007), 6016/SiC/20(p) (Niu et al., 2006), or 6092/SiC/10(p) (Zeyu et al., 2023). In all cases, three characteristic zones of changes under the influence of the laser beam were visible (Figure 9):

- Zone 1: material remelting zone with almost complete disappearance of the reinforcing phase and a large amount of acicular precipitates Al_3C_4 (precipitates do not arise as a result of surface reactions, but as a result of precipitation from the liquid solution during cooling) and pure silicon crystallizing on the surfaces of ceramic particles, originating from the decomposition of silicon carbide;
- Zone 2: Al_3C_4 formation zone as a result of matrix-reinforcement surface reactions and the formation of Al-Si eutectics at the matrix grain boundaries;
- Zone 3: zone with no visible damage to the SiC particles and slight changes in the microstructure of the aluminum matrix alloy.

The scope of the unfavorable changes can be limited, to some extent, by controlling the energy of the laser stream (e.g., the pulsed welding), increasing the speed of the welding process (Zeyu et al., 2023), or introducing a material with a high affinity for carbon into the weld, creating durable and strong compounds with it. Such elements include titanium that, introduced between the joined surfaces in the form of a thin spacer ("in-situ welding"), almost completely inhibits the process of formation of Al_3C_4 in return, creating hard precipitates of TiC, Ti_5Si_3, or Al_3Ti type (Guo, Gougeon & Chen, 2012; Guo, 2012).

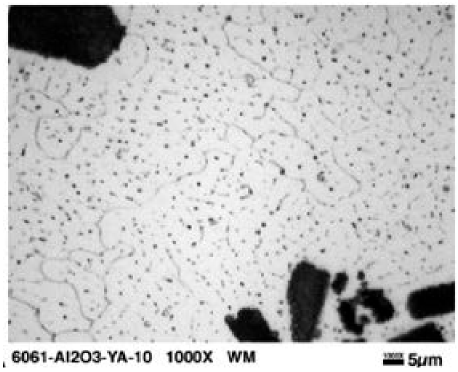

Figure 10. Place of passage of the laser beam. Welded material 6061/Al_2O_3(p) (Liu et al., 2001)

Although, in reinforced composites of Al_2O_3, there is no intensification of the precipitation of surface reaction products, the fact is that aluminum oxide has an even higher ability to absorb the laser beam than silicon carbide. It is almost completely dissolved in the weld pool (Figure 10) (Liu, Zhu & Niu, 2001).

Electron beam welding

Electron welding involves melting the contact area of the joined objects with heat obtained by bombarding it in a vacuum with a concentrated beam of high-energy electrons. Similar to laser welding, it is a high-energy process. However, electron beam welding is characterized by a higher speed of beam movement and its greater concentration (Klimpel, 1999). Unlike in laser welding, the thermal energy of the electron stream is equally absorbed by the matrix alloy and the ceramic reinforcing phase. As a result, fewer unwanted surface reactions of the Al_3C_4 type occur during the electron beam welding process. Their occurrence is usually limited to the upper and central part of the fusion zone. Aluminum carbide is formed in the form of tiny needles, which are smaller than in a weld made in the laser welding process (Lienert, Brandon & Lippold, 1993; Ellis, Gittos & Threadgill, 1996). The disadvantage of the electron welding method is the need to connect the elements in a vacuum, which complicates the process to some extent.

Capacitor discharge welding

In the capacitor welding process, thermal energy is supplied to the joined elements through electrical contact while applying a pressing force. Thermal energy originates from the rapid discharge of the capacitor bank (Devletian, 1987). The rapid heating and rapid cooling processes reduce the volume of the molten metal matrix of the composite. Moreover, the mutual pressure of the joined surfaces pushes the excess liquid phase outside the joining area in the form of a flash (Hashim, Looney & Hashmi, 1999; Lee, Li & Chandel, 1999). Joining tests of the composites, i.e., 6061/SiC(p), 6061/B_4C(p), and 2024/B_4C(p), performed were characterized by a relatively favorable structure. Minimal overheating of a portion of the molten weld pool, and shortening the time of the matrix-reinforcement relationship at high temperatures, significantly reduce the formation of brittle surface reaction precipitates. Welds made using this method were characterized by a very narrow heat-affected zone and very low gas porosity. To improve the wettability of the reinforcing particles by the liquid matrix, spacers made of thin Al1100 foil with a thickness of 20‒40 μm, placed between the joined surfaces, were used (Devletian, 1987).

Solid state processes – welding

Friction welding

Friction welding is a process in which welding heat and a permanent connection are generated as a result of friction in the area of mutual contact between the welded objects and the direct conversion of mechanical energy into thermal energy. Appropriate pressure on objects and the rotation of one of the elements converts kinetic energy into frictional heat. The friction process is continued until the appropriate temperature is reached. At this point, by stopping the relative movement of the elements and applying an upsetting pressure, a welded connection is obtained. There are two conventional types of friction welding process: with continuous drive and with inertial drive (Klimpel, 1999).

Due to the fact that the process occurs at temperatures lower than the melting point of the base material, the formation of surface reactions between the ceramic reinforcing phase and the metal matrix is almost completely eliminated. Tests carried out on friction welding with an inertial drive of elements made of composites 8009/SiC(p) (Lienert et al., 1996) and 357/SiC(p) (Zhou et al., 1997), as well as welding with continuous drive of 360/SiC(p) composites (Lin et al., 1999), showed that, in the contact zone and the zone of complete plastic deformation, significant microstructural changes occur. The metallic matrix was characterized by a fine-grained structure with a centrifugal spiral arrangement. A uniform distribution of reinforcing particles was observed, the size of which in the areas directly adjacent to the contact surface is smaller than in the native material. The zone of total plastic deformation in the joint was narrowed due to the presence of the ceramic phase in the composite, despite the necessary increase in the pressing force compared with traditional aluminum alloys. However, the concentration of plastic deformation forces in a smaller volume of the material causes an increase in internal stresses, which affects the mechanical properties of the welded joint (Figure 11) (Midling & Grong, 1994).

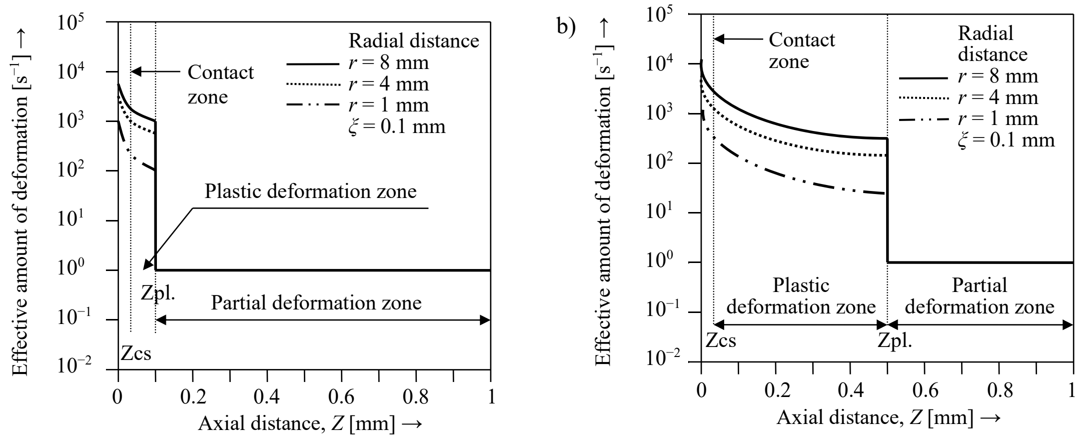

Figure 11. Predicted stress distribution in the heat-affected zone during friction welding with a continuous drive of (a) composite of Al/SiC(p) type and (b) aluminum alloy 6082-T6 (Midling & Grong, 1994)

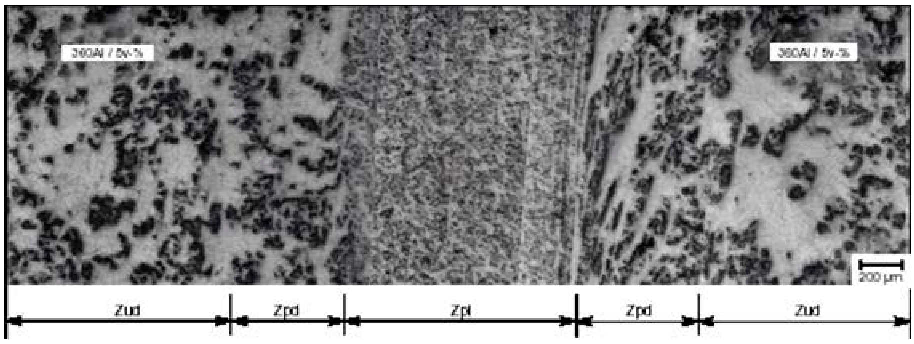

Figure 12. Particle distribution zones in the welded joint 360Al/5%SiC9(p)–360Al/5%SiC9(p) with inertia drive (Lin et al., 1999)

There are three zones of plastic deformation that influence structural changes in the matrix in the joint area:

- the contact zone, where the amount of deformation depends on the rotational speed and, under the influence of friction, the matrix material is partially melted;
- the plastic deformation zone, where the amount of deformation is determined by the rotational magnitude gradient, as well as by radial and axial upsetting;
- the partial deformation zone, where the degree of plastic deformation is controlled by the amount of radial and axial upsetting;
- a zone without deformation, i.e., a structure of the native material.

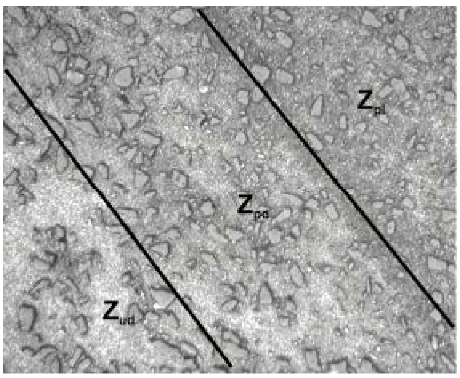

Figure 13. Particle distribution zones in the AlSi9/21SiC(p)-AlSi9/21%SiC(p) welded joint with a continuous drive (Wysocki, Grabian & Przetakiewicz, 2007)

Friction welding tests with inertial drive 360Al/5%SiC(p) and 360Al/10%SiC(p) (Figure 12) (Lin et al., 1999), as well as friction welding with continuous drive AlSi9/21%SiC(p) (Figure 13 and Figure 14(a) and (b)) (Wysocki, Grabian & Przetakiewicz, 2007), showed three characteristic zones of distribution of ceramic particles:

- A zone of fragmentation of ceramic particles in the contact zone;
- A zone of a band-like arrangement of ceramic particles with a twist in the direction of rotation;
- A zone with no change in relation to the distribution of ceramic particles in the base material.

Tensile strength tests and hardness measurements showed that the samples were torn in the contact zone, where the highest concentration of internal stresses occurred, which was confirmed by

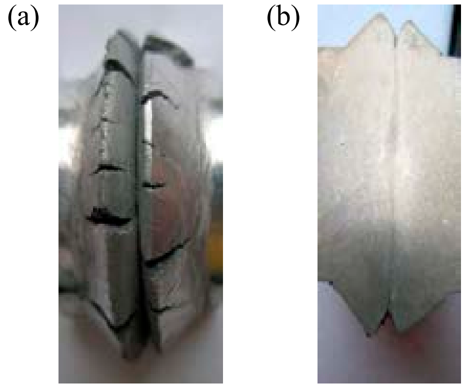

Figure 14. View of a welded joint with a continuous drive AlSi9/21%SiC(p)-AlSi9/21%SiC(p): (a) view of the welded joint and (b) cross-section (Wysocki, Grabian & Przetakiewicz, 2007)

tests of fractures showing the nature of low-plastic damage. The greatest decrease in hardness is noted at the border of the zones of partial and complete plastic deformation (Lin et al., 1999; Wysocki, Grabian & Przetakiewicz, 2007). The size of individual zones and, therefore, the mechanical properties are influenced by the welding process parameters. The rotational speed and pressing force are of great importance here (Khan & Rajakumar, 2018).

Friction stir welding

This method uses a non-fusible, high-speed rotary tool moving along the line of joining the elements. A poking probe pressed into the joined materials penetrates and mixes them, while the rotating pin, which is in constant contact with the upper surface of the joined elements, ensures that the plasticized material cannot flow out of the joint area (Salih et al., 2015). The plasticization of the material occurs due to the heat that is released between the rubbing probe and the material to be welded, as well as the rotating pin and the upper surface of the material to be welded, as shown in Figure 15 (Kallee, Nicholas & Thomas, 2002).

The friction stir welding occurs at a temperature approximately 20% lower than the melting temperature of the material being welded. Therefore, there are no brittle and undesirable surface reaction products at the boundary of the metal matrix ceramic reinforcing phase interface. It is an emission-free technique and does not require additional materials in the form of welding wires or electrodes. However, it requires a friction element that is subject to wear and is reinforced by the presence of the ceramic phase (Figure 16) (Prado et al., 2003).

The basic process parameters are the rotational speed of the rubbing tool, welding speed, pressing force, and the shape of the tool. Their appropriate correlation affects the appearance and structure of the weld (Prado et al., 2001; Prado et al., 2003). Four zones can be distinguished in the welds (Figure 17) (Ni et al., 2013), as described in the following.

Zone 1 is the weld core zone. The welding tests performed, i.e., AA2009/SiC/17(p) (Ni et al., 2013), AA6061/B_4C (Kalaiselvan, Dinaharan & Murugan, 2014), and AA7005/Al_2O_3/10(p) and 6061/Al_2O_3/20(p) (Ceschini et al., 2007), were characterized by the occurrence of the following flow effect caused by friction between the flange of the rubbing tool moving in linear motion with the appropriate axial pressure and the surface of the welded elements. Moreover, there will be a tendency to create the so-called basin with increasing rotational speed.

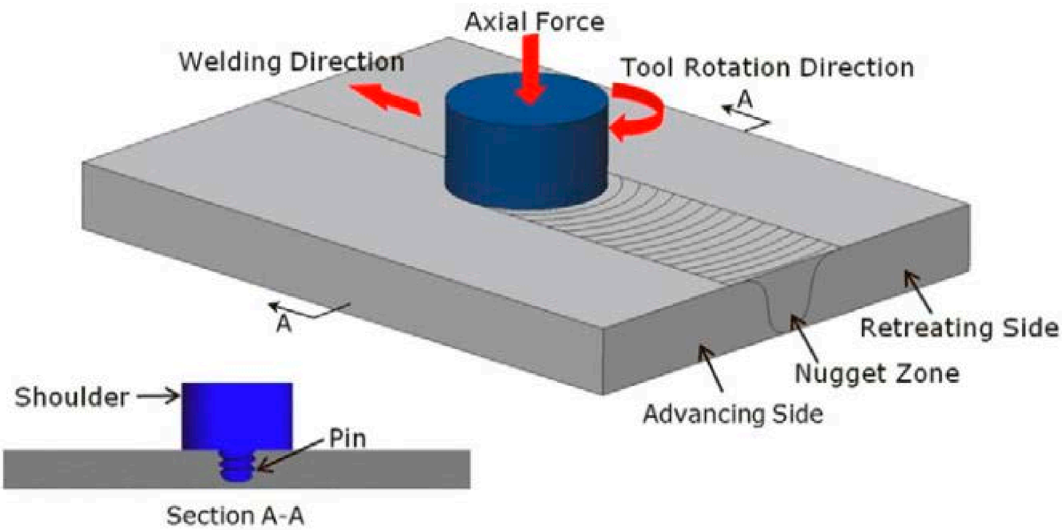

Figure 15. Diagram depicting the friction stir welding (Kallee, Nicholas & Thomas, 2002)

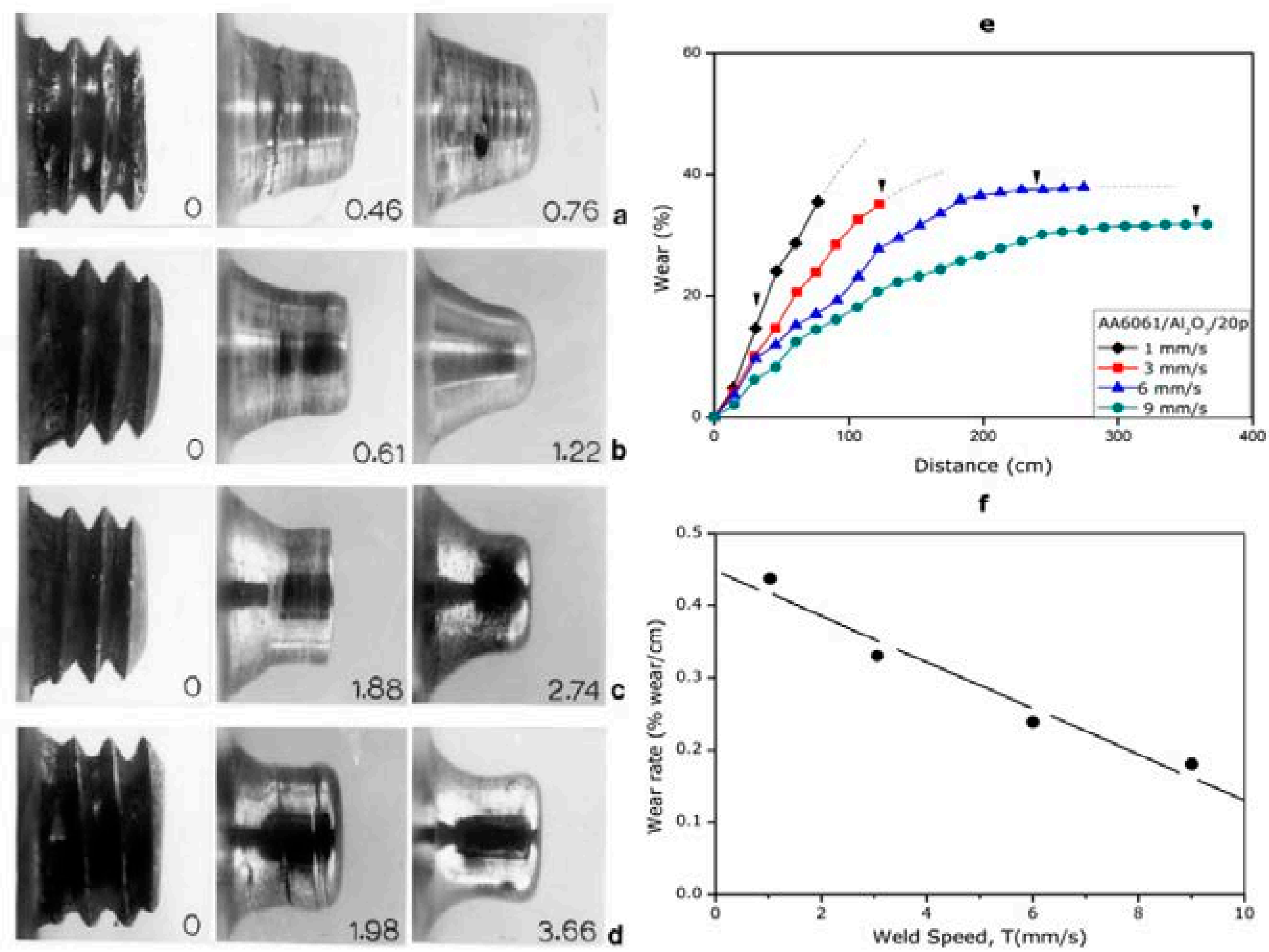

Figure 16. Wear speed of the friction element: (a)-(d) at different weld lengths (in meters), at a constant rotational speed of 1000 rpm, and at different rotation welding speeds: (a) 1, (b) 3, (c) 6, and (d) 9 mm/s; (e) wear rate as a function of weld length at variable welding speed and (f) wear rate as a function of welding speed (Prado et al., 2003)

Figure 17. Cross-sectional view of the welded joint AA2009/SiC/17(p) (Ni et al., 2013)

Another element characterizing the weld core is the formation of a structure resembling onion slices (Figure 18) (Prabhu et al., 2018) as a result of the movement of the plasticized material and the variation in dislocation density. This effect may disappear as the thickness of the joined materials decreases (below 3 mm). In the weld core zone, fragmentation and even distribution of reinforcing particles were noticeable due to contact with the rotating tool. Under the influence of the simultaneous influence of frictional heat and the formation of plastic deformations, a process of dynamic recrystallization of the metal matrix was observed, enhanced by the share of reinforcing particles, which were more evenly distributed in the weld than in the welded material (Kallee, Nicholas & Thomas, 2002; Storjohan et al., 2003). On the other hand, dynamic recrystallization limited by the presence of ceramic particles led to the breakdown of the dendritic phase and the formation of new small equiaxed grains (Periyasamy, Mohan & Balasubramanian, 2012; Madhavi et al., 2022).

Zone 2 is the zone of thermo-mechanical changes. In this zone, where the temperature is slightly lower than in the core, the matrix grains are elongated and oriented in the direction of movement of the rotating tool. The structure is coarse-grained as a result of contact with slower-cooling ceramic particles.

Figure 18. View of the weld with characteristic traces of the "onion slice" effect and deviation in the direction of flow behind the rotating tool (Prabhu et al., 2018)

Zone 3 is the heat-affected zone, which is located between the parent material and the TMAZ, which experiences only a slight temperature increase. Here, the rotating pin does not mechanically deform this area. However, similarly to the zone of thermo-mechanical changes, this zone is characterized by grain growth. Zone 4 is the native material zone.

Diffusion bonding

The connection is achieved under the influence of high pressures at elevated temperatures. The three main parameters of the diffusion welding process are the joining temperature (usually 50–70% of the melting temperature of the matrix alloy), the pressing force, and the holding time. The diffusion welding process does not cause macroscopic deformation or mutual displacement of the welded surfaces (Liming et al., 2001). The disadvantages here are the need to prepare the surface with appropriate smoothness, the precise removal of the oxide layer from the surface of the joined elements, and the need to carry out the process in heating chambers, which limits the use of this method on a wider scale (Lee, Li & Chandel, 1999).

Diffusion welding tests of elements made of the 6061/Al_2O_3(p) composite (Lee, Li & Chandel, 1999; Liming et al., 2001) showed a very low degree of deformation of the joined surfaces and, due to the process temperature, no chemical reactions between the matrix and the reinforcement. The mechanical properties of the joint corresponded to 70% of the values characteristic of the native material. The positive results are also achieved by using thin interlayers, e.g., composed of Al-Li or Ag, when joining elements made of 2124/SiC composites. The purpose of the interlayer is to enter into chemical reactions with the oxide film layer, to clean the joined surfaces, and to increase the strength of the joint by improving the wettability of the reinforcing phase by the metal matrix (Ureña, Gomez de Salazar & Escalera, 1995).

Other processes

Transient liquid phase bonding

Transient liquid phase bonding is similar to diffusion welding using an interlayer. The main difference is the temperature range in which the joining process is carried out. While diffusion welding is carried out at temperatures up to 520 °C, in this method, the process temperature is selected so that the interlayer of Al-Cu or Al-Ag alloys is used; after the melting, it can form eutectics with the composite matrix (Composite Material Handbook, 1999). Thanks to the increased process temperature, it is possible to use a lower pressing force. However, a higher temperature range may cause harmful surface reactions between the metal matrix and the ceramic reinforcement. Brittle chemical reaction products can significantly reduce the mechanical properties of the joint (Hirose, Fukumoto & Kobayashi, 1995). In the case of joining composite A356/SiC/559(p) with Kovar, 4J29 can be used as the nickel plating of the composite's faying surface prior to the application of a solder alloy. This is possible because the solder material zinc-based alloy (Zn–Cd–Ag–Cu) was used with a melting point of about 400 °C. The noticeably enhanced reaction between the molten solder and composites creates a good adhesion between the solder alloy and the Al–SiC composite (Lu et al., 2012).

Brazing

In the case of aluminum-ceramic composites, two methods are mainly used: brazing in a vacuum furnace that, however, creates limitations in terms of joining composites (higher pressure required) and soldering with the addition of fluxes. Although the edges of the joined elements do not melt during the brazing process, an increased temperature is required (Composite Material Handbook, 1999). The extended process time and elevated temperature may lead to undesirable chemical reactions and a reduction in the mechanical properties of the joint. When attempting to join Al/SiC composites, it was noticed that there is a certain optimal temperature at which relatively good results are achieved. Deviations from this temperature affect the quality of the connection. Namely, too low a temperature means no diffusion and solder for the native material, and too high a temperature results in the formation of the above-mentioned harmful chemical reactions (Liming et al., 2001). For brazing 2017/SiC/10(p) to AlSI304L (Grund et al., 2018), brazing filling materials with a melting point below 500 °C were used to minimize the formation of harmful surface reaction products.

Soldering

Soldering is a process carried out at a temperature lower than that used in brazing. During tests of joining AA2014/SiC(p) with Zn-3Al solder (Ureña, Escariche-Fernandez & Gomez de Salazar, 2001) and solders under the trade names Zamak 3(AG40A) and Zamak 5(AG41A), it was noticed that the soldering effectiveness is influenced by the chemical composition of the additional material, the wettability of the reinforcing phase by the molten additional material, its flowability, and the content of the reinforcing phase in the composite. In the brazing process, an unfavorable phenomenon of diffusion of solder components with a low melting temperature across the grain boundaries and the matrix-reinforcement surface into the matrix alloy of the brazed material is observed, causing local undercutting. This leads to defects that reduce the strength of the solder joint. Therefore, it is recommended to use solders with a higher melting point. When testing the soldering of AlSi11/SiC(p) and AlSi9/SiC(p) composites, it was found that the intensification of the penetration phenomenon increases with the percentage of SiC. In the second direction, pure aluminum and reinforcing particles diffuse occur. The ceramic content in the solder reduces the flowability and wettability of the base material and affects the microstructure of the solder. Moreover, the conglomeration of the unwetted reinforcing particles may occur, creating voids (Figures 19(a) and 19(b)) (Wysocki, Gawdzińska & Jasionowski, 2010).

X-ray welding

This is a method based on the use of high-energy X-ray radiation as a volumetric heat source with a wavelength corresponding to 1–8 Å and an energy of 10^5 W/cm^2. The radiation source is directed to the contact line of the joined elements, creating an irradiation zone and, consequently, a refusion zone. The advantage of this method is the fact that, despite the partial melting of the matrix, there is no degradation of the reinforcing phase and its arrangement remains almost unchanged. An important feature of the "X-ray welding" method is the lack of any cracks in the weld zone. This is probably the result of a relatively low rate of heating and cooling of the connection point and, consequently, lower internal stresses. The lack of surface reactions at the matrix/reinforcement interface is also reported. The structure of the weld when joining composite elements 6061/Al_2O_3(p) at the point of the passage of the X-ray beam is shown in Figure 20 (Rosenberg, Goeppner et al., 1997; Rosenberg, Ma et al., 1997).

Joining by plasma spraying

This method involves filling a groove with an angle above 90° with a powdered aluminum alloy

(a) (b)

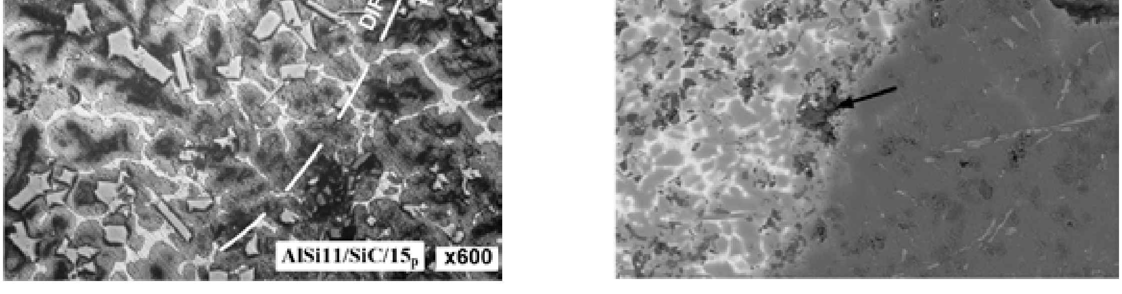

Figure 19. Microstructure of the solder joint in the area of the diffusion line. Brazed material AlSi11/SiC/15(p): (a) displacement of the solder into the base material and particles into the solder and (b) conglomerate of reinforcing particles in the area of the diffusion line (Wysocki, Gawdzińska & Jasionowski, 2010)

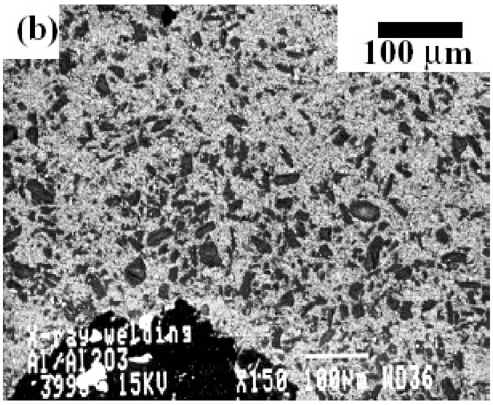

Figure 20. Cross-section image of the mold zone on the X-ray weld of 6061/Al_3O_2/20(p) composite (Rosenberg, Goeppner et al., 1997; Rosenberg, Ma et al., 1997)

containing ceramic particles by plasma sputtering. As shown by tests of bonding composites, i.e., 6061/SiC/20(p) and 6061/SiC/10(p), using an additional material in the form of spherical Al2014 powder containing 15% of SiC particles (volume) is extremely important for the correctness of the process and the quality. The process parameters are the heating temperature of the joined elements, spray distance, and groove angle. The correlation of the above parameters determined the degree of adhesion of the sputtered layer and its cohesion. After the sputtering process, a heat treatment of the joint is recommended, which significantly increases its mechanical properties (Itsukaichi et al., 1991)

Effectiveness of joining methods

The above-presented joining methods show that many of them can be used, with greater or lesser success, to join composites based on aluminum alloys reinforced with ceramic particles. Table 1 shows a comparison of selected common joining methods for aluminum metal matrix composites reinforced with ceramic particles.

In the qualitative assessment of the joint, factors such as the content of the reinforcing phase in the joint, the degree of agglomeration of the reinforcing particles, and voids caused by the lack of wettability of the ceramic particles by the metal matrix are taken into account, in addition to the strength tests. Table 2 summarizes the advantages and disadvantages of joining methods.

It seems that improved results can be achieved with solid-state processes. There is no problem with chemical reactions at the matrix/reinforcement interface and they do not require the use of protective gas, fluxes, or additive material. A significant advantage is the ability to join components made of materials with different chemical compositions.

In continuous or inertia friction welding, the fineness of the reinforcing particles is quite important, but their distribution is uniform. The decrease in tensile strength of the weld compared with the welded material is 10–15%. The rupture of the specimens occurs in the heat-affected zone, where the highest torsional stresses and the banded distribution of reinforcing particles occur (Lin et al., 1999). This is also where the greatest decrease in joint hardness occurs, reaching a value corresponding to approximately 70% of the hardness of the native material. Friction welding with a solid or inertial drive is characterized by significant limitations on the shape and dimensions of the parts to be welded (Wysocki, Grabian & Przetakiewicz, 2007).

Much improved results are presented for a friction stir welding of the material. During welding, the material is heated to a temperature approximately 20% lower than its melting point. The microstructure, the internal stresses, and the uniformity of the distribution of the fragmented reinforcing particles are strongly influenced by the shape, the type of friction tool, the rotary speed, and the travel speed. The mechanical properties also strongly depend on the number and type of reinforcing particles. In most cases, it is specified that the decrease in tensile strength does not exceed 20% and the hardness is similar to the native material or higher in the nugget zone. An important limitation in this case is the

Table 1. Comparison of different common joining methods for aluminum matrix composites reinforced with ceramic particles

Welding method	Propensity to defect	Resulting properties	Productivity	Cost of the process
Metal inert gas (MIG)	moderate (+)	moderate	moderate	low
Tungsten inert gas (TIG)	moderate	moderate	moderate	low
Laser beam	high (−)	moderate (−)	high	high
Electron beam	high (−)	low (+)	moderate (+)	high
Friction welding	low (+)	moderate (+)	low	moderate
FSW	low (+)	high (−)	moderate	low (+)
Soldering	moderate (−)	moderate	low	low

Table 2. Advantages and disadvantages of selected joining methods

Welding method	Advantages	Disadvantages
Metal inert gas	Filler material can be chosen to reduce surface reaction metal matrix/ceramic particles and increase the wettability of particles. Possibly improve mechanical properties by indirect welding. Low-cost process.	High particle degradation. Possible brittle products of the surface reaction (Al_4C_3 in case Al/SiC MMC). Mechanical properties are reduced to unreinforced filling material properties. Possible particle conglomeration at fusion line. Shield gas is required.
Tungsten inert gas	Filler material can be chosen to improve the welding process and reduce surface reaction matric/ceramic particles and/or increase the wettability of particles. Reinforce joint by intermetallic dispersions. Low-cost process.	High particle degradation. Possible brittle products of the surface reaction (Al_4C_3 in case Al/SiC MMC). Mechanical properties are reduced to unreinforced filling material properties. Possible particle conglomeration at fusion line. Shield gas is required.
Laser beam	High-speed welding process. Narrow heat effect zone. Improve bond quality by inserting between bonding elements.	High particle degradation. Possible brittle products of the surface reaction (Al_4C_3 in case Al/SiC MMC). High porosity. Shield gas is required. Precise elements preparation.
Electron beam	High-speed welding process. Narrow heat effect zone. No vacuum is required.	High particle degradation. Possible interface reaction (Al_4C_3 in case Al/SiC MMC). Possible high porosity. Precise elements preparation.
Capacity discharging	Low amounts of surface reaction products. Dissimilar materials can be joined. Interlayers can be used to improve the mechanical properties of bonds.	Possible reinforcement degradation. Geometry limitation.
Friction welding	Lack of matrix–particle interaction. Full bond strength can be achieved after heat treatment. No tendency to porosity. Process below matrix melting point. Dissimilar materials can be joined.	Flash requires removal. Geometry and size of elements limitation.
FSW	Good mechanical properties of the joint. Lack of surface reaction products. No porosity. The process below melting point.	Quality depends on parameters of process. Friction tool consumption. Thickness limitation.
Diffusion bonding	Low amounts of interface reaction. Dissimilar materials can be joined. The interlayer can be chosen to improve the mechanical properties of the bonds.	Possible harmful intermetallic products. Extensive mass transport may produce poor bonds. Low mechanical properties.
Transient liquid phase diffusion bonding	Lack of matrix–particle surface reactions. Interlayer can be chosen to optimize bond properties.	Possible harmful intermetallic products. Expensive process and very low productivity.
Brazing	Very low amount of interface reaction. It can be used to join dissimilar materials.	An inert atmosphere or vacuum could be required. Post-welding heat treatment is required to improve mechanical properties.
Soldering	Lack of matrix–particle interaction. Low-temperature process.	High porosity. Particles conglomeration. Poor mechanical properties.
X-ray welding	No particles degradation. Uniform distribution of reinforced particles in the joint.	Very expensive. Limited application. Complicated equipment requires.
Welding by plasma spraying	Filling material with particles. Mechanical properties can be increased after heat treatment.	Post-welding heat treatment is required. Limited application.

rapid wear of the friction element (Madhavi et al., 2022).

Fusion welding methods are more economical and more flexible, although strength tests indicate that their quality is not always satisfactory. This mainly relates to porosity and reinforcement degradation, which results in a different structure for the weld and the composite material (Zeyu et al., 2023). Mechanical properties of the fusion welding method reported in the literature show a more than 20% decrease in tensile strength with a 25% reduction in hardness in the weld area. Moreover, there is an increased flexural strength compared with the parent material. The use of protective gases is also necessary. Structural changes and a lessening of the reduction of the mechanical properties can be achieved by using an appropriate chemical composition of the additive material to improve wettability (Wysocki, 2007a; 2007b) or by using inserts that reduce the direct effect of the high-energy arc on the parts to be joined (Garcia et al., 2007).

Conclusions

The presented review of methods of joining composites based on aluminum alloys reinforced with ceramic particles was aimed at discussing and influencing the macro- and micro-structural changes taking place in relation to the quality and mechanical properties of the joints. As can be seen from the presented analysis, some of the methods have not found wider application. However, work is still being carried out to optimize methods of joining composite materials.

Fusion welding methods are relatively cheap and mobile. On the other hand, they are mostly fraught with the risk of welding defects due to the disintegration of the reinforcement phase, porosity, and surface reactions at the matrix/reinforcement phase separation interface. The solution may be filler materials with a chemical composition that improves the wettability of the ceramic particles through the metal matrix and offsets the formation of brittle surface reaction products. A suitably selected filler material composition can change the weld crystallization mode and initiate the formation of strengthening intermetallic separations (Wysocki et al., 2024). The selection of welding parameters and the reduction of the energy of the arc acting directly on the material, to be joined by using an intermediate layer (Garcia et al., 2007) or inserts of suitable chemical composition, reduces the porosity and degradation of ceramic particles that, in combination with heat treatment, allows the desired mechanical properties of the welded joint to be restored (Guo, Gougeon & Chen, 2012).

The most promising results are obtained with methods in which the welding process takes place at temperatures below the melting range of the metal matrix. Friction welding, and especially friction stir welding, stand out against this background. The mechanical values of the weld are largely dependent on the choice of welding parameters, as well as the shape of the friction tool. However, it is important to mention that these parameters change depending on the type, size, and content of the ceramic reinforcing particles. There is a need for further work on understanding this relationship so that methods using the friction process can be fully exploited in the production range (Madhavi et al., 2022).

It is necessary to conduct further work to fully understand the phenomena occurring during the bonding process of composite materials and to improve their joining techniques. These methods should ensure a minimizing of the formation of harmful chemical reaction products at the interface between the metal matrix and the ceramic reinforcing phase, selection of bonding conditions, and methods to reduce the degradation of the reinforcing phase or the development of methods to introduce ceramic particles into the liquid weld pool and create a uniform distribution of the reinforcing phase in the joint area.

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The game theory decision models for transport systems selection based on the SWOT analysis on the example of heavy and oversized goods transport

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Abstract

This article addresses the optimal choice of transport mode for a specific transport task. Knowing each branch's limitations, strengths, and weaknesses facilitates decision-making when identifying them for use in a given situation. This is of particular importance when transporting oversized loads and heavy pieces. Therefore, this article aims to propose a new model of the game with nature based on SWOT analyses for transport systems selection for oversized and heavy loads. Firstly, for this solution, it is necessary to define measures for each of the four elements of a SWOT analysis (i.e., strengths, weaknesses, opportunities, and threats). Secondly, these four elements are the states of nature in a defined game with nature. Here, the transport mode builds the scenarios that are possible to select. The SWOT analysis determines the strategic position, market attractiveness (MA), and market position (MP) of transport modes. Next, applying very well-known decision-making criteria in the theory of games with nature makes it possible to create appropriate decision-making models for transport mode selection. The application of the method is shown in the example of selecting the most competitive modes of transport for oversized loads.

Introduction

It is always challenging to optimize the problem of choosing the best mode of transport for transporting a specific type of cargo. Each type of cargo is different, and the conditions at a given moment of the transport process also differ, so it is not easy for freight forwarders and logisticians to select a specific means of transport. Therefore, it is crucial to develop optimization methods under conditions of uncertainty and incomplete information. The literature on the subject is dominated by research on route optimization (Costello, Mooney & Winstanley, 2001; Chłopińska & Gucma, 2020; Neumann, 2021), connection reliability (Loustau et al., 2010; Meng et al., 2020), cost optimization (Chou, 2009; Khan, 2014; Lasić, Rožić & Stanković, 2023), and scheduling problems (Islam, Mahmud & Pritom, 2020). They use a typical approach for the optimization methods.

Another group of optimization methods uses the theory of games with nature (Simon, 1959; Papadimitriou, 1985). These methods allow uncertainty to be taken into account in decision-making. In a game against nature, one of the players is a person or institution acting as a decision-maker. The other player is nature, which can affect the game's outcome to various degrees. Nature constitutes a set of conditions affecting the results of decisions. This type of game is a special case of a two-player zero-sum game where nature is a passive player for whom winning is unimportant. This method has significant importance for solving transport and logistic problems. The literature shows results that use game theory to resolve route choices in transport network graphs (Bukvić et al., 2021) or analyze urban traffic's traffic light control problem (Villalobos, Poznyak & Tamayo, 2008). In a previous paper (Ahmad & Al-Fagih, 2023), the authors provide a comprehensive review of the application of game theory in transportation networks. The authors do this from both microscopic and macroscopic perspectives. They show how game theory can be used to analyze the behavior of individual travelers and transportation providers and to develop strategies for managing congestion, improving efficiency, and reducing emissions.

As mentioned above, uncertainties are essential in transportation system management. Game theory helps analyze this problem (Goodwin & Wright, 2014; Howard & Abbas, 2015). Another paper (Raicu, Popa & Costescu, 2022) analyses, based on game theory with nature, the occurrence and consequences of uncertainties, defined as completely unknown random events ("unknown unknowns"), on transportation system performances.

The main aim of this paper is to propose a new model for the game with nature for a multicriteria optimal choice of transport mode. We propose that the individual parts of the SWOT analysis constitute states of nature. From this perspective, it is a new method for supporting decision-making under uncertainty. As an example of the application of this method, we propose to solve the problem of choosing the means of transport for heavy and oversized loads.

This paper is organized as follows. First, we have the Introduction, where a short literature review is undertaken. Following this is the Material and Methods section. Here, we introduce the SWOT analysis basics and game theory with nature. Next are the Theoretical Results section and the Applications section. Finally, there are Discussion and Conclusion sections.

Material and methods

Basics of SWOT analysis

It is well-known that the strengths, weaknesses, opportunities, and threats (SWOT) method is essential in strategic analysis. It is a comprehensive method for examining the organization's environment and internal aspects. The literature widely describes it, among other things, as a tool for identifying and classifying factors influencing the company's strategy (Baum & Wielkicki, 2024; Pierścionek, 2006; Gierszewska & Romanowska, 2003).

A SWOT analysis is a valuable tool supporting strategic decision-making. It allows us to understand their internal resources and external environment to better use opportunities and effectively manage threats.

A SWOT analysis is based on a simple classification scheme that allows for the division of all factors affecting the current and future position of the organization. As part of this analysis, we distinguish external factors, which constitute external conditions and internal factors that affect the examined entity. Taking this division into account, we can distinguish four categories of factors:

- external positive opportunities,
- external damaging threats,
- internal positive strengths,
- internal opposing weaknesses.

Based on the experts' opinions, we can assign appropriate weight on a scale of 1–5 (for example, use the Likert scale in the survey) for each factor. The weights can equal the mean values of experts' opinions (floor function), but this is not the only possibility. This is a way of describing the condition of the object for analysis. Using these weights, we can plot the graph with strategic points. Locating a strategic point on the chart that symbolizes a vital position is based on a mathematical comparison of the sum of points on the appropriate O-T and S-W axes. To undertake this task, we subtract these values: subtracting less from more significant. Figure 1 presents the possible strategies.

The strategic position is determined by the intersection of the lines perpendicular to the axes that pass through the mentioned points. According to economic theory (Gierszewska & Romanowska, 2003; Pierścionek, 2006; Baum & Wielkicki, 2024), the location of the intersections is described as follows. The location of the point represents the company's strategic position, which has a deep strategic meaning.

The *maxi-maxi* position means a privileged position in the market. There is a preponderance of strengths over weaknesses and opportunities over threats. The organization's strategy should aim to maintain this position. The *maxi-mini* position means that the company's strengths outweigh

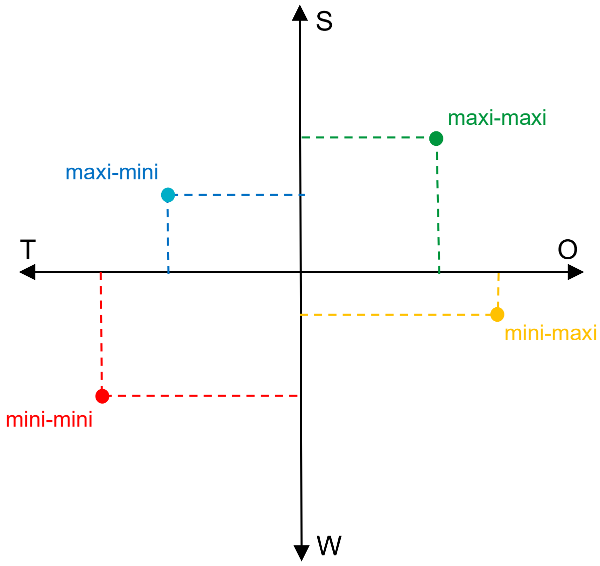

Figure 1. SWOT strategic positions (own research based on Gierszewska & Romanowska, 2003)

its weaknesses, but the environmental threats outweigh the opportunities. The organization's main effort should be to reduce the impact of threats and exploit remaining market opportunities based on its strengths. The *mini-maxi* position means opportunities outweigh threats, but, unfortunately, the company's weaknesses outweigh its strengths. The actions of the company's management should be aimed at improving the company's condition in inefficient (non-competitive) areas because, with such (radical) moves, the company will be able to take advantage of market opportunities.

The *mini-mini* position represents an inefficient enterprise (weaknesses predominate over strengths) in an environment without opportunities for beneficial action (threats predominate over opportunities). If you are considering starting a business, such an investment will fail. In the case of an existing company, the only salvation may be deep restructuring or even a complete change of its operating profile. The lifeline is, above all, the right people in the right place and the strong faith of all employees that overcoming difficulty is possible. Otherwise, the enterprise should be sold as soon as possible if a buyer is found or closed because further operation makes no sense, and bankruptcy is inevitable.

This type of calculation prevents negative values from appearing, which can be represented on a graph as a point representing the strategic position of the analyzed object, e.g., the mode of transport. The procedure is as follows (Baum & Wielkicki, 2024):

Algorithm 1. (Baum & Wielkicki, 2024)

INPUT: weights of S, W, O, and T, i.e., *w*(S), *w*(W), *w*(O), and *w*(T);

OUTPUT: Locating a strategic point (O–T; S–W);

1. *If* $\Sigma w(S) > \Sigma w(W)$, then $\Sigma w(S) - \Sigma w(W)$ and value is located on the S-axis;
2. *Else* $\Sigma w(W) - \Sigma w(S)$ and the value is located on the W-axis;
3. *If* $\Sigma w(O) > \Sigma w(T)$, then $\Sigma w(O) - \Sigma w(T)$ and value is located on the O-axis;
4. *Else* $\Sigma w(T) - \Sigma w(O)$ and the value is located on the T-axis;
5. Return point (O–T; S–W).

We plot the obtained values on the abscissa and ordinate axes to determine the target strategy of the examined branch. The quadrant in which the examined branch is located allows us to choose the strategy.

After calculating the total number of points for each of the four forces, it is possible to determine market attractiveness (MA), which depends on O and T (i.e., opportunities and threats). Market analysis assesses the potential benefits and prospects of a given market or sector. It measures the opportunities and threats that may influence success or failure. This allows for evaluating development prospects, competitiveness, and potential benefits that the industry can achieve in a given transport branch. Market attractiveness is calculated using the following formula (Gierszewska & Romanowska, 2003; Pierścionek, 2006; Baum & Wielkicki, 2024):

$$\mathrm{MA} = \frac{\mathrm{O}}{\mathrm{O}+\mathrm{T}} \tag{1}$$

The next step is to determine the market position (MP) of the transport mode, which is determined based on its strengths (S) and weaknesses (W). Based on identifying strengths and weaknesses, market position refers to the relative position and competitiveness of the railway compared with other industry participants. Determining market position involves assessing and analyzing strengths, i.e., unique abilities, resources, and competencies that constitute a competitive advantage. At the same time, weaknesses and areas where the company may need to be more effective or efficient than the competition are identified. The market position (Gierszewska & Romanowska, 2003; Pierścionek, 2006; Baum & Wielkicki, 2024) also considers external environment analysis, such as competition, market trends, and industry needs analysis. As a result, we can determine our place in the market and adapt our strategy to leverage our strengths and minimize the impact of our weaknesses, striving to achieve a competitive advantage. This relates to the following expression:

$$\mathrm{MP} = \frac{\mathrm{S}}{\mathrm{S} + \mathrm{W}} \tag{2}$$

We can define the probability of strategic success (PSS) based on previous data. It is an indicator or measure that refers to the rail transport industry's chances of implementing its strategy successfully. PSS assesses how likely it is to achieve the intended strategic goals and be successful in the market.

A PSS assessment helps in strategic decision-making, resource allocation, and risk identification. The higher the probability of strategic success, the greater the chances of achieving the intended goals and maintaining a competitive position in the market. The limit value of PSS is 0.5. Below this value, the assessed aspect is assumed to have no chance of development. The formula is given as follows (Gierszewska & Romanowska, 2003; Pierścionek, 2006; Baum & Wielkicki, 2024):

$$\mathrm{PSS} = \frac{\mathrm{MA} + \mathrm{MP}}{2} \tag{3}$$

Game theory with nature

Making multicriteria decisions in conditions of uncertainty is a challenge for decision-makers. For this purpose, we can use a game with nature tool from the literature (Simon, 1959; Raiffa, 1968; Papadimitriou, 1985; McNamee & Celona, 2008; Pažek & Rozman, 2009). It is a two-player game in which one of the players is not interested in the outcome and, simultaneously, does not take risks that may occur with a certain probability.

The player called nature is indifferent to what results both he and his adversary receive, but he does not take any risk when entering the game. However, the player-decision-maker must consider the so-called states in nature, thus operating under uncertain conditions. The literature defines a state by nature as phenomena that occur regardless of the player's expectations and often manifest themselves after choice or implementation. Conditions inherently determine the outcome but are not controlled by the player concerned during the examination.

For analytical purposes, nature was assumed to be a market indifferent to the impact on the decision. The market verifier is a previously performed SWOT analysis for two modes of transport: rail and road. Based on the results obtained from the study, the decision-maker can make decisions independently of subjective preferences.

In the work under study, strengths, weaknesses, opportunities, and threats are states that will select a strategy and decision rules. The assumed states are inherently probability distributions. For this purpose, commonly known criteria should be used (Simon, 1959; Raiffa, 1968; Papadimitriou, 1985; McNamee & Celona, 2008; Pažek & Rozman, 2009):

- the Wald criterion,
- the optimistic criterion,
- the Hurwicz criterion,
- the Savage criterion,
- the Laplace–Bayes criterion.

Moreover, we should also examine the:

- expected monetary value (EMV),
- expected value of perfect information (EVPI),
- expected loss of opportunity criterion (EOL).

The *decision-maker in the Wald criterion* assumes that a worst-case scenario (state of nature) will occur, leading to the worst possible payoff for a given player's strategy. The strategy that maximizes this minimum payoff is then chosen. This is a max-min strategy. It characterizes a player interested in minimizing risk and protecting himself against the worst possible outcome in the event of an unfavorable state of nature. The Wald criterion is derived from the formula (Wald, 1949):

$$v = \min_{i}\{\min_{j}(w_{ij})\} \tag{4}$$

where w_{ij} is the payoff value for strategy a_i, $i = 1,2,\dots,n$ (number of rows), and $j = 1,2,\dots,m$ (number of nature's states).

The *optimistic criterion*, also called the maximax criterion, represents an approach to decision-making in which the decision-maker aims to maximize the best possible outcome for each state of nature. In the case of the optimism criterion, the decision maker assumes that the most favorable state of nature (the best possible scenario) will occur and chooses the strategy that brings the highest possible outcome in this case. In other words, the decision maker is optimistic about future conditions and aims to maximize their potential benefits. This criterion assesses the achieved maximum outcome for each state of nature. This criterion is derived from the following formula (McNamee & Celona, 2008):

$$v = \min_{j}\{\min_{i}(w_{ij})\} \tag{5}$$

where w_{ij} is the payoff value for strategy a_i, $i = 1,2,\dots,n$, and $j = 1,2,\dots,m$.

The *Hurwicz criterion* (Hurwicz, 1951) is used when the decision maker must consider both risk (uncertainty) and the possibility of achieving different outcomes. The following formula is the definition of the Hurwicz criterion:

$$v_i = \lambda \min_j(w_{ij}) + (1-\lambda)\max_j(w_{ij}) \tag{6}$$

where is a caution factor, w_{ij} is the payoff value for strategy a_i, $i = 1,2,\ldots,n$, and $j = 1,2,\ldots,m$.

In practice, the decision maker selects a strategy that considers the possibility of achieving high results in the best case (optimistic scenario) and minimizing risk in the worst case (pessimistic scenario). The Hurwicz criterion allows the decision maker to consider risk and his preferences regarding expected results when making a decision.

The *Savage criterion* (Savage, 1951), also known as the mini-max regret criterion, is another decision-making criterion. This approach minimizes the so-called "regret (r)," the difference between the best possible and actual results in any state of nature. The procedure is based on the decision maker's pessimistic approach, assuming the worst possible scenario. Then, the regret value is calculated for each strategy, expressed as the difference between the highest payoff in a given state of nature and the remaining values for that state. The following formula describes this situation:

$$r_{ij} = \max_i(w_{ij}) - w_{ij} \tag{7}$$

where w_{ij} is the payoff value for strategy a_i, $i = 1,2,\ldots,n$ and $j = 1,2,\ldots,m$.

Then, the highest regret value is selected for each strategy and, in the next step, the lowest of these values is selected using the formula:

$$v = \min_i\{\max_j(r_{ij})\} \tag{8}$$

where $i = 1,2,\ldots,n$ and $j = 1,2,\ldots,m$. So, the final strategy is to minimize the expected value of "regret" in the most pessimistic state of nature.

The *Laplace–Bayes criterion*, also known as the maximum expected value criterion, is another decision-making criterion. It is used when the decision maker has incomplete or imprecise information about the probabilities of various states of nature. According to the Laplace-Bayes criterion, for each state of nature (S_j in S), the decision maker should evaluate the probability of p_j that S_j will occur. The decision rule is as follows (Pažek & Rozman, 2009):

Algorithm 2 (Pažek & Rozman, 2009)

INPUT: game with nature (state of nature (S_j), m is the number of nature's states, and payoff value);

OUTPUT: the maximum expected value criterion;

1. $p_j = P(S_j) = 1/m$ to each S_j in S, for $j = 1,2,...,m$.
2. For each payoff matrix row a_i, calculate its expected value: $E(a_i) = \Sigma_j\, p_j(w_{ij})$, where w_{ij} is the payoff of ith row and jth column.
3. To $i = 1,2,...n$ because p_j is a constant, $E(a_i) = p_j\, \Sigma_j\ (w_{ij})$.
4. Choosing the higher $E(a_i)$ value is the optimal decision under uncertainty.

The Laplace-Bayes criterion is based on treating all possible states of nature equally and is used when more detailed information about probabilities is lacking. It is a simple and intuitive method that allows the decision maker to choose the strategy with the highest average outcome value, regardless of the probability of the individual states of nature occurring, i.e., according to the formula:

$$v = \max_i[E(a_i)] \tag{9}$$

The criteria for games with nature used to indicate the most advantageous transport system are complemented by the abovementioned criteria: expected opportunity loss (EOL), expected monetary value (EMV), and expected value of perfect information (EVPI). The first of these refers to the evaluation of various alternatives. The losses from making a specific decision are assessed, considering all the possible outcomes and probabilities. EOL compares alternatives and chooses the one that minimizes the expected loss of opportunity. The following formula is used to determine the value of this criterion (Kumar, 2015):

$$\mathrm{EOL}(a_i) = \sum_{j=1}^{m} s_{ij} \cdot p_j \tag{10}$$

where a_i is the ith strategy (ith row of payoff matrix), p_j is the jth nature's state (jth column of payoff matrix), and s_{ij} is the payoff value for strategy a_i with the probability of nature's state p_j. EOL values for different decision alternatives can be compared with selecting the one that minimizes the expected opportunity loss. The lower the EOL value, the better the decision alternative.

It is essential to understand that the EOL criterion requires an evaluation of the losses associated with different outcomes or scenarios. These losses can be subjective and depend on the decision-maker's preferences and priorities. The decision alternative's final choice should consider both the EOL criterion and other factors such as risks, costs, benefits, and the decision maker's goals. The expected opportunity loss criterion is calculated from the regret matrix, and the assigned probability distribution from the expected payoff criterion was calculated for the payoff matrix.

EMV, on the other hand, is used to assess project risk. It involves estimating the financial value associated with the potential effects of risk. It allows us to analyze different scenarios and assign them appropriate expected values to assess the impact of risk on the value of the project. This method is based on the probability of a given risk scenario occurring. The product of the likelihood of this scenario occurring and the corresponding financial value is calculated for each risk scenario. The sum of these values for all risk scenarios gives the project's expected value (EMV). The choice of a risk management strategy or decision is based on maximizing EMV.

It should be assumed that the probability distribution of the occurrence of the state of nature is known. Then, the expected monetary value for choosing the ith strategy (a_i) for jth nature's state probability (p_j) is as follows (Tulsian & Pandey, 2016):

$$\text{EMV}(a_i) = \sum_{j=1}^{m} w_{ij} \cdot p_j \tag{11}$$

where a_i is the ith strategy (ith row of payoff matrix), p_j is the jth nature's state (jth column of payoff matrix), and w_{ij} is the payoff value for strategy a_i with the probability of nature's state p_j. The optimal decision is the maximal value of the EMV, i.e.:

$$d_{\text{EMV}} = \max \text{EMV}(a_i) \tag{12}$$

The expected value of perfect information (EVPI) measures the theoretical maximum value achieved by having complete, accurate information before deciding. This criterion determines the value of additional information that can influence the decision and reduce risk.

To calculate EVPI, we need to compare two situations: one in which we have complete information before deciding, and the other in which we do not have this information and choose based on the available data. The EVPI value is the difference between the expected value of the outcome with complete information (EVWPI) and the expected value without this information (EVWOPI) equal to EMV. This approach is helpful in decision analysis because it allows us to assess whether it is worth investing in additional information or how much it is worth paying for such information.

EVWPI is calculated from the sum of the products of the probabilities of the occurrence of individual states of nature (p_j) and the maximum value of the game for a given state of nature $\max\{w_{ij}\}$. Mathematically, this means the following (Heath, Kunst & Jackson, 2024; Jackson et al., 2024):

$$\text{EVWPI}(a_i) = \sum_{j=1}^{m} \max_i (w_{ij}) \cdot p_j \tag{13}$$

Finally, the equation for determining EVPI takes the following form (Heath, Kunst & Jackson, 2024; Jackson et al., 2024):

$$\text{EVPI} = \text{EVWPI} - \text{EMV} \tag{14}$$

Theoretical results

First, a SWOT analysis should be conducted for the transport modes under consideration following the subsection *basics of SWOT analysis*. The most essential factor in the analysis is to make an objective point assessment of individual factors. In this respect, the best scale is 1–5 (e.g., Likert), with one being the lowest score and five as the highest. These values form the basis for building the payoff matrix. However, in the case of weaknesses and threats in the decision-making model, we assume negative values in these two columns of the payoff matrix.

In the next step, we build a model of the game with nature. This game has four states: S, W, O, and T. The options to choose from are the indicated/considered transport modes. Then, the payoff matrix is built based on the point assessments of individual analysis factors except that, in the case of "W" and "T", we must assume negative values for these assessments.

In this way, we have prepared a game with nature. Using the criteria and decision-making methods described in the subsection *game theory with nature,* we can indicate the means of transport most suited to a given task. The proposed model of the game with nature is shown in Table 1.

In the interpretation of the theory of games with nature for the SWOT analysis, in particular in the case of the Laplace–Bayes criterion, negative values

Table 1. General schema of a game

Strategies	Nature's contingencies			
	Strengths (c1)	Weaknesses (c2)	Opportunities (c3)	Threats (c4)
Strategy 1	Payoff_s1	−payoff_w1	Payoff_o1	−payoff_t1
Strategy 2	Payoff_s2	−payoff_w2	Payoff_o2	−payoff_t2
Strategy 3	Payoff_s3	−payoff_w3	Payoff_o3	−payoff_t3

in the state of nature for weaknesses and threats should be taken into account because the result would be falsified if we assume that the highest score obtained is the decisive value for the choice. Without considering this relationship, the decision maker choosing the highest score could select the decision that generates weaknesses and threats.

We build a SWOT matrix for each mode of transport. First of all, we propose the general decision-support algorithm:

Algorithm 3

INPUT: decision problem;

OUTPUT: optimal or quasi-optimal strategy;

Step 1. Define the decision problem.

Step 2. Make the SWOT analysis.

Step 3. Built game with nature, where S, W, O, and T are the nature states.

Step 4. Resolve the game according to known decision criteria described in the subsection *game theory with nature*.

Step 5. Find the EMV, EOL, and EVPI.

Step 6. Provide the decision about the strategy based on steps 2–5.

The procedure given above is simple. As nature states, an innovative aspect of the presented method is using the SWOT parts.

Application

The purpose of creating a SWOT analysis is to indicate whether road or rail transport is substitutable for transporting dangerous and oversized loads. It combines branches to make a rational choice based on game theory. We use Algorithm 3. As the INPUT, we provide two transport modes, i.e., road and railway, for transporting heavy goods. The OUTPUT provides the optimal transport node for this cargo type. We start from step 2 – a SWOT analysis for road and railway transport modes.

SWOT analysis for rail transport mode

In this section, we investigate the railway transport mode.

Strengths:

1. Energy efficiency. Rail transport is more energy efficient than other modes of transport, such as trucks or airplanes. Rail trains can transport significant amounts of goods or passengers with low energy consumption.
2. Large transport capacity. Rail can transport large quantities of goods at once. Long freight trains can transport huge quantities of goods in a single journey, which makes rail transport attractive to logistics companies.
3. The ability to transport heavy and dangerous goods. Rail offers a safe and controlled way to transport heavy and dangerous goods such as fuels, chemicals, and explosives.
4. Uninterrupted transport time to the destination. Rail transport is not limited by a mandatory ban on movement at designated intervals.

Weaknesses:

1. Limited route flexibility. Rail is limited to existing routes and networks. It is not easy to create new routes, especially in urban areas, which can lead to inefficient connections between different regions.
2. Limited speed and travel time. Rail transport is usually slower than planes or cars, which can affect the delivery time of goods and the attractiveness to passengers on short routes.
3. Integrated infrastructure. Rail transport often uses developed infrastructure, such as railway lines, stations, and transshipment terminals, which require additional investment and expansion with additional point points.

Opportunities:

1. Sustainable transport. Given growing environmental awareness and efforts to reduce greenhouse gas emissions, rail transport is seen as a more ecological alternative to other modes that generate significantly more CO_2 emissions. For this reason, governments and international institutions promote the development of rail transport as part of sustainable development.
2. Infrastructure development. Many countries are investing in expanding rail infrastructure, allowing faster and more efficient movement of goods and passengers. The modernization of tracks, the construction of new stations, and the development of logistics systems are conducive to the development of rail transport.
3. T-ENT network. Designation of the T-ENT network determines increased investment outlays on selected transport lines.
4. Global rail integration plays a significant role in promoting international trade integration. Rail connections between countries and continents facilitate large-scale freight transport. Initiatives such as the Silk Road, which aims to strengthen rail connections between Europe and Asia, offer the potential for international rail transport.

Threats:

1. Lack of schedule flexibility. Rail often depends on schedules and timetables, making adapting to

individual customer needs difficult. Other modes of transport, such as trucks, offer greater flexibility and customization regarding delivery time and location.
2. Infrastructure constraints. Existing infrastructure constraints, such as congested rail networks and the need to modernize and maintain rail lines, may threaten the efficiency and competitiveness of rail transport. Lack of appropriate investment in infrastructure may limit the possibilities of developing the industry.

Based on this analysis, we provided a survey to calculate the weights of the factors. Based on 32 answers, we obtained the following results (Table 2). This survey was carried out anonymously and voluntarily among representatives of a dozen transport companies specializing in the transport of oversized loads and heavy ones. Since transport of this type of cargo is highly specialized, there are not many such transport companies on the market in the Pomeranian Voivodeship and surrounding areas. Hence, the number of questionnaires selected for analysis is 32.

According to the survey results, every factor is weighted on a 1–5 scale. Based on this, we obtain the following:

$$S = 19;\ W = 11;\ \text{S-W: } 19 - 11 = 8\ (S) \quad (15)$$

$$O = 15;\ T = 7;\ \text{O-T: } 17 - 7 = 8\ (O) \quad (16)$$

Table 2. Summary of weights for factors in rail transport for the SWOT analysis

Category	Symbol	Factor	Weight
Strengths	S1	Low energy consumption	5
	S2	High cargo capacity	5
	S3	Ability to transport oversized and dangerous goods	4
	S4	Uninterrupted transport time to destination	5
		Sum of weights	19
Weaknesses	W1	Limited route flexibility	5
	W2	Limited speed and travel time	3
	W3	Integration of infrastructure	3
		Sum of weights	11
Opportunities	O1	Sustainable transport	5
	O2	Infrastructure development	4
	O3	TEN-T network development	4
	O4	Global integration	2
		Sum of weights	15
Threats	T1	Lack of flexibility in the schedule	5
	T2	Infrastructure constraints	2
		Sum of weights	7

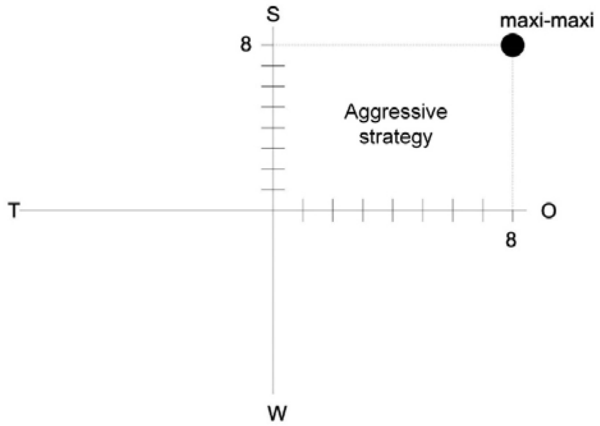

Figure 2. SWOT strategic position for rail transport

Then, we plot the obtained values on the *x*- and *y*-axis to determine the target strategy for rail transport, as shown in Figure 2.

In the case under study, rail transport is in the maxi-maxi area, which means a unique position in the market where strengths outweigh weaknesses and opportunities outweigh threats. Developing a strategy to continue this trend is crucial to maintaining this position. As part of the "maxi-maxi" strategy (referred to in the literature as an aggressive strategy), the rail industry should strive to maximize its strengths and benefits from emerging market opportunities. This approach is based on aggressively using competitive advantage and development opportunities. As part of this strategy, the rail industry focuses on identifying and using its greatest assets, such as unique capabilities, resources, or technological advantages. At the same time, the analyzed transport industry takes risks and actions to maximize the benefits from various opportunities that appear on the market.

The railway must demonstrate flexibility, adaptability, and innovation to implement a maxi-maxi strategy successfully. It must monitor market changes to identify new opportunities and adjust the strategy based on changing conditions. To maximize its market presence and succeed, it must focus its resources and efforts on areas with a competitive advantage.

SWOT analysis for road transport mode

Now, we propose a SWOT analysis for road transport.

Strengths:

1. Efficiency and flexibility. Road transport is widely available and flexible, allowing easy movement of both people and goods.

2. Large road network. Many countries have extensive road infrastructure, allowing efficient transport over various distances.
3. Short delivery times. Road transport can be fast, especially for short and medium distances, which benefits companies that need goods delivered quickly.

Weaknesses:
1. Environmental pollution. Road transport is responsible for significant emissions of greenhouse gases and other air pollutants, which negatively impact the environment and public health.
2. Congestion. Heavy traffic and traffic jams can cause delays and frustration for drivers and transport companies.
3. Limited capacity. Trucks have limited cargo capacity compared with other modes of transport, which can be a challenge for carriers handling large volumes of goods.
4. Mandatory stops during cargo transport to the destination. The legislator sets the hours for the transport of dangerous and oversized cargo.

Opportunities:
1. Development of electric technologies. The growing popularity of electric vehicles can help reduce air pollution emissions and dependence on fossil fuels for road transport.

Table 3. Summary of weights for factors in road transport for the SWOT analysis

Category	Symbol	Factor	Weight
Strengths	S2	Efficiency and flexibility	5
	S3	Large road network	5
	S4	Short delivery times	4
		Sum of weights	14
Weaknesses	W1	Environmental pollution	5
	W2	Congestion	5
	W3	Limited capacity	3
	W4	Mandatory stops	4
		Sum of weights	17
Opportunities	O1	Development of electric technologies	5
	O2	Automation and intelligent transport technologies	5
	O3	Integration with other means of transport	5
		Sum of weights	15
Threats	T1	Competition with alternative means of transport	3
	T2	Risk of road accidents	4
	T3	Dependence on road infrastructure	4
		Sum of weights	11

2. Automation and Intelligent Transport Technologies. Advances in automation and intelligent transport technologies can help increase road transport's efficiency and safety.
3. Integration with other modes of transport. Road transport can be combined with other modes of transport, such as rail or air.

Threats:
1. Competition from alternative means of transport. The growing importance of rail and sea transport may constitute competition for road transport, especially on long routes.
2. Risk of road accidents. Road transport carries the risk of road accidents, which can lead to more extraordinary human, material, and financial losses than other modes of transport.
3. Dependence on road infrastructure. The condition of road infrastructure, such as roads, bridges, and tunnels, limits road transport. If the infrastructure is insufficient or requires repairs, it can lead to delays and disruptions to transport.

According to the survey results, every factor is weighted on a 1–5 scale. Based on this, we obtain the following:

$$S = 14;\ \ W = 17;\ \ S, W: 17 - 14 = 3\ (W) \quad (17)$$

$$O = 15;\ \ T = 11;\ \ O, T: 15 - 11 = 4\ (O) \quad (18)$$

Table 3 presents a summary of the weightings of factors in road transport for the SWOT analysis.

Then, we plot the obtained values on the *x*- and *y*-axis to determine the target strategy for road transport, as shown in Figure 3.

In the case under study, road transport is in the maxi-mini area, which determines the trends for competitive strategy. In the road transport industry, aspects with a smaller scale of problems

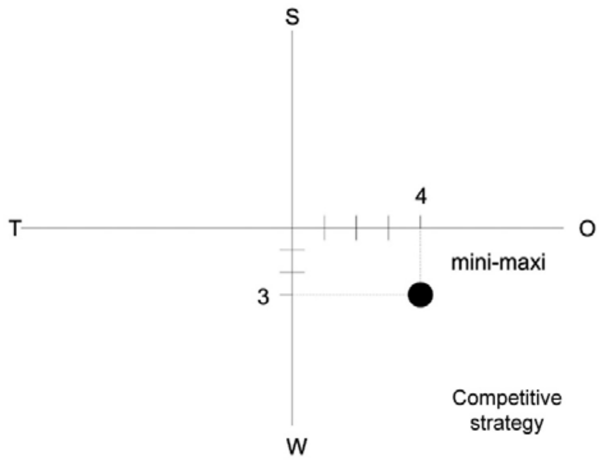

Figure 3. SWOT strategic position for road transport

dominate compared with those with clear potential, and emerging opportunities prevail in the environment. However, the use of these external perspectives is limited due to the internal weaknesses of this industry. Hence, the key strategy for road transport should be to minimize weaknesses and maximize opportunities. Thus, it focuses on using the benefits resulting from the environment while reducing its weak points. This process manifests in the overall improvement of the sector, increasing capital, and maintaining a competitive advantage. The following steps can be considered as part of the competitive strategy:

- expansion of existing resources,
- increasing efficiency,
- reducing costs,
- maintaining competitive advantage.

Next, based on equations (1)–(3), we calculate the MA, MP, and PSS parameters (see Table 4).

Table 4. Values of the MA, MP, and PSS parameters

Transport nodes	MA	MP	PSS
Road transport	0.57	0.45	0.51
Railway transport	0.68	0.63	0.655

The PSS threshold value is 0.5. Below this value, it is assumed that a given transport branch has no chance of development. According to the results shown in Table 4, rail transport has achieved the PSS = 0.655 indicator. This means a high probability of achieving strategic success and maintaining a competitive position in the market. In the case of road transport, PSS = 0.51, which is a value slightly higher than the threshold. This means caution is needed when further investing in the road transport branch.

Results of game theory with nature

We now realize step 3 of Algorithm 3, i.e., we built a game with nature, where S, W, O, and T are the nature states. Table 5 shows the payoff matrix for the proposed game. The values are from the SWOT analysis (Tables 2 and 3).

Table 5. Payoff matrix

Transport nodes	Nature's contingencies			
	S	W	O	T
Road transport	14	−17	15	−11
Railway transport	19	−11	15	−7

Taking into account this matrix, we resolve the game according to known decision criteria described in the subsection *game theory with nature*. The game values for every criterion are given in Table 6. In the case of the Hurwicz criterion, we arbitrarily assume a caution factor of $\lambda = 0.3$ and $1 - \lambda = 0.7$.

Analyzing the results in Table 6, it should be pointed out that, according to all the criteria, rail transport is the most advantageous choice. In the case of the Wald and Savage criteria, the wins indicate negative values. In the first case, rail transport brings a smaller scale of potential losses (looking at the weaknesses and threats). In the case of the Savage criterion, a negative value of the regret matrix de facto means a gain for the decision-maker when choosing rail transport.

Following Algorithm 3, we go to step 4 and calculate the EMV and EOL values. Table 7 shows the game's results according to every criterion.

Finally, we calculate the EVPI (according to formula (14)). It equals 9.2, which is the cost of obtaining perfect information. This is the maximum value to use to improve market information. According to the above results, it should be noted that road and rail transport operate as substitutes, competing for the common market simultaneously. These two entities are at different stages of development and, therefore, investment. While the road transport market is saturated with solutions, and the chosen strategy should be maintained, the rail market is still underinvested. There are no sufficient solutions, only the

Table 6. Results for a particular criterion

Transport node	Wald criterion	Maxi-max criterion	Hurwicz criterion	Savage criterion	Laplace Bayes criterion
Road transport	−17	17	−2	5	0.25
Railway transport	**−11**	**19**	**8**	**-6**	**4**

Table 7. Results of the game with nature criteria

Transport node	Wald criterion	Maxi-max criterion	Hurwicz criterion	Savage criterion	Laplace-Bayes criterion	EMV criterion	EOL criterion
Road transport	−17	17	−2	5	0.25	3.1	1.5
Railway transport	**−11**	**19**	**8**	**−6**	**4**	**6.6**	**−2**

desired direction of action. Therefore, the probability of success in rail transport is relatively more significant than in road transport.

Based on the obtained research, it is stated that the strategic position of rail transport exceeds that of road transport. The rail market is becoming more attractive, although still underestimated, with a growing tendency. Although the share of road transport in total transport is still growing very intensively, it can be stated that this branch is on the verge of investment profitability, especially in transporting dangerous and oversized loads. Customers may choose rail transport when transporting oversized and hazardous loads. Still, service providers should adapt their offer and expand to the target market, especially since there are premises for this.

The SWOT analysis shows that both branches are in different strategic quadrants. This results from obtaining different parameters. Therefore, legislators, users, and companies creating supply should apply different strategic variants depending on the emerging trends. Rail transport is characterized by an aggressive strategy located in the maxi-maxi quadrant. Strengths dominate the examined transport industry, and there are many opportunities outside it. Such a situation requires applying a "maxi-maxi" strategy based on substantial expansion and diversified development. This results from the accumulation of opportunities and strengths of the company, which prevail. An aggressive strategy of conquering new markets, investing, and strengthening the competitive position in the sector is possible.

The "maxi-maxi" strategy also uses synergy between the branch's strengths and the environment. In the transport industry, this means using the development potential based on strengths and taking advantage of favorable market conditions. The railway can focus on expansion by conquering new markets, investing in new technologies and services, and strengthening its competitive position in the transport sector.

Activities related to the "maxi-maxi" strategy also include building strategic partnerships, establishing synergies with other companies, searching for innovative solutions, and using scale effects. The railway can also focus on developing various areas of activity to minimize risk and maximize available opportunities. As a result, the "maxi-maxi" strategy allows the railway to develop dynamically, conquer new markets, and strengthen its competitiveness, using existing strengths and favorable environmental conditions.

Regarding road transport, the focus should be on a competitive strategy within the mini-maxi area. Based on the conducted research, it is concluded that weaknesses prevail compared with strengths. However, it is necessary to emphasize favorable external conditions while reducing internal shortcomings. It can also be stated that the industry is so invested and developed that another round of investment could be associated with costs that would not bring a sufficient rate of return on investment.

Conclusions

This article's aim has been achieved. A new method of defining the states of nature using individual parts of the SWOT analysis has been proposed. Additionally, the criteria for deciding under conditions of uncertainty have been extended to include EMV, EOL, and EVPI. As a result, we have also obtained a purely economic approach to decision-making.

This method was used to indicate the most appropriate mode of transport for heavy and oversized loads. The results showed the advantage of rail transport over road transport. At the same time, the SWOT analysis conducted before solving the game with nature enabled, based on the survey results, an indication of these advantages. In the future, this research will be supplemented by analyzing the criticality of transport network elements based on graph theory and the theory of two-person zero-sum games.

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Efficient dispute resolution mechanisms in marine insurance contracts: Legal perspectives and emerging trends

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JEL Classification: K41, G22, K33, D86

Abstract

The marine insurance contract primarily aims at providing security for the performance of the commercial activity of transporting goods. This contract has a special nature that aims to indemnify the insured against losses to the marine adventure. Marine insurance contract disputes, like several other types of disputes, are determined by various resolution procedures, either in the courts or through alternative methods such as arbitration, negotiation, and mediation. This characteristic influences the choice of the substantive and procedural rules that will apply to resolve possible conflicts between the parties. If disputes do arise, peaceful and quick resolution is in the interest of everyone involved. Commercial parties usually insert in marine insurance contracts the choice of court and applicable law clauses that determine a timely resolution of disputes. The choice of dispute resolution method is therefore critical. In this paper, we discuss modern, quick, and effective resolutions to ensure that the disputes arising from a marine insurance contract are resolved at the lowest cost. We also analyze several cases.

Introduction

A contract of marine insurance embodies all details associated with risks and losses that may be encountered during the course of shipping. It is an agreement between the insurer and the insured. The main objectives of every marine insurance policy are to protect shipowners against claims by third parties, to enable them to indemnify themselves against losses, and also to protect the owners of the cargo. International risk-insuring authorities abound, including Lloyd's and P&I clubs. It is, therefore, self-evident that disputes over entitlement to gain indemnity, or the size of the indemnity to which one is entitled, are bound to arise (Gürses, 2023). The identification and settlement of these disputes are, therefore, special problems for marine insurance, and the courts have, from early times, adopted special rules of policy in this regard. Almost every provision in an insurance policy represents what may happen if the insured events take place, and an equitable style of resolving the conflict between the parties should a dispute arise out of such an event. Policies contain various provisions to deal with disputes in which the issue between the parties is whether the alleged loss is covered by the policy and, if so, to what extent. The courts, therefore, are involved in the process of interpreting and granting effect to those procedural and substantive provisions that encompass the manner in which ship-owning and cargo interests are to be protected (Thomas, 2023).

The insurance industry provides individuals, businesses, and organizations with a risk management solution that allows them to gain a degree of control over an unpredictable future. However, in the event of a loss, the industry shifts its focus to claim processing. In cases where disputes develop, insurance claims are addressed through dispute resolution processes. Marine insurance contract disputes are resolved by many procedures, either in the courts or via alternative dispute resolution methods such as arbitration, negotiation, and mediation. In the future, these processes may be refined to enhance the resolution of insurance disputes (Gürses, 2023).

This paper adopts a mixed-method approach to explore dispute resolution mechanisms in marine insurance contracts. By integrating doctrinal legal analysis with case study evaluations, the methodology examines statutory frameworks, international conventions, and arbitration practices. Comparative analysis is used to highlight differences across jurisdictions, while specific case laws serve as empirical evidence for theoretical principles. The research also incorporates a review of alternative dispute resolution (ADR) methods, focusing on arbitration, mediation, and emerging technologies such as online dispute resolution (ODR). This approach ensures a comprehensive understanding of both traditional and innovative resolution mechanisms, aligning with the study's aim of proposing effective and efficient solutions to resolve marine insurance disputes.

Literature review

Due to the unique risks associated with maritime activities, marine insurance contracts have long been recognized for their complexity. Such contracts aim to indemnify the insured against losses stemming from marine perils, and the dispute resolution mechanisms embedded in such contracts are of particular importance due to the international nature of shipping (Gürses, 2023). The special nature of marine insurance, often governed by international conventions and national legislation, requires robust procedural and substantive rules that address the specific needs of both insurers and insureds (Thomas, 2023).

Dispute resolution in marine insurance contracts often relies on a combination of traditional court litigation and ADR methods such as arbitration, mediation, and negotiation. As Coyle (Coyle, 2022) explains, the nature of international shipping means that parties are frequently located in different jurisdictions, making it essential for dispute resolution mechanisms to minimize costs and expedite outcomes. The importance of quick and cost-effective dispute resolution is further underscored by Singh (Singh, 2023), who suggests that parties in commercial relationships value efficiency due to the significant economic repercussions of prolonged disputes.

International conventions, such as the Marine Insurance Act of 1906 and its later iterations, provide the foundational legal framework for these contracts (UK Parliament, 1906). These conventions set the standards for coverage, claims handling, and dispute resolution procedures (Curtis, Gaunt & Cecil, 2020). Furthermore, as Baatz (Baatz, 2020) discusses, international law and various conventions attempt to balance the rights and obligations of the insurer and insured, protecting the insured's interests while also managing the liabilities of the insurer.

Litigation in national courts remains a common method of resolving disputes, but it is often seen as costly and time-consuming. ADR mechanisms, particularly arbitration, have emerged as preferable options for many marine insurance contracts. Arbitration is praised for its flexibility and confidentiality, and for the expertise of arbitrators in maritime law (Sturley, 2024). Emerging forms of dispute resolution, such as ODR and the use of blockchain technology in "smart contracts," have also been identified as potential future trends in marine insurance (Pu & Lam, 2020).

While ADR mechanisms offer numerous advantages, such as faster resolutions and lower costs, they are not without challenges. Bundy (Bundy, 2012) notes that, despite their advantages, ADR methods may still result in unsatisfactory outcomes if the resolution is not grounded in sound economic and legal principles. A combination of mediation and arbitration, often referred to as "med-arb," has gained popularity due to its ability to streamline the resolution process (Menkel-Meadow, 2018). However, there are concerns about the enforceability of arbitration decisions across different jurisdictions, a topic explored by Fu (Fu, 2022).

Fundamental elements and importance of marine insurance dispute resolution

Insurance policies

Courts in many countries have acknowledged the unique character of marine insurance contracts and the need for particular laws and processes to resolve disputes resulting from such contracts (Simanjuntak

& Widiarty, 2022). The risk of loss or damage to ships and cargo has, therefore, been specially regulated and, to a large extent, accommodated in maritime practice, mainly following rules of a commercial and cooperative nature. Indeed, members of the maritime community usually show a remarkable willingness to settle or compromise in disputes that may arise from the application of such rules (Sturley, 2024). It is essential for all concerned in a shipping venture to know from the outset where they stand in relation to rights, liabilities, and consequences, as uncertainty could paralyze the process. Thus, the contracting parties' willingness to follow accepted commercial norms and precedents can prevent or significantly reduce the likelihood of such disputes. Marine insurance is a contract of indemnity and is based on the payment of a premium, which secures financial compensation in the event that the insurance's subject matter suffers harm due to certain perils (Thomas, 2006).

Importance of dispute resolution mechanisms

A method of resolving disputes that assures the parties of a quick and effective settlement reduces the likelihood of adverse economic consequences. However, it is one thing to seek a speedy and low-cost resolution of a dispute; it is quite another to seek such a resolution if the price is a decision that makes no economic or legal sense (Singh, 2023). The purpose of this essay is to explain the generally accepted international dispute resolution mechanisms for marine insurance contracts. In undertaking such a task, it is useful, first, to identify the importance of these mechanisms. It has been suggested that the importance of a method of resolution of disputes between commercial parties derives from one or more of three separate sources (Bundy, 2012). First, the procedure should reduce the cost of resolving the dispute. In most international commercial relationships, the parties are located in different countries; this is normally true of the relationship between the assured and the insurer under a marine insurance contract. The cost of litigating in a foreign country is frequently prohibitive. Second, the procedure should provide a speedy resolution. Delays in the resolution of disputes can have adverse economic consequences beyond the mere expenses of rights determination (Pu & Lam, 2020). Finally, the effectiveness of a dispute resolution mechanism is also determined by its enforceability, ensuring that decisions are recognized and upheld across jurisdictions (Fu, 2022).

International conventions and national legislation

Marine insurance contracts are private contracts. The main legal rules that regulate these contracts are currently found in the Navigation Codes and the Commercial Codes. Because of the large number of legislative interventions in the private insurance sector, the complex body of case law, and the fact that private insurance regulations come from a variety of sources, marine insurance is, at least on a national level, very unstable. However, the shortcomings of the legislative framework do not, in our opinion, significantly impinge on the efficacy of the contractually stipulated dispute resolution mechanisms (Gürses, 2023).

National legislation governing maritime transportation has implemented incorporation rules allowing carriers to include certain terms in their contracts of carriage, typically via standard form contracts. The requirement of written form contained in most jurisdiction and arbitration clauses makes them more likely to prevent discussion as they cannot easily be demonstrated. Marine insurance contracts that are underwritten in England are governed by the various sets of Standard Marine Clauses, which frequently eliminate the power of the presumptions set by the Marine Insurance Act of 1906. Jurisdiction and arbitration clauses are included in charter parties, bills of lading, and other transport documents by reference. The difference in treatment is mainly due to the fact that under bills of lading, the incorporated terms must be approved, whereas in charter parties, the parties can agree on any terms. These provisions are recognized in the national laws of most countries and are usually considered incorporated, save for some exceptions. However, to prevent disputes about the satisfaction of the form requirements, it has been suggested it would be better to specifically repeat the terms in each contract (Gee, 2020).

The conventions that contain provisions applicable to marine insurance contracts are the 1906 French Title on Civil Code Maritime (FCC); the Luxembourg Protocol, in force in Austria, France, Luxembourg, Monaco, and Switzerland; and the United Kingdom Marine Insurance Acts of 1906 and 2015 (Stebbings et al., 2020). These legislative instruments collectively establish the legal framework governing marine insurance, defining the rights and obligations of insurers and insured parties. International conventions and treaties have attempted to describe certain situations in which the liability of the insurer would exist or be limited, or in which, as between conflicting interests, the superiority of one or the other of the parties could be supported. Examples include provisions related to the insurable interest of the assured or the mortgagee, the civil commotion risks, the illicit traffic risks, and warranties of seaworthiness (Baatz, 2020). However, those who drafted these provisions mostly intended them to protect the assured rather than derogate from his rights; therefore, such provisions do not determine the chances of the parties within the commercial context. If a commercial dispute arises, the commercial interests of the parties are determined by the commercial rules that govern the interpretation of the contract terms, which are the same as those applied to the non-mandatory provisions of the conventions or treaties. Commercial interest rules are applied to grant either party the power to support their legal position (Baker & Logue, 2015).

Types of disputes in a marine insurance contract

The first set of disputes that can arise in a marine insurance contract is over the legality of the contract itself. This legitimacy can be challenged under the general law of contract on the grounds of misrepresentation, non-disclosure, mistake, duress, or undue influence. Additionally, since the laws governing shipping and navigation frequently restrict or interact with marine insurance, a contract that violates these laws may be void or voidable (Baker, 2020). The Institute Time Clauses Hulls 1/10/83, which forbid using improper shipping terms, deal with the validity of these grounds for dispute, albeit in a non-shipping context. Thus, disputes over the legality of a marine insurance contract may arise from problems that are common to all contracts or to shipping, or from problems exclusive to insurance contracts (Thomas, 2006).

Disputes may also arise due to the perils insured; an aspect unique to insurance. The contract transfers the risk of those events, which the parties guarantee to be true. Where the contract does not warrant the existence of such a risk, the insured party may challenge the legality of the contract by asking the court to declare the contract void. To help prevent disputes over perils insured, the Institute Cargo Clauses list the insured perils and thus operate on a named-perils basis. However, all risk clauses list certain events, and therefore, they operate on a non-named-perils basis. This is evidence that the insurance market does allow for properly drafted non-named-perils clauses (Dunt, 2024).

Coverage disputes

Institute Cargo Clause A offers comprehensive coverage by encompassing all potential risks of loss or damage to the goods. In addition to the risks specified in Clauses B and C, the Institute Cargo Clauses do not provide coverage for risks such as wars, strikes, riots, and civil commotions. Nevertheless, the insurer has the option to offer this coverage in exchange for an extra payment of marine insurance premiums (Klopott, 2022). Institute Cargo Clause B provides an extra level of safeguarding. In addition to encompassing all the risks specified in Clause C, this coverage extends to protection against occurrences such as earthquakes, volcanic eruptions, rainwater or seawater damage, and other related events. It also provides compensation for any loss or damage to the package during loading and unloading, as well as if it falls overboard (Gürses & Hjalmarsson, 2020). The Institute Cargo Clause C offers fundamental coverage and encompasses a limited range of risks. The coverage includes protection for the shipment in the event of occurrences such as fire, cargo discharge during distress, explosions, collisions, and other accidents (Lee & Seung-Lin, 2024). Some argue that the cargo insurer is even more responsible because the assured must not “deliberately sacrifice” the insured cargo and must tell the insurer if they plan to do so. If the assured does not protect the cargo from an insured peril that is about to happen or is already happening, the assured must sacrifice the cargo in order to save the transport vehicle and the lives of those on board. Most hull and some cargo policies respond in the event of physical loss or damage to the subject matter insured, from whatever cause. Such “all risks” policies are said to provide “accidental damage” cover. For cargo policies that provide such cover and also include, as they often do, cover for “sue and labor,” the scope of the marine insurer’s liability is indeed wide. Not only must the insurer respond to the peril of the sea, but he is also liable to indemnify the assured for any loss falling within the express terms of the policy that the cargo may suffer as a result of any of the insured perils (Hobbs, 2020).

Premium disputes

Disputes concerning the payment of premiums may be referred to arbitration. The arbitration clause usually found in a marine insurance policy is as follows: “all differences arising out of this contract shall be referred to [one or three] indifferent persons, their award to be final, and for the purpose of appointing an arbitrator, the parties have fifteen days after a request in writing has been made by one of them naming the other party involved." The effect of the premium dispute being referred to arbitration is that both the insured and the insurer lose their rights to litigate the matter in court, and the decision of the arbitrators will prevail (Gürses & Hjalmarsson, 2020). To provide protection, the shipowner will usually have entered into a short-term "binding authority" with the insurer. This will permit the lodging of a short-term certificate with the mortgagee in order to comply with the requirements of ship finance. These may include fraudulent conduct or non-disclosure of material circumstances; breach of a warranty; market practice, especially where there is a slipping or some other form of substitution of a risk after the commencement of the policy; or the commencement of the risk before the contract of insurance is concluded (Myburgh, 2024).

Claims disputes

In the event of a payer being dissatisfied with a claim presented by a payee, unless the parties involved are able to settle the matter between themselves, the ultimate recourse is to some form of arbitration. Some form of formal recourse is essential in order to make a judgment enforceable. Any such matter referred to arbitration will generally be resolved at an informal hearing. However, prior to resorting to formal arbitration, it is increasingly common practice to refer the dispute to a mediation process. The mediation process has much to commend it, particularly given the potentially costly hearings that need to be convened (Bundy, 2012). If the matter in dispute is so serious that one of the parties requires urgent interim protection pending a final resolution, and either a national court or an appropriate forum of arbitration has the power to grant such relief, then that party must apply for such protection. One disadvantage of arbitration compared to mediation is that an arbitrator can do nothing more than give a final and binding judgment. Both mediation and arbitration have the drawback of subjecting any dispute to a court of law, which has all the authority necessary to grant any form of relief (Kamanga, 2021).

Case analysis in marine insurance disputes

The practical application of marine insurance law is shaped by judicial decisions that interpret its principles. This paper has already explored theoretical frameworks and their significance; this section presents landmark cases that provide evidence of these principles in action. Each case offers insight into how courts resolve disputes, emphasizing the interplay between legal doctrines, contractual terms, and judicial reasoning.

Arbitration and waiver of rights: Consort Shipping Line Ltd. v. FAI Insurance (Fiji) Ltd.

This case underscores the judiciary's support for arbitration as a cornerstone of dispute resolution in marine insurance. The insured initiated legal proceedings after the sinking of two vessels, unaware of a mandatory arbitration clause in the policy. Upon discovering the clause, they sought a stay in proceedings to refer the matter to arbitration. The insurer argued that initiating legal action constituted a waiver of arbitration rights. However, the court held that such a waiver must be explicit and in writing, as required by the contract (Consort Shipping Line Ltd. v. FAI Insurance, 1998). This decision reinforces the importance of arbitration as an efficient and binding dispute resolution mechanism, demonstrating how arbitration clauses operate within marine insurance contracts and their enforceability in legal disputes (Gürses, 2023; Sturley, 2024).

Compliance with express warranties: Kingdom of Tonga & Shipping Corporation of Polynesia Ltd. v. Allianz Australia Insurance Ltd.

The enforcement of express warranties, as discussed in the subsection "Importance of dispute resolution mechanisms," is pivotal in marine insurance. This case involved the insured's voluntary removal of a vessel from classification, breaching an express warranty that required it to remain in class. After the vessel sustained cyclone damage, the insurer denied liability, citing the suspension of coverage. The insured argued that coverage would be reinstated upon compliance with lesser certification standards, but the court rejected this claim, ruling that the breach of warranty precluded coverage. The court further clarified that each renewal constitutes a fresh contract, negating the applicability of prior agreements unless explicitly incorporated (Kingdom of Tonga v. Allianz Australia Insurance Ltd., 2005). This decision highlights the rigidity of express warranties and their foundational role in maintaining coverage (Curtis, Gaunt, & Cecil, 2020; Dunt, 2024).

Seaworthiness and disclosure requirements: Laho Ltd. v. QBE Insurance (Vanuatu) Ltd.

This case provides a critical examination of the principles of seaworthiness and disclosure, aligning with the subsection "Coverage disputes." The insured's vessel sank under unexplained circumstances, prompting a claim for indemnity. The insurer denied liability, arguing that the insured had failed to demonstrate seaworthiness and had withheld material information. The court held that the presumption of loss due to perils of the sea applies only if seaworthiness is established at the voyage's commencement. Furthermore, material non-disclosures, such as post-certification repairs and an increased passenger load, were found to have voided the policy (Laho Ltd. v. QBE Insurance, 2001). This decision highlights the insured's duty to ensure seaworthiness and disclose relevant information, reinforcing the importance of compliance with express warranties and full transparency (Gürses, 2023; Dunt, 2024).

Statutory time limits and indemnity claims: Pimco Shipping Pty Ltd. v. Moeder, Hermann and Moeher Trading Pty Ltd.

This case underscores the enforcement of statutory time limits in marine insurance, as discussed in the subsection "Premium disputes." The plaintiff sought indemnity after being held liable for damage caused to goods transported on its vessel. However, the claim was filed outside the one-year limitation period prescribed under the Sea-Carriage of Goods Act. The court dismissed the claim, emphasizing the need for strict adherence to statutory deadlines to ensure finality in marine insurance disputes (Pimco Shipping Pty Ltd. v. Moeder et al., 1987). This decision highlights the judiciary's insistence on enforcing time limits as a mechanism to promote certainty and efficiency in legal proceedings (Baatz, 2020; Thomas, 2023).

Historical practices and policy interpretation: Westpac Banking Corporation v. Dominion Insurance Ltd.

This case illustrates the impact of historical practices and renewal notice wording on policy interpretation, connecting to the subsection "Claims disputes." Despite the insured's non-payment of premiums, the court upheld the validity of the policy, noting that renewal notices did not clearly state that coverage would be canceled due to non-payment. Additionally, the parties' historical dealings revealed a consistent practice of renewing coverage despite premium arrears (Westpac Banking Corporation v. Dominion Insurance Ltd., 1996). The judgment underscores the importance of clarity in policy terms, and the role of established commercial practices in shaping contractual obligations (Nottage, 2021; Sturley, 2024).

Traditional dispute resolution mechanisms

Most of the following analysis will focus on special aspects of arbitration as they relate to marine insurance. Although the discussion here is largely limited to arbitration, much of what is said can be applied to other forms of ADR, whether a mini-trial, mediation, or expert determination. The importance of resolving disputes quickly and efficiently is demonstrated by the willingness of the parties to accept the judgment of an arbitrator, who has no legal authority. For many years, arbitration has been the most popular means of resolving maritime disputes over both domestic and international policies (Xhelilaj, 2022).

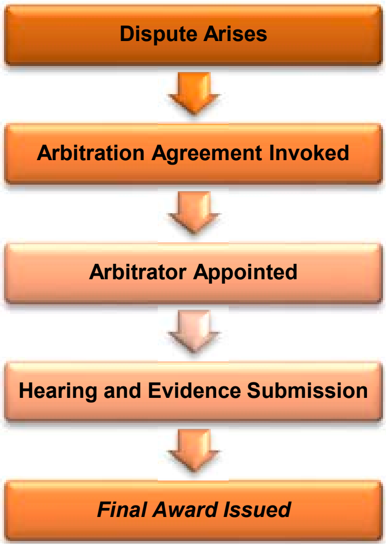

Figure 1. Arbitration Process Flowchart: This flowchart visually outlines the key steps involved in the arbitration process for resolving marine insurance disputes, highlighting its structured and efficient progression from dispute initiation to final award issuance

These provisions are examples of the many ADR mechanisms that have been included in maritime policies over the years. The establishment of special maritime commercial courts, and the development of other specialist judges, have provided the shipping community with an efficient system for resolving disputes relating to shipping, thereby reducing the impediments to trade (Fu, 2022).

Litigation in national courts

There are currently several dispute resolution mechanisms for marine insurance contracts. In the case of national courts, litigation is conducted in a country's court system following established substantive and procedural rules. Litigation is the most traditional and enduring method of dispute resolution. Every country has a court system in which cases are resolved based on the presentation of evidence and legal arguments (Coyle, 2022). The growth of international trade and shipping has, over the years, led to the establishment of specialist commercial courts in many countries. While such courts can resolve maritime disputes, their greatest perceived disadvantage is that their decisions are subject to review by another court and may be appealed on questions of fact or law. This is a time-consuming and expensive process (Dimitropoulos, 2021).

National courts can hand down decisions that bind the parties and resolve the issues before the court. In certain instances, especially in unincorporated arrangements, national courts can issue injunctions preventing one party from proceeding with a matter until the dispute is resolved. This is unlike arbitration, where the tribunal's jurisdiction to grant interim relief may depend on the institutional rules or the law of the seat. At the same time, national courts can sometimes be convenient forums, especially if one of the parties is impecunious or has few assets, as there is little point in commencing arbitration proceedings if the prospective respondent is unlikely to meet its share of the costs (Beresford & Turnbull, 2020).

Arbitration

Two of the most commonly used international arbitration venues are the International Chamber of Commerce (ICC) and the London Court of International Arbitration (LCIA). Both have developed arbitration procedures that can be used without party insistence on special rules. The International Centre for Dispute Resolution, the London Maritime Arbitrators Association, and the Society of Maritime Arbitrators in New York are also frequently used. The most commonly invoked national laws that require or allow for arbitration are the United States Arbitration Act, the English Arbitration Act, and the UNCITRAL International Commercial Arbitration Rules. In addition to being flexible, arbitration has the advantage of being final. In the absence of fraud, national courts will almost never review the merits of an arbitration decision (Menon, 2021). In the maritime setting, arbitration has the advantage of allowing the parties to choose decision-makers with special competence and experience in maritime commercial matters. They will share a bond of experience, trade practices, and understanding of the risks involved in the conduct of maritime commerce. Arbitration is a form of contract: the parties can fashion the procedures to meet their peculiar needs, subject only to any limitations posed by applicable national law. The arbitration decision is private: the public will never have access to it unless one of the parties is foolish enough to challenge it in a public court (Ramanathan, 2021).

The drawback of combining mediation and arbitration is that the mediator's ruling is not usually subject to appeal, and for this reason, parties are less likely to agree to the process. If, however, the dispute involves only a point of law, or where the claim is below a certain amount, the question of the appeal may be deemed to be less crucial. This might encourage the parties to accept med-arb or mediation (Thirgood, 2004).

Future trends in marine insurance dispute resolution

If the parties are unable to come to an agreement, the mediator has the authority to render a final and binding decision. If the mediator's decision is issued during the mediation process, it will very likely be shorter and less expensive than an arbitration decision. Since the mediator has already familiarized themselves with the issues and has likely received the parties' feedback and arguments during the mediation phase, there will be no need to repeat the process at the arbitration level, as is usually the case with a standard arbitration hearing. Mediation can be a very effective tool for adjusting and resolving marine insurance disputes. Arbitration has traditionally been the foremost alternative to court litigation in insurance contracts, and it will remain so. However, a relatively new form of arbitration, known as "med-arb," is a combination of mediation and arbitration and seems to be gaining in popularity, primarily because of the speed and low cost of the process (Menkel-Meadow, 2018).

Specialized dispute resolution mechanisms

When arbitration is to occur in a specialized forum, with specialized arbitrators applying specialized rules, arbitration is transformed from a general appeal process into a unique fact-finding process and a law-applying method of final dispute resolution. Currently, popular forms of arbitration that involve some degree of specialization are mini-trials, summary jury trials, and other hybrid forms of ADR (Robles, 2023).

London market clauses

London Market standard clauses are an important part of the English marine insurance market. The Institute of London Underwriters, the London Insurance Market, and the Lloyd's Market Board all issue them. The objectives of the standard clauses are primarily to state coverage as clearly as possible and to expedite claim handling by eliminating certain proof requirements. The standard clauses make no changes to the law. They are optional and frequently amended (Gürses, 2023). The Time Clauses for Hulls cover loss or damage to the hull and machinery of a vessel. The Institute Time Clauses Hulls and the associated Institute Replacement 1/10/83 Clause have been significantly amended so that they have lost the status of standard market clauses. They address loss, stating that "subject to the perils of, the insurers shall pay the insured for physical loss of or damage to the subject matter" (Zavos, 2006).

Lloyd's open form

Dispute resolution mechanisms for marine insurance contracts fall into three main categories: litigation in national courts, arbitration, and ADR. Litigation is often the default position, not least because either the insurer or the insured may have easy access to the national courts. Where the commercial parties are from different jurisdictions and have confidence in neither legal system, a neutral forum may be preferred. Arbitration is often chosen because parties have greater control over the process, either because they can choose the arbitrators or because the procedures are less formal than those of the national courts, and they have more say over the substantive law that will apply. The major advantage of arbitration, however, with the appropriate choice of law and arbitration forum, is that the award is likely to be readily enforceable in other countries (Bundy, 2012). Should parties wish to avoid arbitration and choose a less formal ADR process, they can do so by contract. Such clauses may specify mediation, conciliation, or expert determination. In some cases, where the issues have more to do with fact than law, party-appointed experts may be called in to give an independent opinion. The Lloyd's Open Form (LOF) is a standard form of salvage agreement that is widely used in the shipping industry. It does not, however, cover all services that may be classified as salvage; any services not covered by the LOF would fall outside its scope. There are two main advantages to a service being classified as LOF salvage. First, there is no right of the salvors to claim a conventional salvage award; salvage awards are generally the subject of negotiation, with the master of the salving vessel having the right to agree. Conventional awards may be enforced against the vessel in rem. It is possible to agree on an award for LOF services, but this is calculated by applying a formula to ascertainable variables; the formula is set out in the LOF agreement. Second, LOF salvage has priority over other maritime liens (Mukherjee, 2022).

Advantages and disadvantages of different mechanisms

Maritime law often requires that disputes be resolved with specific types of special laws that are unique to both the subject matter and the circumstances of the case. The main dispute resolution mechanisms for marine insurance contracts arise from the commonly used special clauses in these contracts. For instance, the sue and labor clause enables the assured to take all necessary measures and institute legal proceedings to protect the subject matter of the insurance and to safeguard the insurer's interests. In doing so, the assured acts on behalf of and for the benefit of the insurer.

Table 1. Comparison of Dispute Resolution Mechanisms. This table provides a comparative overview of various mechanisms – litigation, arbitration, mediation, and ODR – based on criteria such as cost, time efficiency, enforceability, and confidentiality

Mechanism	Cost	Time Efficiency	Enforce-ability	Confiden-tiality
Litigation	High	Low	High	Low
Arbitration	Moderate	Moderate	High	High
Mediation	Low	High	Moderate	High
ODR	Low	High	Varies	Moderate

Specifically, arbitration is a method of private dispute resolution that has long been included in maritime contracts, and clause arbitration has been used extensively in marine insurance contracts over many years. The submission of a particular dispute to arbitration may come from an express agreement between the parties or from a subsequent agreement to submit the dispute to arbitration following a difference that has arisen and which the parties wish to resolve (Lee & Pak, 2020). One of the advantages of arbitration, generally speaking, is that it is a procedure selected and controlled by the parties for the resolution of their disputes. Arbitration has other advantages, provided that it proceeds in a manner that is fair and impartial.

At the time of signing the marine insurance contract, the parties must discuss and take into account the potential benefits and drawbacks of various dispute resolution mechanisms. They should pick the most appropriate procedure, bearing in mind the type of contract and the nature of the risks. This requires some knowledge not only of how arbitration proceedings operate but also of how courts operate if the matter is submitted to litigation. The parties must balance these considerations and assess the potential consequences of their choice of dispute resolution (Okudan & Çevikbaş, 2022).

Efficiency and speed

Most No Longer Used Policies (NLUP) policies contain beached-total-loss clauses, which suspend the running of the policy while the ship is laid up and, in effect, release the shipowner from the obligation to insure. Lay-up clauses were included at a time when there was an oversupply of tonnage and shipping was in a recession. Such clauses can operate harshly in individual cases to deprive the insured of coverage. However, from a societal point of view, they reflect a desirable contractual arrangement that allows inefficient operators to withdraw from the market temporarily. Lay-up clauses fulfill a crucial role in the insurance contract that loss-prevention warranties cannot carry out, by releasing the shipowner from the obligation to insure (Jansen, Kalas, & Bicchieri, 2021). When lay-up and loss-prevention clauses call for the insurance to be suspended, the court must carefully weigh the interests of the insurer and the insured. Lay-up and loss-prevention provisions seek to protect the insured from speculative risks and bar coverage for as long as the particular risk exists. These clauses can be very harsh in situations where the assured's financial difficulties cause or exacerbate the vessel's unseaworthiness. Lay-up and loss-prevention clauses make it easier for the assured to withdraw ships from a specific trade when losses are being incurred and to allocate the risk of loss to other insurers. From the shipowner's perspective, the ability to withdraw a ship from operation without incurring insurance premiums is a valuable option that safeguards his capital (Gürses & Hjalmarsson, 2020).

Confidentiality

Confidentiality is one of the main perceived advantages of arbitration, and has often been considered an essential requirement of maritime and insurance dispute resolution. Indeed, trade and reputation are sufficiently important in both the shipping and insurance industries for commercial parties to prefer a dispute resolution mechanism that safeguards the secrecy of their dealings. The element of secrecy that attaches to commercial arbitration, mainly performed behind closed doors, is not, however, without cracks in the privacy wall. These have appeared particularly during the past decade, when parties to arbitration, especially those in the maritime and insurance communities, have become more vocal in their demands for greater transparency in arbitral awards. The less serious structural limitations stem from the fact that arbitration is part of the judicial process, and essential justice requires some decisions to be made in public (Nottage, 2021).

Enforceability of decisions

Many of the available extrajudicial processes culminate in an arbitral award. Some of them also facilitate conciliation. An arbitral award may be enforced either through court proceedings or through the direct involvement of local authorities. Generally, national law requires no more than careful scrutiny of the formal validity of an arbitral award. If such requirements are met, an arbitral award is binding. National courts enforce binding awards even when they are contrary to local law, unless they offend the most basic notions of morality and justice. In the maritime context, enforcement has become relatively easier with the passage of time. Certain mercantile and maritime cities have enacted specific laws concerning arbitration; these were enacted long before other cities adopted similar provisions in their general codes. As long as arbitrators explained their decisions in accordance with trade usage, they encountered no problems (Simanjuntak & Widiarty, 2022). The process of conciliation may lead to a conciliation settlement, which is amenable to limited scrutiny or review, depending on the municipal law. National courts in several countries lend their support to conciliation settlements, provided that they do not offend against public policy. In some jurisdictions, a conciliation settlement has the same effect as a court judgment, enforcing parties to perform their obligations. The judiciary of that jurisdiction will also enforce the settlement. In other jurisdictions, however, parties seeking enforcement must resort to the normal procedure for enforcing an agreement. With respect to maritime disputes, conciliation and conciliation settlements are becoming increasingly significant in the overall process of ADR (Dong, 2023).

Recent developments in dispute resolution

England stylistically has a pro-arbitration regime, but one that expresses a preference for party autonomy. The Arbitration Act merely states that it is the policy of the law to encourage commercial arbitration, and that the court's powers are essentially limited to supporting the parties' choice of tribunal, enforcing the tribunal's rulings, and removing obstacles during the course of the arbitration. Choice of law and jurisdiction clauses and arbitration provisions are both sensitive subjects in pure marine insurance policies, and efforts have been made to ensure that the insured's rights are protected. While the general preference is for disputes to be resolved through the more flexible system of commercial arbitration, the UK courts have belatedly embraced the principle of competence, giving support to arbitration tribunals where disputes over their jurisdiction arise. In the process, they have defined the limits of their supervisory jurisdiction. Unlike in many other countries, this support is not a matter of course and may depend upon the wording of the arbitration agreement (Gaillard, 2023).

Emerging technologies

Advances in technology do not only offer the insurance industry new products and distribution channels. They can also assist in the resolution of disputes and in the enforcement of the results. It is likely that the partnership between the insurance industry and big data companies will result in a faster and more accurate settlement of claims. It may, however, be argued that many of the current uses of new technologies are "normal" occurrences that are adding to the products and services offered by the insurance industry. Emerging technologies are likely to have an important impact on many of the areas in which marine insurance disputes arise. The recent development of parametric products for some of the risks affecting shipping has the potential to speed up the resolution of disputes that are focused on the amount of the insured interest. Modifications to the product could create a situation in which arguments about the cause of the insured loss are resolved in a similar way. The use of blockchain technology as a basis for "smart contracts" may significantly affect the resolution of disputes about the terms of the insurance contract (Lin & Kwon, 2020).

ODR platforms

A much quicker and cheaper option for resolving disputes that is beginning to be used in the wider business world is ODR (Thomas, 2023). However, the wider shipping world has yet to fully embrace ODR, but it is surely only a matter of time before this happens. The ODR platform selected must, however, be able to resolve insurance-related disputes, which are often more complex than other commercial disputes. When selecting an ODR platform to resolve marine insurance disputes, it is important that the platform has clear procedures. In the world of marine insurance, it is likely that an appointed panel of experts will actually make the decision, because the platform does not need to have the necessary expertise.

Research contributions and achievements

This study makes several significant contributions to the field of marine insurance dispute resolution by addressing critical gaps and providing innovative solutions to enhance both theoretical understanding and practical application. The key achievements are outlined below:

1. Comprehensive Analysis of Dispute Resolution Mechanisms
   This research provides a detailed examination of both traditional and ADR mechanisms, such as litigation, arbitration, mediation, and emerging ODR platforms. By integrating doctrinal legal analysis with case studies, the study highlights the strengths, weaknesses, and practical implications of these mechanisms within various jurisdictions.
2. Identification of Emerging Trends
   The study emphasizes the role of technological advancements, such as blockchain technology and smart contracts, in revolutionizing the landscape of marine insurance dispute resolution. It provides a forward-looking perspective on how these technologies can enhance transparency, efficiency, and enforceability in the resolution of disputes.
3. Innovative Integration of Med-Arb Processes
   By exploring the growing popularity of med-arb processes, this study demonstrates how hybrid

models can provide a cost-effective and expeditious alternative to traditional methods. The research highlights how med-arb can balance the strengths of mediation and arbitration to resolve disputes amicably while ensuring enforceability.

4. Case Law Insights
The inclusion of landmark cases such as Consort Shipping Line Ltd. v. FAI Insurance (Fiji) Ltd. and Laho Ltd. v. QBE Insurance (Vanuatu) Ltd. showcases the application of theoretical principles in real-world scenarios. These cases illustrate how courts interpret and enforce marine insurance policies, providing valuable precedents for practitioners and scholars.

Conclusions

Maritime perils give the shipping industry complicated insurance requirements. This paper has discussed the effectiveness and efficiency of ADR methods such as arbitration and highlighted their limitations. It has also compared ADR with litigation in national courts. This paper has shown how marine insurance disputes can be handled by court lawsuits, arbitration panels, mediation, or other dispute resolution methods. National courts can bind parties legally and resolve conflicts in compliance with set rules; arbitration is a widely used method of private dispute resolution that provides both effectiveness and efficiency. This paper has concluded that the principle of starting proceedings does not waive the right to arbitration under the mandatory arbitration provision. The med-arb process, which combines mediation and arbitration, is increasingly favored due to its expeditiousness and cost-effectiveness. The paper has also highlighted the impact of London Market Clauses and Lloyd's Open Form, and discussed future development methods such as ODR. The progress made in technology, namely in blockchain and smart contracts, is anticipated to have an effect on conflicts in marine insurance. ODR platforms, though not extensively used at present, need to be able to handle insurance-related disputes, which are sometimes more complex than business disputes.

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Case study for containerships' seakeeping performance analysis

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Abstract

Seakeeping capabilities represent a crucial aspect of marine hydrodynamics research. Calculating the movements, amplitudes, and accelerations of the ships offers valuable support for assessing and forecasting their safety and security parameters while the ships are in use. While experimental data on ship movements in consistent wave patterns are considered reliable, they also come with high impacting costs. This research is particularly designed to estimate the seakeeping performance by assessing the hydrodynamic response of a 192-meter-long container ship vessel in both regular and irregular waves. The present computational study is focused on predicting the six degrees of freedom responses for a ship at zero speed for different heading angles. Using the panel method within Maxsurf Motions software, RAOs for all degrees of freedom are obtained. In irregular sea simulations, the ITTC spectrum is employed.

Introduction. Literature review

This study presents the practical importance of containership classes by addressing their unique structural and operational challenges. Containerships, characterized by their large cargo capacities and lengthy structures, require precise hydrodynamic analysis to ensure efficient navigation and safety at sea. The adoption of advanced analytical methods enables more accurate predictions of seakeeping performance and structural integrity under various loading conditions. This not only enhances the safety standards but also improves fuel efficiency and operational reliability. By refining the design and assessment processes, the maritime industry can better meet the escalating demands for environmental sustainability and economic efficiency in global trade (Abhilash & Falzarano, 2015).

This research primarily concentrates on examining the movements of ships in both steady and unpredictable wave conditions, providing valuable insights into their dynamic behavior. The evaluation of these movements is conducted using response amplitude operators (RAOs) for the ship's six degrees of freedom – i.e., surge, sway, heave, roll, pitch, and yaw (Firdaus & Ali, 2017). By considering waves under various directional conditions, comprehensive RAOs are produced for all degrees of freedom, offering a detailed understanding of the 192-meter containership response to different sea states.

Recent advancements in computational methods, particularly the application of the boundary element method (BEM), have significantly enhanced the hydrodynamic analysis of ships (Wulandari et al., 2024). A BEM facilitates an in-depth examination of hydrodynamic pressure and force distribution on a vessel's hull under wave impact, identifying critical pressure zones and maximum pressure points (Umeda et al., 2016). Studies have shown that areas near the bow can experience pressures reaching approximately 160 N/mm² (Olusegun et al., 2024), underscoring the necessity for reinforced vessel designs in these high-pressure regions to prevent structural fatigue from repeated wave impacts (Scurtu et al., 2022). Furthermore, the BEM has proven efficiency in simulating fluid dynamics (Askarian & Ketabdari, 2019) around maritime structures, handling infinite domains such as open sea conditions with greater computational resource efficiency compared with other methods.

In addition to structural considerations, the analysis of wave excitation forces and their impact on a vessel's stability and structural stress across all six motion modes is paramount (Wulandari et al., 2024). Advanced BEM simulations (Olusegun et al., 2024) incorporate factors such as nonlinear wave effects and interactions with other structures, enhancing the accuracy of predictive models. These simulations provide critical operational insights that inform optimized structural reinforcements and cargo placement strategies, thereby improving vessel stability, performance, and longevity under various sea conditions (Dyachkov & Makov, 2005).

The integration of a BEM into maritime engineering practices is vital for the design, safety, and efficiency of container vessels, which are indispensable assets in global trade. As the maritime industry continues to evolve, the adoption of sophisticated hydrodynamic analysis methods such as a BEM becomes essential for developing safer and more efficient vessels (Ozturk et al., 2021). This comprehensive approach not only addresses the immediate challenges associated with wave-induced forces but also contributes to the long-term sustainability and resilience of maritime operations.

Advancing beyond semi-empirical design methods by incorporating detailed hydrodynamic analyses using a BEM represents a significant step forward in enhancing ship safety standards (Nguyen et al., 2024). By leveraging these advanced computational techniques, researchers and engineers can achieve more accurate predictions of ship behavior in complex wave conditions, ultimately leading to the development of vessels (Nam, Park & Yoon, 2024) that are both safer and more efficient in their operational environments.

Case study methodology. Boundary element method simulation

Research objectives

The seakeeping performance of a 192-meter-long containership is analyzed using the panel method within Maxsurf Motions software, primarily due to its precise and efficient computation of the ship's hydrodynamic responses in six degrees of freedom. Although alternative methods such as computational fluid dynamics (CFD) and empirical approaches are also widely utilized in marine hydrodynamics, the panel method was selected for its robust capability to simulate both regular and irregular wave patterns at reduced computational costs. This choice allows for detailed and accurate predictions of the ship's performance across various sea conditions, thereby optimizing both the safety and efficiency of maritime operations.

This case study is focused on a seakeeping performance analysis for a containership with a length of 192 m, aiming to reveal how ships react to waves, approaching a critical area of applied research within naval architecture and marine engineering. Understanding and predicting ship movements and the loads induced by wave interactions (Scurtu & Atodiresei, 2015; Scurtu et al., 2015) are essential for ensuring the safety and operational security of vessels (Clauss, Lehmann & Ostregaard, 2015). The main dimensions of the container ship used in the numerical model are listed in Table 1, while details of the ship's hull are illustrated in Figure 1.

Figure 1. Ship geometry for 192-meter containership

Table 1. Ship's main dimensions

Length at waterline [m]	192
Breadth [m]	32.2
Draft [m]	10.5
Block coefficient	0.54
Displacement volume [m^3]	35,054
Wetted hull surface [m^2]	7195
Service speed [knots]	25

Numerical solver

The boundary element method (BEM) is a numerical technique widely employed in marine engineering to analyze the hydrodynamic behavior of ship hulls. This method involves discretizing the vessel's hull into a mesh of boundary elements or panels, which serves as the foundation for simulating fluid-structure interactions (Kjellberg, Gerhardt & Werner, 2022). In the context of Maxsurf Motions, a specialized software tool for maritime hydrodynamic analysis, the BEM plays a crucial role in evaluating the potential flow around the hull's intricate geometry (Lupchian, 2020; Song, Wang & Xu, 2021).

The discretization process begins by breaking down the complex shape of the ship's hull into smaller, manageable boundary elements. Each of these elements represents a discrete portion of the hull's surface, allowing for a detailed and localized analysis of hydrodynamic forces. By applying the BEM, equations solve the boundary integral equations associated with each of these elements, effectively capturing the influence of the surrounding fluid on the hull. This approach ensures a high degree of accuracy in predicting how the vessel interacts with various wave conditions.

One of the primary advantages of using the BEM is its ability to accurately calculate the pressure distribution over the hull's surface. This pressure distribution is critical for determining the resultant forces and moments acting on the vessel. By integrating these pressures, the BEM provides comprehensive insights into the ship's motion responses across six degrees of freedom: surge (fore and aft), sway (side to side), heave (up and down), roll, pitch, and yaw. These motions are essential parameters in assessing a ship's seakeeping performance, as they directly influence the vessel's stability, comfort, and safety during operation.

Moreover, the BEM's capability to handle infinite fluid domains, such as open sea conditions, makes it exceptionally well-suited for simulating real-world maritime environments. Unlike other numerical methods that may require extensive computational resources to model large or unbounded fluid domains, the BEM efficiently manages these scenarios with relatively lower computational demands. This efficiency is particularly beneficial when conducting extensive simulations to evaluate a ship's performance under a wide range of wave conditions and sea states.

In addition to pressure distribution and force calculations, the BEM facilitates the analysis of wave-induced motions and structural responses. By incorporating advanced wave theories and accounting for nonlinear wave effects, the method enhances the accuracy of motion predictions. This is critical for identifying potential operational limitations and ensuring that the vessel can maintain optimal performance and safety standards even in challenging sea conditions.

The integration of the BEM in seakeeping performance analysis also supports the optimization of vessel design. Insights gained from the BEM simulations enable naval architects and marine engineers to make informed decisions regarding hull form modifications, structural reinforcements, and weight distribution. For instance, identifying areas with high-pressure concentrations, such as the bow region where pressures can reach approximately 160 N/mm², allows for targeted design enhancements to mitigate structural fatigue and enhance overall vessel resilience.

Furthermore, the predictive capabilities of the BEM extend to evaluating the effects of wave directionality and frequency on ship motions. By generating response amplitude operators (RAOs) for each degree of freedom under various wave conditions, the BEM provides a detailed framework for assessing how different sea states will impact the vessel's behavior. This comprehensive analysis is instrumental in ensuring that container ships can navigate safely and efficiently, minimizing risks associated with excessive motions and structural stresses.

In summary, the boundary element method offers a robust and efficient approach to analyzing the hydrodynamic performance of container ships. By accurately modeling potential flow around the hull and predicting motions across six degrees of freedom (depicted in Figure 2), the BEM provides valuable insights into a vessel's seakeeping abilities and operational limitations. This detailed hydrodynamic analysis not only enhances the accuracy of seakeeping performance assessments but also supports the development of safer, more efficient, and resilient container ship designs, thereby contributing

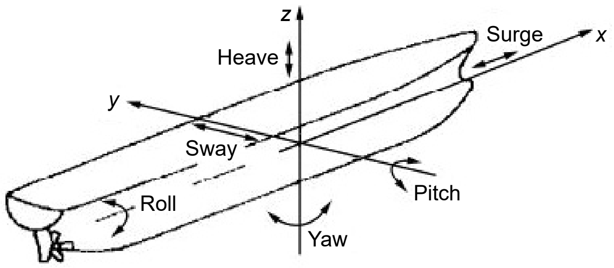

Figure 2. Ship's degrees of freedom

significantly to the advancement of maritime engineering practices.

Mathematical model

Using the potential flow assumptions, the flow is considered incompressible, inviscid, and irrotational. The velocity is obtained from the velocity potential function Φ as follows:

$$V = \nabla \Phi \tag{1}$$

For irregular waves, the ITTC wave spectrum is used for the operation conditions at a Beaufort scale of 5, where the significant wave height is $H_S = 4$ m. The wave spectrum $S_\zeta(\omega)$ and the encounter spectrum $S_R(\omega_e)$ equations are written as

$$S_\zeta(\omega) = \frac{A}{\omega^5} e^{-\frac{B}{\omega^4}} \tag{2}$$

$$S_R(\omega_e) = \text{RAO}^2\, S_\zeta(\omega) \tag{3}$$

where $A = 0.7795$, $B = 3.11/H_S^2$, and subscript R originates from the response while

$$\omega_e = \left(1 - \frac{\omega V}{g} \cos\mu\right) \tag{4}$$

when $V = 0$ and $\omega_e = \omega$.

Simulation conditions

The geometry of the ship is verified for any potential geometric issues that could impact the quality of the simulation using the Maxsurf modeler, which then generates 1860 panels. Note that the student edition of Maxsurf is capable of handling up to 2000 panels.

The analysis is conducted with the ship fully loaded, stationary, and its heading varying from 0° to 180° in 30° increments, with wave frequencies from 0.2 to 2 rad/s. Figure 3 shows the heading angles from the aft of the ship (Firdaus & Ali, 2017). The study first examines the ship in regular wave conditions and then utilizes response amplitude operator data to simulate the ship's behavior in irregular waves. This simulation runs on a 6-core PC equipped with a 3.3-GHz Ryzen 5 processor and 16 GB of DDR5 RAM, taking approximately 30 minutes of real-time.

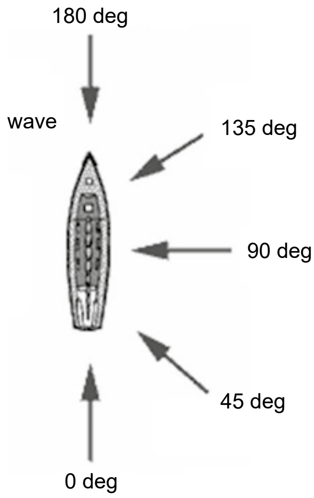

Figure 3. Heading angles

Results and interpretations

The simulation is conducted with a stationary ship, analyzing heading angles from 0° to 180° in increments of 30°. It models a regular wave with an amplitude of 1 m and a wave height of 3 m. The units for the RAO measurements are meters per meter (m/m) for translational motions and degrees per meter (°/m) for rotational motions. Translational motions include surge (movement along the *X*-axis), sway (movement along the *Y*-axis), and heave (movement along the *Z*-axis), while rotational motions encompass roll (rotation around the *X*-axis), pitch (rotation around the *Y*-axis), and yaw (rotation around the *Z*-axis). The outcomes of these simulations are detailed in Figures 4–9.

In the surge degree of freedom, the vessel exhibits its maximum response at the lowest studied frequency of 0.2 rad/s, with the RAOs reaching 0.966 and 0.965 at headings of $\mu = 0°$ and $\mu = 180°$, respectively. This indicates a significant longitudinal movement when encountering waves head-on or from behind. The minimum surge response approaches zero at the highest frequency (2 rad/s), indicating insensitivity to high-frequency wave encounters across all headings.

For sway, the maximum RAO of 0.974 is observed at $\mu = 90°$, also at 0.2 rad/s, reflecting the vessel's vulnerability to beam seas where lateral motion is most

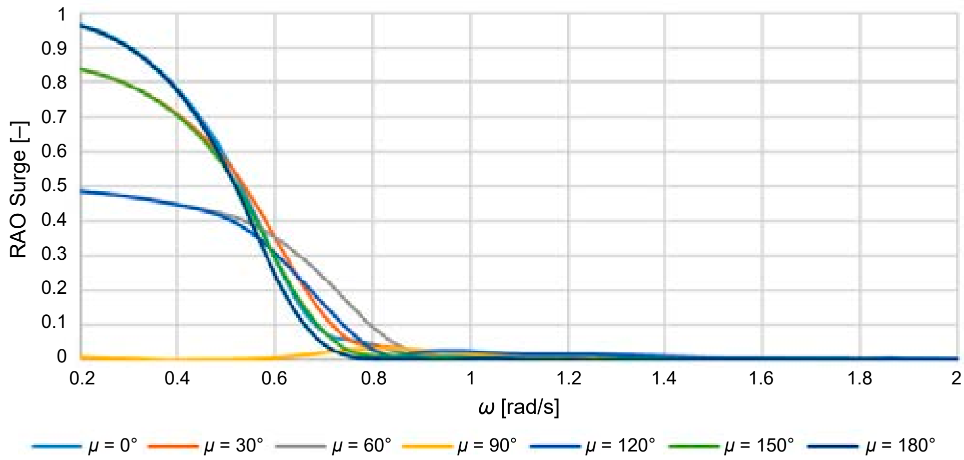

Figure 4. Surge RAO (Firdaus & Ali, 2017)

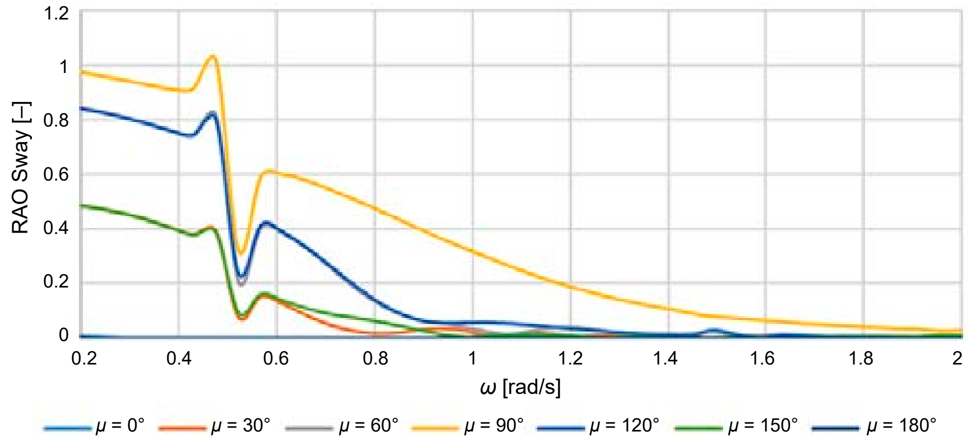

Figure 5. Sway RAO

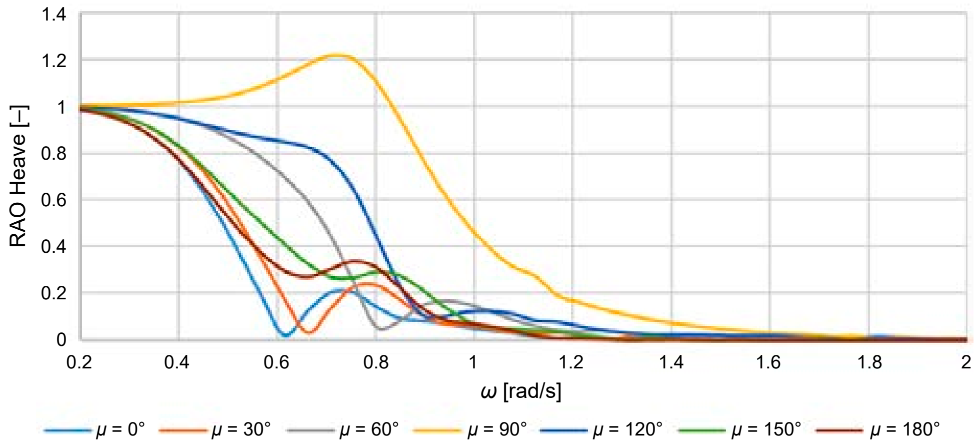

Figure 6. Heave RAO

pronounced. Heave motion peaks at an intermediate frequency of 0.477 rad/s with an RAO of 1.033 at $\mu = 90°$, demonstrating a substantial vertical motion in beam seas.

Pitching motion displays a maximum RAO at the lowest frequency (0.2 rad/s) with a value of 1.01 at $\mu = 0°$, which suggests a pronounced pitching in head seas. Roll motion is most significant at $\mu = 90°$ with the highest RAO recorded at 9.645 for a frequency of 0.523 rad/s, underscoring the vessel's sensitivity to roll in side-on seas.

Lastly, the yaw motion reaches its peak RAO of 0.366 at a frequency of 0.2 rad/s for a heading angle of $\mu = 60°$, suggesting the greatest yawing motion

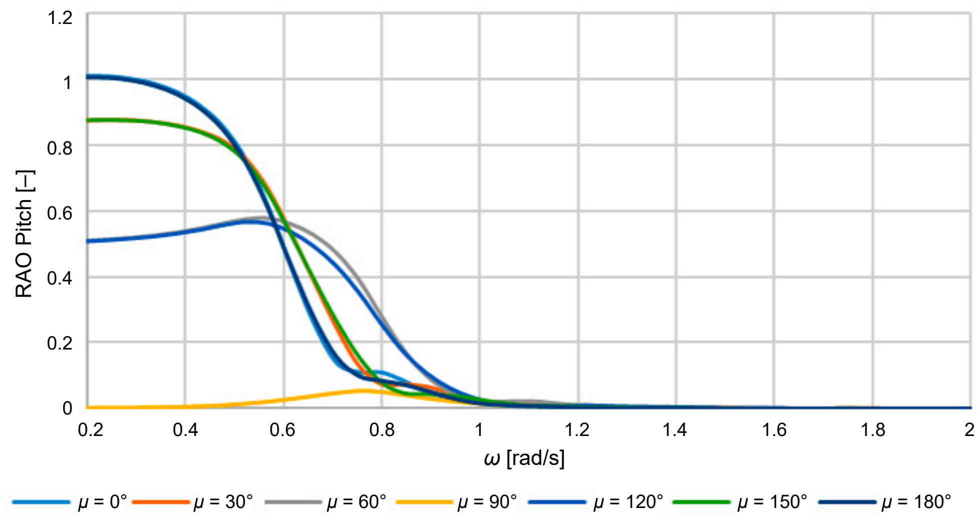

Figure 7. Pitch RAO

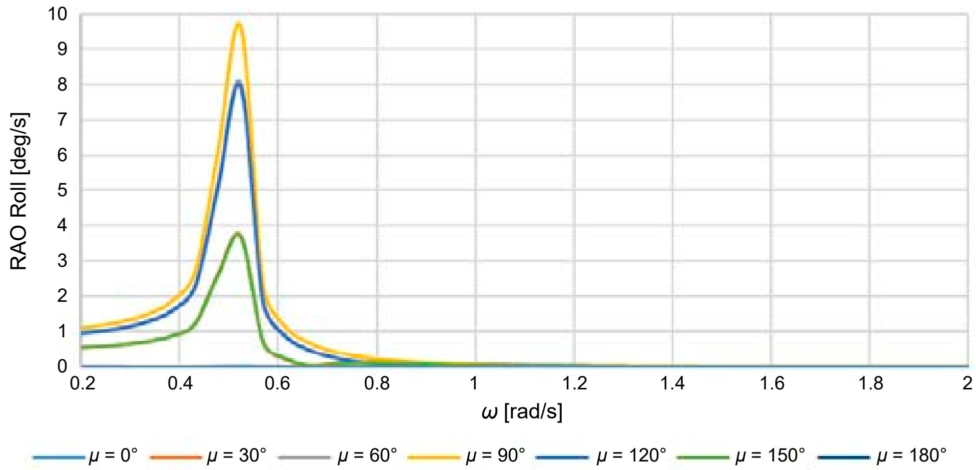

Figure 8. Roll RAO

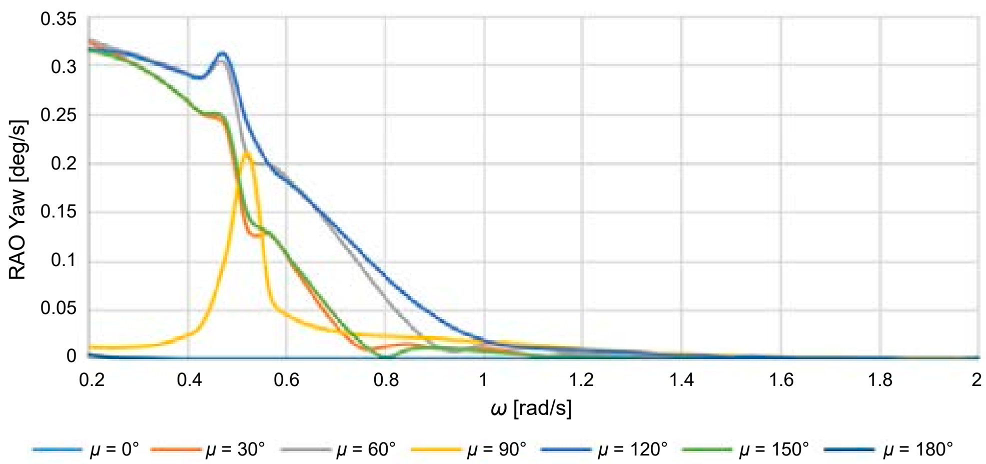

Figure 9. Yaw RAO

occurs when waves strike the vessel at an oblique angle from the bow.

An ITTC spectrum is used to represent the general sea conditions at a Beaufort scale of 5, where the corresponding significant wave height is 3 m. The ITTC wave spectrum for $h_{1/3}$ = 3 m is represented in Figure 10. The response spectra for all the degrees of freedom are represented in Figures 11–16.

The response spectra analysis illustrated in Figures 11–16 elucidates the vessel's dynamic response under various degrees of freedom at a significant wave height $h_{1/3}$ = 3 m. The spectra distinctly highlight the vessel's roll motion response, which exhibits prominent peaks when encountering beam seas. This response is emblematic of a vessel's typical behavior in such conditions, where the lateral approach of waves poses substantial stability challenges due to the potential for large roll angles.

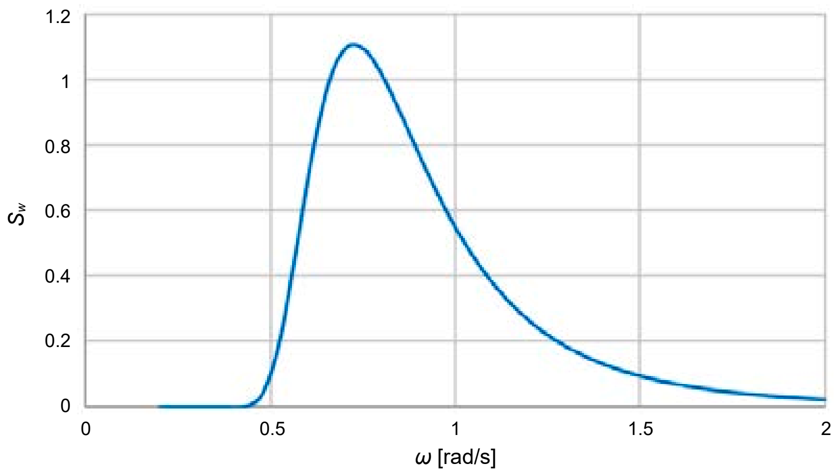

Figure 10. ITTC wave spectrum – $h_{1/3}$ = 3 m

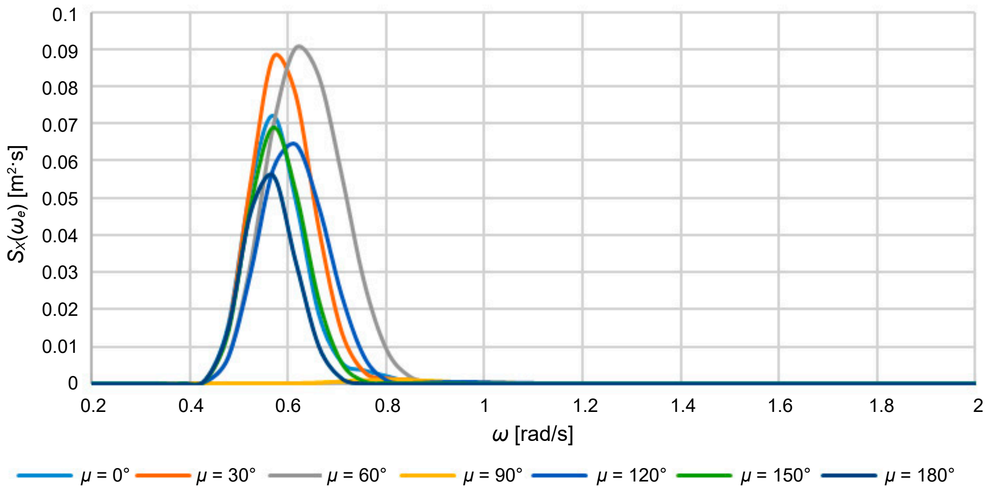

Figure 11. Response spectrum – surge

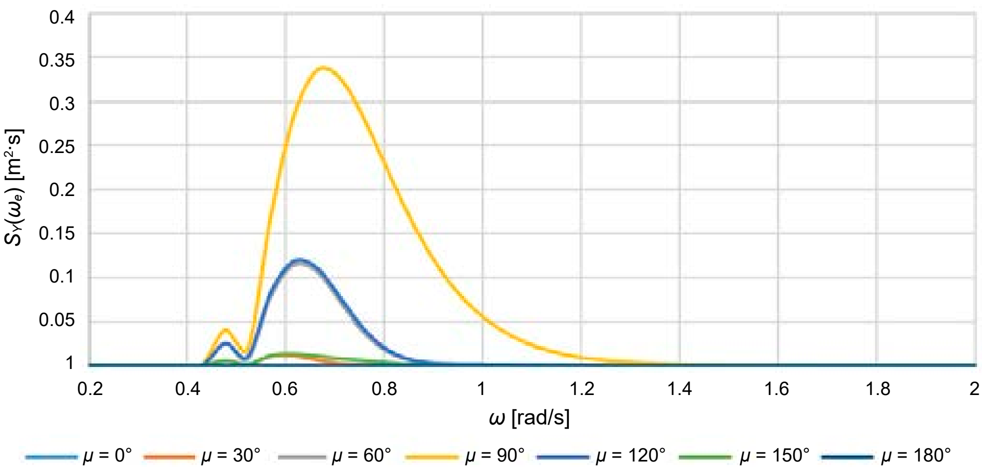

Figure 12. Response spectrum – sway

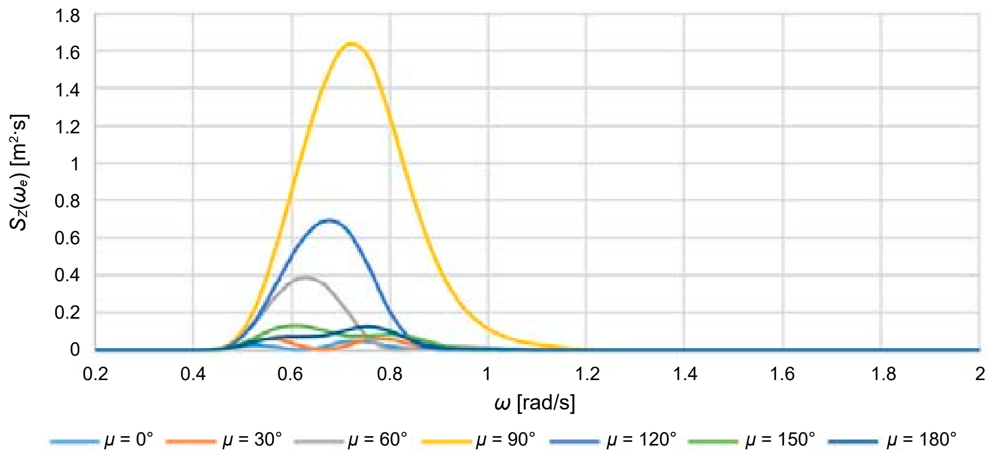

Figure 13. Response spectrum – heave

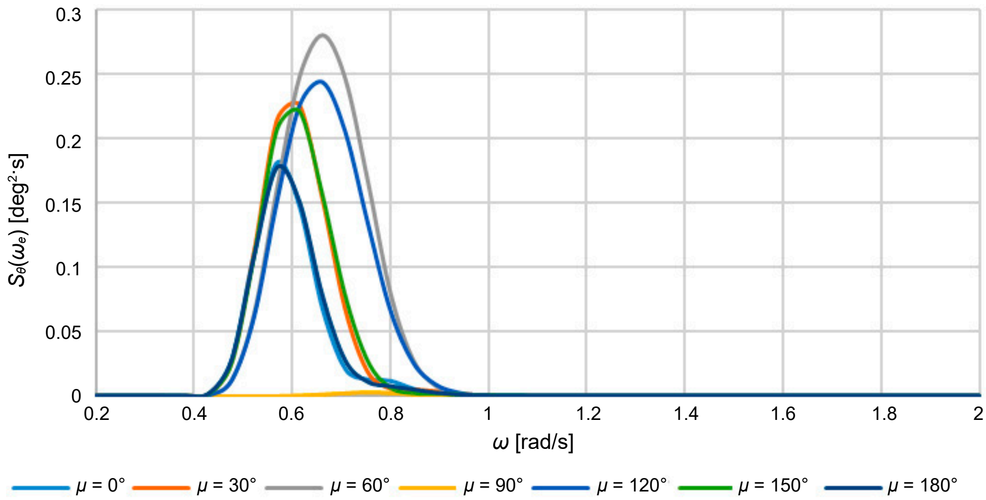

Figure 14. Response spectrum – pitch

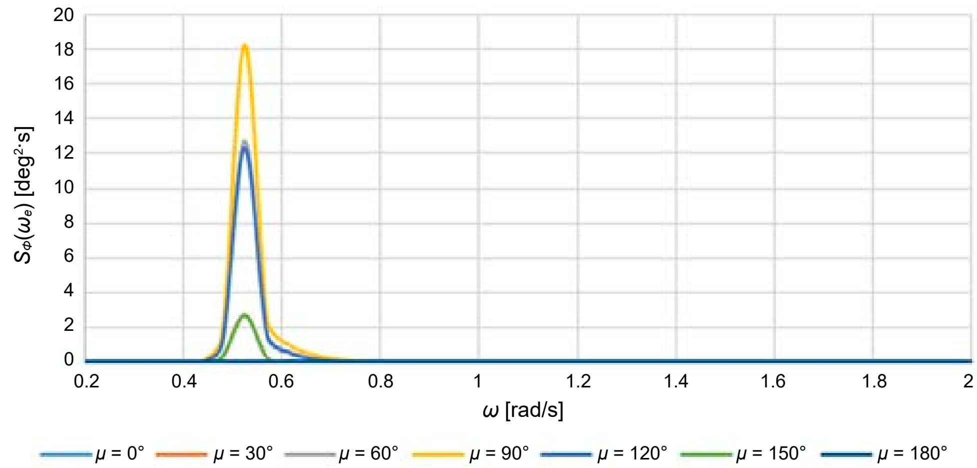

Figure 15. Response spectrum – roll

Contrasting the pronounced roll motion, the other degrees of freedom – i.e., pitch, heave, surge, sway, and yaw – demonstrate more subdued responses in their respective spectra. Pitch and heave motions show lower magnitudes, inferring a reduced resonance tendency and suggesting that these motions are better damped compared to the roll. Meanwhile, translational motions such as surge, sway, and yaw manifest the lowest energy responses, implying their relatively minor significance

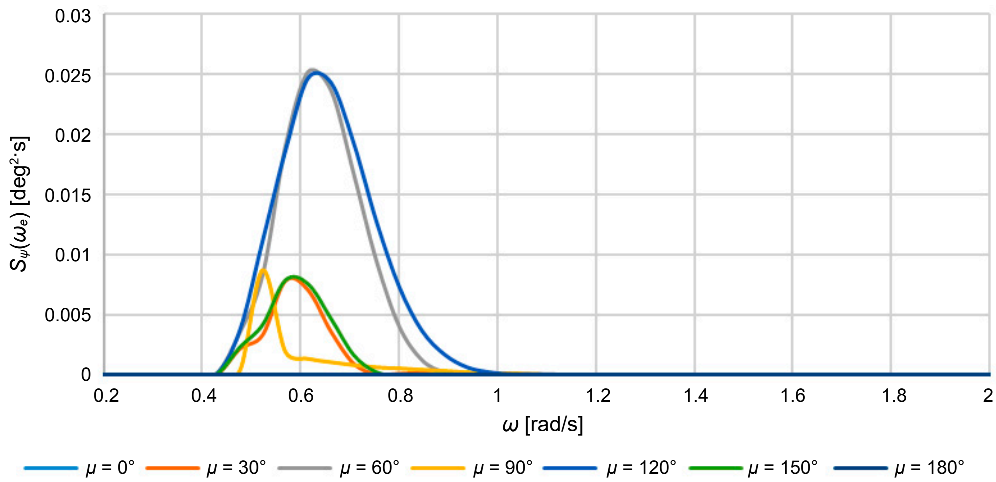

Figure 16. Response spectrum – yaw

for vessel operations under the studied sea state conditions.

Conclusions

This study makes contributions to the field of marine hydrodynamics, focusing on estimating the hydrodynamic response of a 192-meter-long container ship in waves. Utilizing the panel method within Maxsurf Motions software, the response amplitude operators (RAOs) for all six degrees of freedom were obtained for different heading angles with the ship at zero speed. This approach provides an efficient and accurate methodology for predicting the safety and security of the ship under various wave conditions while also reducing the need for other costly experimental data, which is conducted on physical laboratory simulation. The use of the ITTC spectrum for irregular sea simulations highlights the model's capability to handle variable wave conditions, thereby laying a solid foundation for future research. The results of this research present a path for optimizing the hydrodynamic response of a 192-meter-long container ship vessel in operation, emphasizing the importance of calculating hydrodynamic responses in modern naval engineering.

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Passenger traffic in Polish seaports in the face of the COVID-19 pandemic

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Keywords: maritime transport, passenger traffic, seaports, COVID-19 impact, Poland, forecasting, seasonality, seasonal ARIMA, Holt-Winters model, STL model

JEL Classification: C30, C52, C53, L91, R41

Abstract

The outbreak of the COVID-19 pandemic had a profound impact on the global economy and disrupted daily life across many regions of the world. Restrictions imposed at the time, such as the closure of national borders and restrictions on mobility, led to unprecedented challenges for the transportation sector and related tourism services compared with any prior crisis. This disruption also affected maritime passenger transport in Poland. This article aims to assess the impact of the COVID-19 pandemic on passenger traffic in Polish seaports and to develop mathematical models that could support management in the event of future epidemic threats. Three different models are proposed, which showed that the epidemic crisis resulted in a significant decline in passenger traffic at Polish seaports. The most accurate proved to be the SARIMA model. The Holt-Winters model also demonstrated high fitting and predictive performance. In turn, the STL model offered intriguing insights with its time series decomposition, enabling a detailed analysis of individual components. A comparative analysis of the proposed models confirms their usefulness in forecasting passenger traffic in seaports in the face of disruptions such as the COVID-19 pandemic. These models can be an effective decision-support tool, helping to reduce the negative effects of future epidemic threats.

Introduction

Threats such as pandemics, geopolitical conflicts, climate change, and terrorist attacks significantly influence the modern world and global economy. The COVID-19 pandemic outbreak in 2020, for example, dramatically and unexpectedly affected social and economic systems, causing widespread destabilization across nearly all sectors (Clemente-Suárez, 2021). Maritime transport, essential for global passenger and cargo movement, was also impacted by the coronavirus. In response to the global epidemic crisis, shipping lines and operators had to adjust their operations to fit a new reality (Chua et al., 2022). Strict restrictions and health guidelines were imposed to curb the spreading of the virus and enhance public safety. Governments enforced widespread lockdowns and mandated social distancing and personal protective measures. Travel became more challenging due to temporary border closures, increased border checks, and mandatory quarantines upon entry into countries (Sobczuk, 2024). These restrictions, along with evolving legal regulations and new safety standards, affected the operational performance and transport outcomes. In the face of a dynamically changing situation, passenger maritime transport in Poland has faced the challenge of adapting to restrictions and new operating standards. The lack of appropriate analyses may make it difficult to understand the real scale of the problem and limit the sector's adaptive capacity, especially from the perspective of a potential recurrence of similar events. Therefore, this study aims to assess the impact of the COVID-19 pandemic on passenger traffic in Polish seaports and to develop mathematical models that can support management in the event of future epidemic threats. This study not only showed the scale of disruptions caused by COVID-19 in passenger traffic in Polish seaports but, above all, provides effective forecasting tools for the maritime transport sector, which can be used for operational and strategic planning in the face of potential epidemic threats. This will enable a more effective response to similar challenges in the future, which will consequently reduce the negative effects of crisis events such as pandemics.

Literature review

In recent years, maritime transport in Poland has seen consistent growth. Port facilities have been modernized, and infrastructure has been expanded and enhanced through modern technologies. These investments aimed to increase cargo volumes and improve passenger comfort. As a result, the importance of maritime transport grew, leading to an increase in both passenger numbers and cargo volumes (Bocheński et al., 2021). However, this positive trend was disrupted by the outbreak of the COVID-19 pandemic in 2020. The pandemic led to a decrease in demand for transport services, port closures, and extended waiting times for port operations (such as docking and cargo handling) due to expanded security checks. Business and corporate travel were either postponed or replaced by virtual meetings for safety reasons. Tourists, constrained by mobility restrictions in most countries, opted for domestic travel, often using personal transportation. This shift was evident in transport statistics, particularly for summer cruises. The pandemic also led to rising freight and charter rates in container transport. Additionally, decreased demand for and prices of oil resulted in reduced deliveries, necessitating the storage of oil on floating tankers. These disruptions contributed to rising insolvencies and even bankruptcies among maritime carriers (Cullinane & Haralambides, 2021; Węcel et al., 2024).

Numerous publications have examined maritime transport during the COVID-19 pandemic. These studies analyze the operational activities of carriers and assess the measures taken to mitigate the negative impacts of reduced revenues from passenger transport and ferry services (Urbanyi-Popiolek, 2020). Another study explored the crisis's implications for the future of European maritime transport and proposes directions for further development (van Tatenhove, 2021). There have also been analyses of the impact of the pandemic on cargo maritime transport based on vessel types and the evaluations of cargo throughput in ports (Borucka & Kozlowski, 2023). Additionally, the need to reconfigure global supply chains managed by container transport and enhance their resilience through new digital solutions has been emphasized (Grzelakowski, 2022). The system of maritime navigation, with a focus on passenger traffic and trends within the European Union, has also been studied (Gracan, 2022). Some studies have visualized the impact of the COVID-19 pandemic on maritime transport in Poland and developed long-term forecasts for passenger traffic (Barczak, 2023). Nevertheless, there is a noticeable lack of focus on mathematical models that can evaluate and forecast passenger traffic in Polish seaports amid the pandemic's disruptions, which is the primary focus of this publication.

Materials and methods

This study utilized quarterly data on the passenger numbers to and from Polish seaports from 2004 to 2024, provided by Eurostat, to construct the time series necessary for the analysis (Eurostat, 2024).

Time series models were employed to identify and forecast temporal changes, allowing for the description of the process under study, the detection of the deterministic components, and the representation of the process as a function containing components such as the trend, seasonal variations, cyclical fluctuations, and random variations (Borucka & Guzanek, 2022; Bouboulas et al., 2022; Oszczypala et al., 2023). By identifying these components and the internal dynamics of the time series, future values of the time series can be forecast (Rodrigues et al., 2022; Kozlowski et al., 2023). Three different models were applied in this study, and their results were compared (Liu et al., 2024). If observations of the lagged series appear as dependent variables in the model, it is appropriate to apply autoregressive processes AR (p). If the variables in the model are a combination of lagged external disturbances, moving average models are suitable MA (q). Often, combining these two models – i.e., ARMA (p,q) – is the most effective approach.

However, for non-stationary series that can be transformed into a stationary form (through differencing), it is appropriate to use ARIMA (p,d,q) models. When seasonal components are also included in the model, the SARIMA (p,d,q)(P,D,Q)[S] model is obtained (Riaz et al., 2023), i.e.,

$$\begin{aligned}&\left(1-\varphi_1 B-\varphi_2 B^2-\cdots-\varphi_p B^p\right)\cdot\\ &\cdot\left(1-\Phi_1 B^s-\Phi_2 B^{2s}-\cdots-\Phi_P B^{Ps}\right)\cdot\\ &\cdot\left(1-B\right)^d\left(1-B^s\right)^D y_t=\\ &=\left(1+\theta_1 B+\theta_2 B^2+\cdots+\theta_q B^q\right)\cdot\\ &\cdot\left(1+\Theta_1 B^s+\Theta_2 B^{2s}+\cdots\Theta_Q B^{Qs}\right)\varepsilon_t\end{aligned} \tag{1}$$

where $\varphi_1,\varphi_2,\ldots,\varphi_p$ is the autoregression coefficients, $\Phi_1,\Phi_2,\ldots,\Phi_P$ is the seasonal autoregression coefficients, $\theta_1,\theta_2,\ldots,\theta_q$ is the moving average coefficients, $\Theta_1,\Theta_2,\ldots,\Theta_q$ is the seasonal coefficients of the moving average, B is the differentiation operator $B_{yt} = y_t - y_{t-1}$, and ε_t is the random error at time t.

The Holt-Winters model, which is applicable to time series with trend, seasonal, and random fluctuations, was also used. There are two variants of this model that differ in the nature of the seasonal components. The additive model is preferred when seasonal variations are roughly constant across the series, while the multiplicative model is used when seasonal variations change proportionally with the series level (Koehler et al., 2001; Ribeiro et al., 2019). This study used a multiplicative model consisting of the forecasting equation Y^*_{t+m} and three smoothing equations – i.e., the level L_t, trend B_t, and seasonality S_t – which are expressed as

$$Y^*_{t+m}=\frac{L_t+B_t\cdot m}{S_{t-s+m}} \tag{2}$$

$$L_t=\alpha\frac{Y_t}{S_{t-s}}+\left(1-\alpha\right)\left(L_{t-1}+B_{t-1}\right) \tag{3}$$

$$B_t=\beta\left(L_t-L_{t-1}\right)+\left(1-\beta\right)B_{t-1} \tag{4}$$

$$S_t=\gamma\frac{Y_t}{L_t}+\left(1-\gamma\right)S_{t-s} \tag{5}$$

respectively, where α, β, and γ are the exponential smoothing coefficients such that $\alpha, \beta, \gamma_\varepsilon (0;1)$, Y_t is the actual value at time t, S is the length of the seasonality cycle (for quarterly data, $L = 4$), and m is the forecast horizon (Wang, 2019).

The last model employed was the seasonal-trend decomposition using LOESS (STL), which decomposes the time series to analyze each component separately. As a result, the value of the variable under study (Y_t) at time t is expressed as the sum of the trend, seasonal, and remainder so that:

$$Y_t = M_t + S_t + R_t \tag{6}$$

where M_t is the trend at time t, S_t is the seasonality at time t, and R_t is the remainder component at time t.

The component values are determined through a series of locally weighted regression (LOESS) smoothing procedures, which are based on fitting a weighted polynomial regression to the observation time (Dagum & Luati, 2003). The time series is iteratively adjusted until the trend and seasonality stabilize using a multi-step process involving alternating moving averages and LOESS smoothing. The seasonal, trend, and remainder components are then extracted using the following equations:

$$S_t=S_t^{(k+1)} \tag{7}$$

$$M_t=M_t^{(k+1)} \tag{8}$$

$$R_t = Y_t - S_t - M_t \tag{9}$$

respectively, where k is the number of iterations for the respective steps.

A model selection was based on the Akaike information criterion (AIC) and the Bayesian information criterion (BIC), which are calculated using the following formulae:

$$\text{AIC} = 2\,k - 2\ln(L) \tag{10}$$

$$\text{BIC} = k\ln(n) - 2\ln(L) \tag{11}$$

where k is the number of parameters in the model, L is the reliability function, and n is the number of observations. Lower AIC and BIC values indicate a better model fit.

For each of the models used, the accuracy of the determined forecasts was also evaluated. Forecast accuracy for each model was assessed by calculating the mean absolute error (MAE), mean square error (MSE), and root mean square error (RMSE) via:

$$\text{MAE}=\frac{1}{n}\sum_{t=1}^{n}\left|Y_t^*-Y_t\right| \tag{12}$$

$$\text{MSE}=\sum_{t=1}^{n}\frac{\left(Y_t^*-Y_t\right)^2}{n} \tag{13}$$

$$\text{RMSE}=\sqrt{\text{MSE}}=\sqrt{\sum_{t=1}^{n}\frac{\left(Y_t^*-Y_t\right)^2}{n}} \tag{14}$$

where Y_t^* is the forecasted value at time t, Y_t is the actual value at time t, and n is the number of observations. Lower error values indicate higher forecast accuracy and, thus, better predictive performance of the model (Saigal & Mehrotra, 2012).

In this paper, time series analyses and the development of all the mathematical models were performed using R Core software (version 4.3.3) with packages that provide a set of algorithms for data preprocessing and time series forecasting (R Core Team, 2024).

Comparison of the mathematical models describing passenger traffic in Polish seaports

This study began with an analysis of the passenger numbers in Polish seaports using basic descriptive statistics. Data from each quarter of 2004–2023 were analyzed and displayed using a box plot, as shown in Figure 1.

Transport data from 2004–2023 were also analyzed by quarter (Q1–Q4), as illustrated in Figure 2.

The plots reveal significant variability in the passenger numbers from year to year, especially compared to 2019. Notably, 2020–2021 show distinct outliers, which are attributed to the disruptions caused by the COVID-19 pandemic, which led to temporary mobility restrictions, including maritime travel (Chua et al., 2022; Węcel et al., 2024).

Additionally, the data exhibit quarterly seasonality, with the highest passenger numbers in the third (Q3) and second (Q2) quarters. This pattern is due to favorable weather conditions for maritime travel during the spring and summer months, leading to increased cruise bookings. The third quarter's

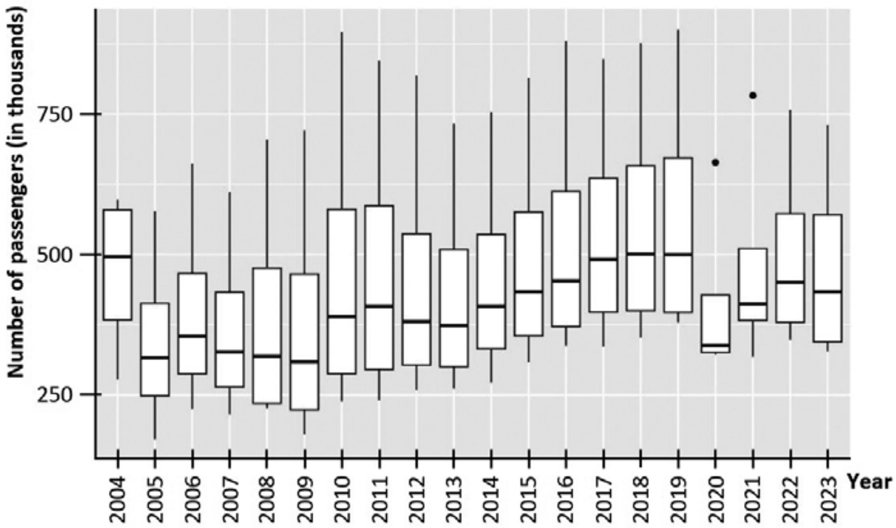

Figure 1. Box plot of the passenger numbers in Polish seaports from 2004 to 2023 (based on Eurostat, 2024)

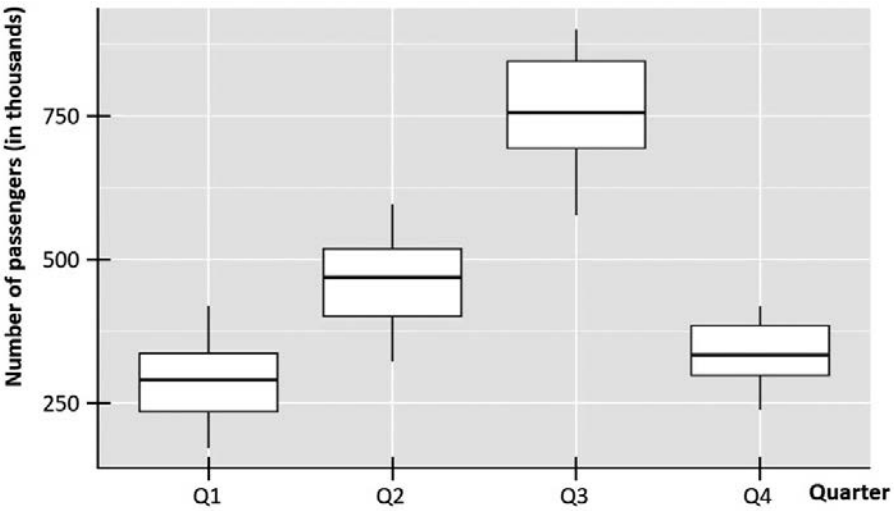

Figure 2. Box plot of the number of passengers in Polish seaports by quarter based on data from 2004 to 2023 (based on Eurostat, 2024)

holiday season also significantly contributes to increased passenger traffic in seaports. In the remaining parts of the year (Q1 and Q4), there are fewer passengers, primarily due to business travel and less frequent tourist trips (Gracan et al., 2022; Barczak, 2023).

Next, a time series analysis of the quarterly passenger numbers from 2004–2023 was conducted. The dataset was divided into training and testing sets, with the division occurring at the end (Q4) of 2022, as shown in Figure 3.

The SARIMA model was initially proposed. The best model, determined based on information criteria, was SARIMA (1,0,0)(0,1,1)[4]. The estimated parameter values for this model are presented in Table 1.

Table 1. SARIMA (1,0,0)(0,1,1)[4] model parameters

Model parameters		
Coefficients	AR 1	SMA 1
	0.6488	−0.3189
Standard error	0.1009	0.1432

The values of the individual information criteria (i.e., AIC and BIC) are similar and are summarized together in Table 2.

Table 2. Evaluation of SARIMA (1,0,0)(0,1,1)[4] model fit

Evaluation of the model fit	
Aikike information criterion (AIC)	791.71
Bayesian information criterion (BIC)	798.54

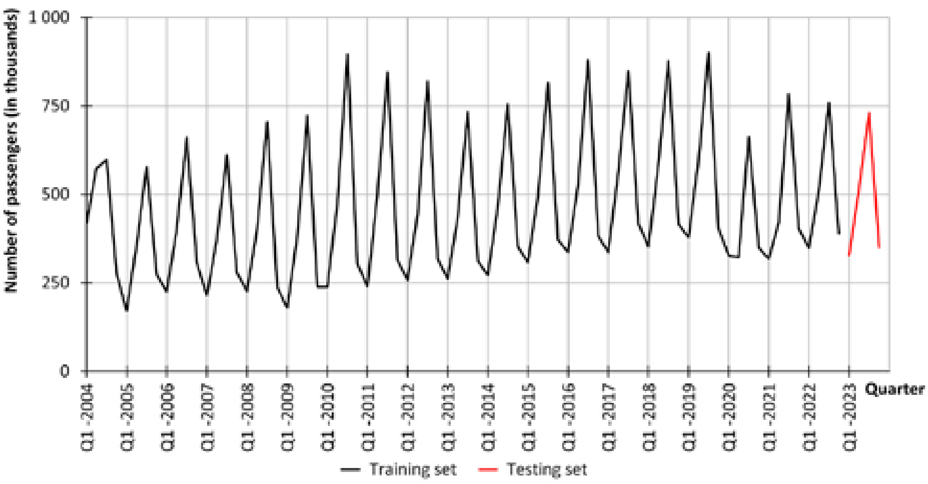

Figure 3. Dataset division into training and testing sets (based on Eurostat, 2024)

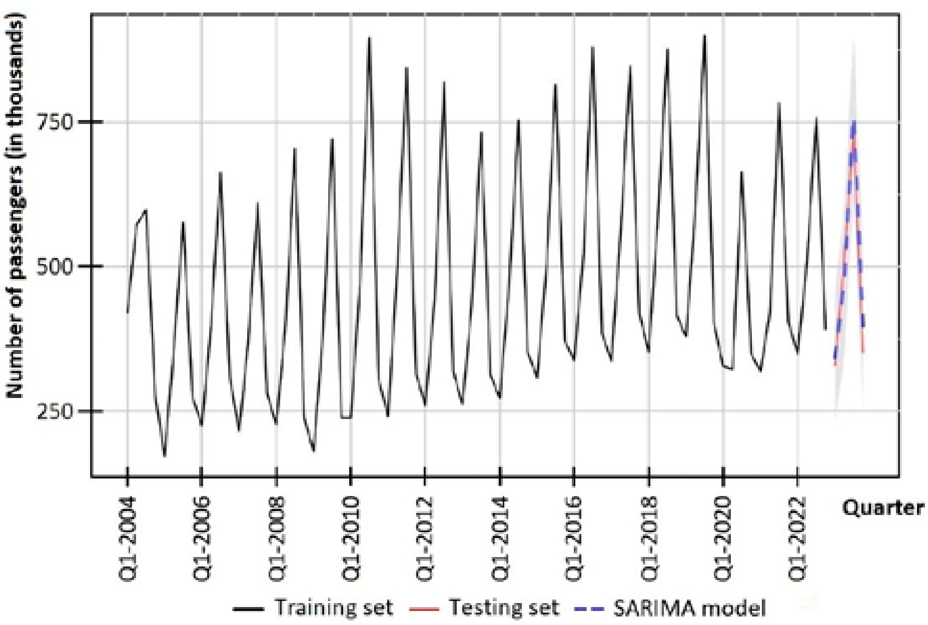

Figure 4. Passenger numbers in Polish seaports with SARIMA (1,0,0)(0,1,1)[4] model forecast

The MAE, RMSE, and MSE forecast errors were also determined. The results were satisfactory, with lower errors for the testing set, indicating high prediction accuracy (Table 3).

Table 3. Forecast accuracy measures for the SARIMA (1,0,0)(0,1,1)[4] model

Forecast accuracy measures		
	Training set	Testing set
MAE	36.6301	29.6084
RMSE	54.8371	31.6947
MSE	3007.1097	1004.554

The actual passenger numbers in Polish seaports from 2004–2023, along with the forecast based on the SARIMA (1,0,0)(0,1,1)[4] model, are shown in Figure 4.

The next proposed model was the Holt-Winters model with multiplicative seasonality. The values of the smoothing parameters and initial parameters are presented in Table 4.

Table 4. Parameters of the multiplicative Holt-Winters model

Model parameters			
Smoothing parameters		Initial parameters	
Alpha (α)	0.3655	l	550.1898
Beta (β)	0.0001	b	0.2276
Gamma (γ)	0.6344	s	1.3228
			1.1652
			0.8699

The Holt-Winters model was also evaluated using information criteria (Table 5). The values obtained were higher than those for the SARIMA model, indicating a poorer fit than the SARIMA (1,0,0)(0,1,1)[4] model.

Table 5. Evaluation of the multiplicative Holt-Winters model fit

Evaluation of the model fit	
Aikike information criterion (AIC)	951.47
Bayesian information criterion (BIC)	972.45

Forecast errors for the Holt-Winters model were also determined (Table 6). The error values were satisfactory for both the training and test datasets. Moreover, for the testing set, the MAE and RMSE errors were lower than those for the SARIMA model, indicating that the forecasts from this model have smaller prediction errors.

Table 6. Forecast accuracy measures for the multiplicative Holt-Winters model

Forecast accuracy measures		
	Training set	Testing set
MAE	38.7481	29.1471
RMSE	56.0513	27.0655
MSE	3141.7505	849.5518

The actual passenger numbers in Polish seaports from 2004 to 2023, with the 2023 forecast from the multiplicative Holt-Winters model, are shown in Figure 5.

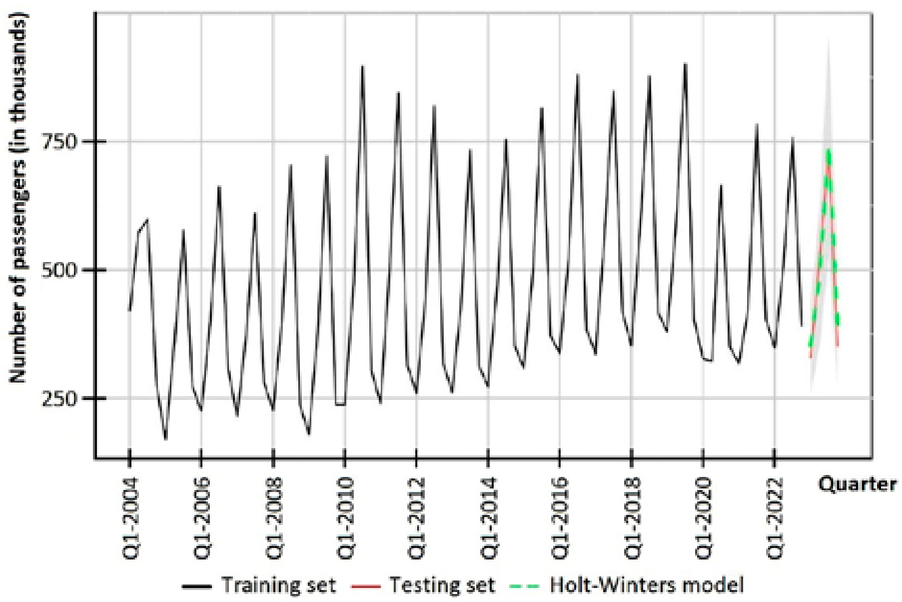

Figure 5. Passenger numbers in Polish seaports with the multiplicative Holt-Winters model forecast

The last model proposed is seasonal-trend decomposition using LOESS (STL), which allows for the decomposition of the time series into seasonal, trend, and remainder components. The STL model components and interquartile range (IQR) calculations are presented in Table 7.

Table 7. STL model components with IQR calculations

Timeseries components			
	Seasonal	Trend	Remainder
Min.	−178.3537	342.6228	−143.8509
1st Qu.	−137.745	397.6869	−18.0134
Median	−60.7633	463.6279	−0.3256
Mean	0.00001	461.5133	−0.6449
3rd Qu.	76.9817	507.9549	19.9074
Max.	299.8803	582.0477	110.5635
Inter-quartile range calculations (IQR)			
STL seasonal	STL Trend	STL remainder	Data
214.73	110.27	37.92	274
78.4%	40.2%	13.8%	100.0%

As before, the forecast errors were also determined for the STL model, the values of which indicate high prediction accuracy (Table 8).

Table 8. Forecast accuracy measures for the STL model

Forecast accuracy measures	
MAE	28.8357
RMSE	37.1778
MSE	1382.186

The decomposition of the analyzed time series (Figure 6) reveals certain regularities within its components. Most notably, throughout the entire period, quarterly seasonality remains consistent, unaffected by global events such as the COVID-19 pandemic. However, when discussing disruptions, the trend line, as determined by the STL model, highlights the significant impact that the spread of the SARS-CoV-2 virus had on societal mobility, particularly on maritime passenger transport.

Analyzing the trend in passenger numbers from Q3 in 2019 to Q3 in 2020, a significant decline is evident, attributable to the epidemic crisis during that period. Therefore, considering both the seasonal component and the overall trend, it can be concluded that the COVID-19 pandemic outbreak had a substantial impact on transport outcomes, reducing passenger traffic at Polish seaports. However, it did not disrupt the established pattern of seasonal interest in cruises across different quarters.

The actual passenger numbers in Polish seaports from 2004 to 2023, along with the forecast generated using the STL model, are presented in Figure 7.

The last phase of this study involved comparing the results obtained by each of the mathematical models under consideration. Actual values were compared with forecasts for the individual quarters of 2023. The higher forecasted values, compared with the actual figures (except for Q2 2023), were obtained across all the models, which confirm that the SARS-CoV-2 pandemic significantly disrupted passenger traffic (Table 9). All the proposed models were also compared graphically with the testing set (Figure 8).

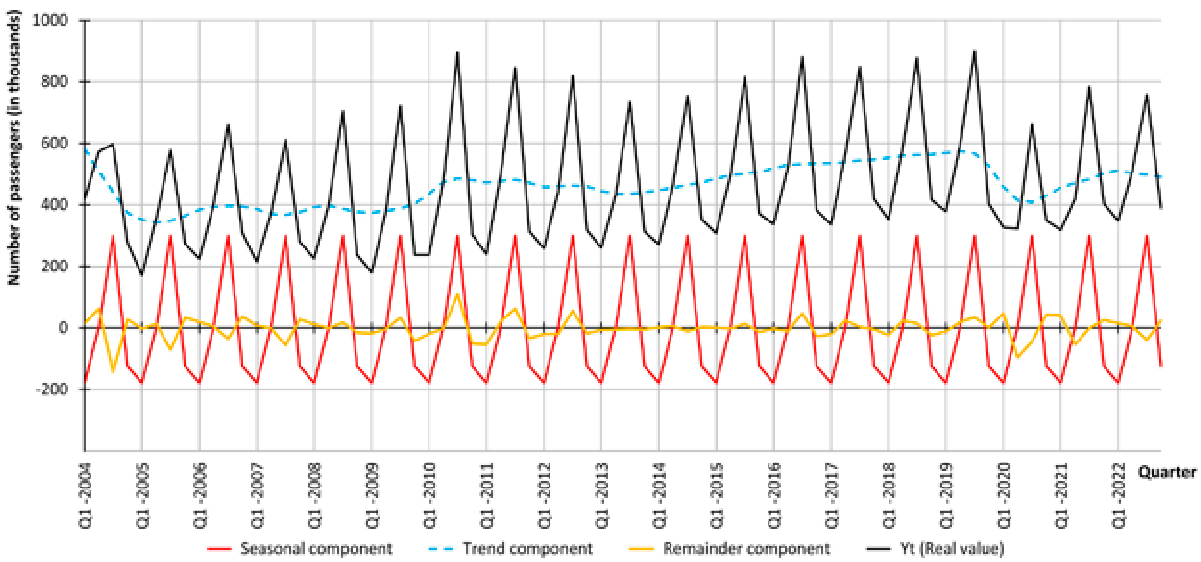

Figure 6. Decomposition of the time series of passenger numbers in Polish seaports using the STL model

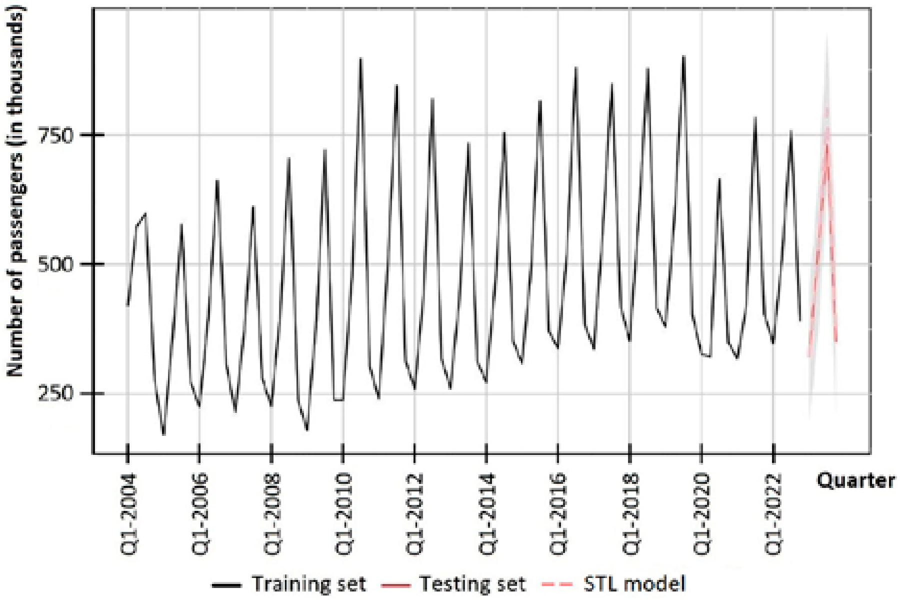

Figure 7. Passenger numbers in Polish seaports with the STL model forecast

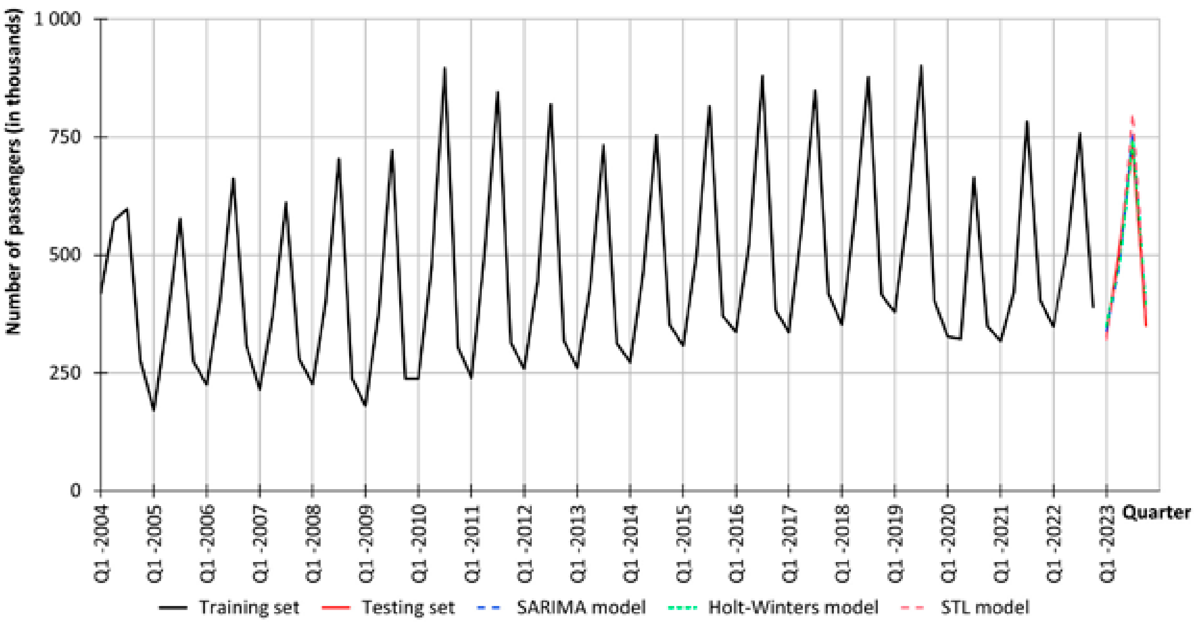

Figure 8. Comparison of mathematical models for passenger numbers in Polish seaports

Table 9. Comparison of forecasts obtained by individual mathematical models

	Q1-2023	Q2-2023	Q3-2023	Q4-2023
Actual value	328.00	517.00	731.00	350.00
SAIRMA model	339.23	479.71	760.60	390.32
Holt-Winters model	348.66	483.61	744.20	391.02
STL model	320.77	501.81	799.00	374.92

The results indicate that the SARIMA model provided forecasts closest to the actual values. Satisfactory results were also achieved with the multiplicative Holt-Winters model, while the STL model showed the lowest accuracy, particularly for the forecast of Q3 in 2023. Nevertheless, each proposed model offers valuable and effective tools for forecasting passenger traffic in Polish seaports, even amid global disruptions such as the COVID-19 pandemic.

Conclusions

The impact of the COVID-19 pandemic on maritime transport was evident globally. In passenger transport, the disruptions were primarily linked to restrictions imposed, including those regarding mobility, resulting in a decrease in cruise passengers. The aim of this study, which was to assess the impact of the COVID-19 pandemic on passenger traffic in Polish seaports and to develop mathematical models that could support management in the event of future epidemic threats, has been achieved. This publication provides an evaluation of passenger traffic in Polish ports as a case study. For this purpose, mathematical models that accounted for both seasonality and trends in the time series were employed and then compared. The study confirmed that the epidemic crisis led to a marked decline in passenger traffic at Polish seaports. The forecasts produced were generally higher than the actual figures, highlighting the disruptions caused by the pandemic. This finding is reinforced by the comparison of the results obtained by three different mathematical models. Based on the values of the information criteria and the comparison of actual data with the forecasts, the SARIMA model proved to be the most accurate. The Holt-Winters model also demonstrated high fitting and predictive performance. The STL model offered intriguing insights as well, with its time series decomposition enabling a detailed analysis of individual components in light of the disruptions caused by the pandemic. In summary, the comparative analysis of the proposed models (i.e., SARIMA, Holt-Winters, and STL) has shown their usefulness in forecasting changes in the number of passengers in Polish seaports in the face of disruptions such as the COVID-19 pandemic. These models can be an effective decision-making support tool, helping to limit the negative effects of future epidemic threats. Conclusions based on these models can be used to develop strategies in the event of a recurrence of similar challenges.

However, despite the obtained results, the study has several limitations. First of all, the analysis was based on data concerning Polish seaports only, which may limit the universality of the proposed models and the possibility of generalizing conclusions for other countries. Another limitation is the lack of an in-depth qualitative analysis, which could complement the analyzed quantitative results by better understanding the factors determining the variability in passenger traffic. It is also worth noting that the study focused on the relatively short-term effects of the pandemic, which may ignore long-term changes in passenger behavior and preferences. An additional limitation of the study was the availability of only quarterly data, which may translate into the predictive performance of the proposed models and, therefore, may not reflect changes occurring in the months following the outbreak of the pandemic. Hence, it may not take into account the full scope of external influences, such as global economic changes or current initiatives related to crisis management.

Taking into account the obtained results, further research should focus primarily on extending the analyses to other countries or regions in order to understand global trends and their local diversity. This would also allow for an assessment of the universality of the developed forecasting models in terms of their application to other transport markets. Another direction of research may be to consider more advanced models using, among others, machine learning algorithms and analyses based on Big Data sets. This would make it possible to consider additional factors, which in turn would improve the performance of the models and the precision of the forecasts. Such studies should include a detailed analysis of the impact of external factors, including state policy and sanitary regulations. Another important direction of the research is to prepare recommendations and proposals for solutions aimed at increasing the safety of the Polish maritime transport sector in the event of similar events in the future. The authors plan to conduct more detailed analyses in this area in future studies.

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Implications of dry port development in Nigeria: Empirical evidence from the southeast zone of Nigeria

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JEL Classification: L91, L92, R41

Abstract

International trade has skyrocketed in recent decades, with global trade expected to grow by 3.5 between 2017 and 2050. There have been diverse scholarships in the study of inland nodes to enhance seaport-inland connectivity and efficient global supply chain. A dry port is described as the most common inland node. However, research on dry ports is mostly lacking in developing nations like Nigeria, with developed economies dominating the space. We used mixed methods, combining qualitative and quantitative approaches for data collection, analysis, and interpretation to evaluate seaport efficiency and competitiveness indicators. A 5-point Likert scale structured questionnaire was administered to 478 respondents (the sample size), including logistics companies, importers, distributors, and marketers. A total of 383 respondents completed and returned their questionnaires. The study shows that existing seaports lack fully effective and functional conditions to support growing trade demands. Secondly, the study showed high interest in dry ports as complementary facilities that enhance logistical efficiency and regional competitiveness. Thirdly, space inadequacy, congestion, and challenges in handling high cargo volumes drive dry port development. Fourthly, dry port development can enhance seaport-inland transportation networks, improve seaport-inland access, provide adequate space for containerized cargo, expand seaport facilities to the hinterland, extend customer and value-added services inland, improve seaport flexibility and reliability, reduce inland distribution costs, and increase ship call frequency in Nigeria, particularly the southeast zone. These findings can shape regulatory and policy landscapes for implementing dry ports in other developing jurisdictions to expand research and data limitations on dry port operations in developing nations. We recommend replicating this study in other data-constrained locations and land-locked areas to promote seaport efficiency and competitiveness.

Introduction

International trade has skyrocketed in recent decades, with this trend predicted to continue, as global trade is expected to grow by a factor of 3.5 between 2017 and 2050 (ITF, 2017). In order to meet this increasing global trade volume, it is crucial to improve hinterland connections and inland ports, particularly in Africa. Over the past few decades, there has been a significant evolution and development in the study of inland nodes (Witte, Wiegmans & Ng, 2019). This concept has been more varied than only the logistics center and the extension of the period. Dry ports, inland clearance depots, inland container depots, inland terminals, inland ports, logistics centers, logistics parks, freight villages, etc., are some of the terminologies used to refer to inland nodes (Rodrigue & Notteboom, 2009). The many functions of these inland nodes are the emphasis of each term, with the dry port being the most common (Nguyen & Notteboom, 2019). The term "dry port" generally refers to a supply chain concept that incorporates all logistical modalities. UNCTAD (UNCTAD, 1991) defines a dry port as a hinterland terminal serving seaports, often connected by road or rail to transport maritime freight to interior locations. According to Nguyen and Notteboom (Nguyen & Notteboom, 2016), a dry port is an inland terminal with a direct and high-capacity connection to seaports that offers interchangeable services with seaports. Customers can leave and/or pick up their containerized units at a dry port, which is defined as an inland intermodal terminal directly connected to a seaport by rail (Roso, Woxenius & Lumsden, 2009). By increasing the transportation system's capacity and cost-effectiveness, a dry port helps the seaport alleviate congestion and develop its hinterland (Roso, Woxenius & Lumsden, 2009). The primary benefits to society are increased safety, the creation of jobs, and a decrease in externalities such as noise and pollutants. Europe's entire seaports, including some Asian seaports, employ dry ports in their hinterland network since the importance of these ports has been highly acknowledged (Veenstra, Zuidwijk & Van Asperen, 2012).

In contrast, Africa, including Nigeria, has not seen many of these advances because of historically smaller trade levels. Essentially, research on dry ports is primarily absent in emerging nations, such as Nigeria, and frequently concentrates on developed economies. However, the recent rapidly expanding freight quantities and transportation are drawing more scientific attention to this problem. Southeast Nigeria, which is described as mostly a landlocked nation with expensive transportation, is mostly affected by the limited development of the hinterland node due to limited and overstressed transportation infrastructures. Moreover, with 65% of seaborne containers received through the Lagos and Tin Can Island seaports having the final destination in the southeast cities, especially Onitsha and Aba, a dry port development could improve economies of scale and inland cargo distribution networks in the southeast.

Similar to southeast Nigeria, a sizable portion of the European market is inland, which has enhanced the development of dry ports in Western Europe and has significantly impacted various member countries' extensive intermodal integration systems, leading to a more commercially dominated hinterland supply chain. In order to accommodate cargo flows between the seaports and the hinterland, this scenario has led to the development of a coordinated inland supply chain strategy in Europe. For example, the development of the European Distribution Centers (EDC) has been impacted by the Rhine-Scheldt Delta, Europe's most significant hinterland gateway that connects a sizable population of dry ports. This has resulted in desirable logistics investments from most regions of Belgium and the Netherlands (De Langen & Chouly, 2004).

This study evaluates the implications of dry port developments in Nigeria in the context of the potential opportunities it represents in the southeast zone of the country, which is rated as one of the most cosmopolitan commercial and industrial hubs. As a result, the study is a conceptual analysis of the significance of dry ports using information obtained through observational documentation of behaviors and perceptions of relevant stakeholders from southeast Nigeria to expand the limited dataset and information on dry port operations in developing contexts. This study is structured around the following specific objectives: (i) assess the performance indicators of existing container seaports and their relationship to seaport efficiency and competitiveness, (ii) ascertain stakeholders' perception of the relevance of dry ports to the economic development of the southeast and entire Nigeria, (iii) examine the drivers of dry ports and their impact on seaport efficiency and competitiveness, and (iv) evaluate the effects of dry ports on seaport efficiency and competitiveness. The findings of this study can inform regulatory and policy frameworks for the implementation of dry ports in other developing jurisdictions.

Methods and materials

The study area is based on Amansea (6.253 and 7.145-Lat. /Long. or N 6° 15' 12" and E 7° 8' 40"). Amansea is a town bordered by the Anambra and the Enugu States. This location is justified based on accessibility to major commercial and industrial areas in southeast Nigeria, namely Onitsha and Nnewi, Anambra State and Aba, Abia State, and particularly its inland characteristics. This study adopted a survey design, which assisted in examining relationships among the critical variables (Aquino et al., 2018) and involved a critical observation of subjects, ideas, and events without an attempt to control the condition of such phenomena. This study applied mixed methods, combining qualitative and quantitative approaches for data collection, analysis, and interpretation to address the study's objectives (Johnson, Onweugbuzie & Turner, 2007, p. 123). The rationale for using mixed method research is founded on its effectiveness in providing a broader output compared with any mono methods (Onwuegbuzie & Leech, 2004), as well as the superior output that can be generated from a combination of insights and procedures from the two diverse paradigms, giving rise to more productive and workable solutions to the research problems (Johnson & Onwuegbuzie, 2004). The study used primary sources of data obtained through a survey instrument (i.e., a questionnaire) administered to respondents physically and online. Secondary data, such as journals, newspaper publications, annual reports, bulletins, white papers, and magazines, provided the basis for validating the primary data. The study population included seaport logistics companies, shipping companies with offices and business activities in southeast Nigeria, importers, marketing companies (distributors), and businesses that rely on imported raw materials, products, and goods and operate in southeast Nigeria. A sample size of 383 individuals was attained using Bill Godden's formula (Godden, 2004), which was used for this study. In selecting the actual elements that make up the sample size, a purposive sampling method/technique was used. This is because a specific category of individuals (i.e., the operators) in the shipping sector constitute the main objects of interest in the study. Therefore, we sampled respondents with the necessary background knowledge of the subject area: importers (95), logistics companies (100), distributors (133), and marketers (150). The Statistical Package for Social Sciences (SPSS) was used to measure the questionnaire items' internal consistency (i.e., reliability) with the composite reliability test. We used descriptive statistics to demonstrate the effects of dry ports on the socioeconomic and infrastructural developments of the southeast of Nigeria. The mean and standard deviation values assisted in determining the most influential indicators of seaport efficiency and competitiveness affected by the dry port development, coupled with the effects of a dry port on seaport efficiency and competitiveness.

Results and discussion

Objective (i): Assess the performance of the existing container seaports and their relationship to seaport efficiency and competitiveness.

Table 1 shows the results on the performance of existing container seaports and their relationship to seaport efficiency and competitiveness. The results show that existing seaports are not fully optimized to support growing trade demands, and strategic enhancements are essential for improved performance.

Objective (ii): Ascertain stakeholders' perceptions of dry port's relevance to the economic development of southeast Nigeria

Table 2 shows the results of stakeholders' awareness and perception of the importance of dry ports. This result highlights the stakeholders' readiness

Table 1. Analysis of Objective (i)

	N	Min.	Max.	Mean	Std. Dev.	Kurtosis	
							Std. Error
Patronage of our seaports is encouraging	383	1.0	5.0	3.648	1.3277	−0.100	0.249
Seaport accessibility is easy	383	1.0	4.0	2.073	0.8217	0.286	0.249
Seaport infrastructures are adequate and fully functional	383	1.0	4.0	1.984	0.8560	0.447	0.249
Seaport personnel are well-trained and skilled	383	1.0	5.0	2.804	1.1049	−0.094	0.249
Seaports cope with increasing container flow	383	1.0	4.0	2.371	1.0700	−1.140	0.249
Equipment and capacity of seaports improve the quality of services	383	1.0	5.0	3.833	1.3569	−0.504	0.249
There is adequate space for container handling	383	1.0	5.0	2.499	1.1160	−0.034	0.249
Waiting time for loading and offloading of containers is encouraging	383	1.0	5.0	2.104	1.2278	0.726	0.249
Container-clearing process is satisfactory	383	1.0	5.0	2.629	1.3217	−0.659	0.249
Container inspection procedures are simple and satisfactory	383	1.0	5.0	2.501	1.0705	0.160	0.249
Security of personnel and containers is satisfactory	383	1.0	5.0	2.971	1.2414	−1.129	0.249
The container transportation system is efficient	383	1.0	5.0	2.295	0.7157	5.711	0.249
Valid N (listwise)	383						

Table 2. Analysis of Objective (ii)

	N	Min.	Max.	Mean	Std. Dev.	Kurtosis	
							Std. Error
I understand the concept of a dry port	383	1.0	5.0	3.486	1.2083	−0.537	0.249
I understand how dry port functions	383	1.0	5.0	3.381	1.0440	0.486	0.249
Dry ports exist in Nigeria	383	3.0	5.0	3.671	0.6066	−0.648	0.249
A dry port supports a container seaport system	383	3.0	5.0	3.953	0.5992	−0.209	0.249
A dry port is necessary due to the growing international trade volume in Nigeria	383	3.0	5.0	4.272	0.6219	−0.630	0.249
A dry port is needed in southeast Nigeria	383	3.0	5.0	4.603	0.5597	0.091	0.249
The southeast has one of the busiest flows of containerised goods	383	3.0	5.0	4.572	0.6783	0.339	0.249
The southeast is a center of major commercial and industrial activities	383	1.0	5.0	4.230	0.9376	3.156	0.249
Valid N (listwise)	383						

Table 3. Analysis of Objective (iii) (research data 2024)

	N	Min.	Max.	Mean	Std. Dev.	Kurtosis	
						Statistic	Std. Error
Space inadequacy at seaports	383	1.0	5.0	4.172	0.9581	2.368	0.249
Congestion at the seaports	383	1.0	5.0	4.326	0.8746	5.700	0.249
The challenge of handling high rates and quantity of cargo	383	3.0	5.0	4.345	0.6360	−0.677	0.249
Flexible cargo distribution system	383	1.0	5.0	2.726	1.1095	0.115	0.249
Nearness to most consumers, distributors, marketers, etc.	383	1.0	5.0	2.710	1.2666	−1.059	0.249
Prolonged waiting and service time at the seaports	383	3.0	5.0	4.379	0.5836	−0.710	0.249
Expanding maritime infrastructures	383	1.0	5.0	3.606	1.2816	−0.059	0.249
A high volume of international trade	383	2.0	5.0	4.164	0.8571	0.320	0.249
The southeast is a hub of major commercial and industrial activities	383	2.0	5.0	4.381	0.8505	2.211	0.249
Public-private partnership	383	3.0	5.0	4.219	0.6970	−0.922	0.249
Ports supply chain expansion	383	2.0	5.0	4.060	0.7753	−0.042	0.249
Valid N (listwise)	383						

Table 4. Analysis of Objective (iv) (research data 2024)

	N	Min.	Max.	Mean	Std. Dev.	Kurtosis	
						Statistic	Std. Error
Expand seaport-inland transport networks	383	1.0	5.0	4.253	0.8445	5.135	0.249
Improve seaport-inland access	383	1.0	5.0	4.243	0.8868	3.778	0.249
Provide adequate space for containerised goods	383	1.0	5.0	4.319	0.7912	7.925	0.249
Expanded facilities for seaports	383	1.0	5.0	4.183	1.0223	2.124	0.249
Improved inland container transportation	383	1.0	5.0	4.123	1.0016	2.137	0.249
Extend value-added seaport services to inland	383	1.0	5.0	4.269	0.9256	3.003	0.249
Support seaport flexibility	383	1.0	5.0	4.016	1.1756	1.112	0.249
Reduce inland distribution costs	383	1.0	5.0	4.102	1.0523	1.201	0.249
Increase seaport reliability (stability of service quality)	383	2.0	5.0	4.042	0.8673	0.226	0.249
Increase ship call frequency	383	1.0	5.0	4.175	1.0198	2.121	0.249
Increase accessibility to and from seaports	383	1.0	5.0	2.170	1.4142	−0.996	0.249
Valid N (listwise)	383						

to embrace dry ports as complementary facilities that can drive logistical efficiency and regional competitiveness.

Objective (iii): Examine the drivers of a bulk dry port and their impacts on seaport efficiency and competitiveness.

Table 3 shows the results on the drivers of bulk dry ports and their impacts on seaport efficiency and competitiveness. The results imply that space inadequacy, congestion, and challenges in handling high cargo volumes are the primary factors driving dry ports' consideration.

Objective (iv): Evaluate the effects of dry ports on seaport efficiency and competitiveness

Table 4 shows the effects of dry ports on seaport efficiency and competitiveness. These results indicated that, for dry ports to realize their full potential, more efforts are needed to ensure seamless connectivity between inland and coastal logistics systems, thereby enhancing the overall competitiveness of seaport operations.

Seaport performance and its relationship to seaport efficiency and competitiveness

This study found that seaport infrastructures in Nigeria, such as docks, channel harbors, anchorages, cranes, container storage areas, etc., have been inadequate and functioning below optimum capacity. Moreover, the 2023 global report on the Container Port Performance Index (CPPI) published by the World Bank Group Transport Global Practice in partnership with the Global Intelligence and Analytics division of S&P Global Market Intelligence ranked the Lagos seaport and Tin Can Island values of 309 and 364, respectively, out of a total of 405 seaports assessed (World Bank, 2024). These overall ratings could result from the prolonged waiting or vessel time generally associated with the Nigerian container seaports. This scenario suggests an act of economic sabotage, which may have contributed to the low rating of the Nigerian seaports as the costliest in the world, coupled with the attendant low patronage of our seaports (Njoku, 2009), as confirmed in this study. Although the astronomical increase in the average annual cargo volume was attributable to compliance with addressing the challenge of port inefficiencies through infrastructure development efforts, such as expanding berthing facilities across many seaports, the challenge shifted from space-related to cargo-service-related problems. This scenario has resulted in the limited capacity of the existing seaports to cope with pressures from shipping companies, shippers, clearing agents, importers, exporters, etc., who experience operational challenges due to unmet customer expectations caused by seaport infrastructural inadequacy.

This is consistent with the findings from Khaslavskaya and Rosso (Khaslavskaya & Rosso, 2020), who showed that larger ships and heavier container loads generate a heavy burden on seaports, highlighting the need for seaport infrastructures to expand to the hinterland with increasing containerised goods. They claimed that seaport performance as a whole and the effectiveness of the entire supply chain depend on the efficient handling and distribution of cargo to and from the hinterland (container transportation system). Lamii et al. (Lamii et al., 2020) also demonstrated that the accelerated growth in containerised goods can exacerbate the challenge of containerised seaports in multifaceted ways, such as increasing difficulty in container management, lack of space, congestion at seaport access points, and negative environmental impacts, thereby limiting its performance. On the other hand, Wei, Sheng, and Lee (Wei, Sheng & Lee, 2018) and Mohan and Naseer (Mohan & Naseer, 2022) also agree that the growth in containerisation of seaports has resulted in overcrowding at seaports globally, propelling the integration of intermodal transport systems to enhance seaport performance and competitiveness.

Relevance of a dry port to the economic development of southeast and entire Nigeria

Most respondents strongly agreed on the relevance of dry ports in Nigeria, particularly the importance of or a need to locate dry ports in the southeastern region, which was anchored on the rapidly growing volume of international and local trade in the country's main seaports. This viewpoint agreed with the findings of Onifade (Onifade, 2020), who studied port productivity and efficiency, evaluating the effectiveness of port systems using measures such as cargo throughput, turnaround time, berth occupancy rate, human capacity development, etc. He suggested the development of a dry port to mitigate the city logistics problem, especially in the inland, as a sustainable measure to address the infrastructural expansion challenge resulting from the enormous cost of acquiring ample land space and other supporting seaport infrastructures associated with Lagos and Tin Can Island container seaports and surrounding areas. Generally, due to space constraints and environmental concerns, several seaports have had to deal with restrictions on physical development through strategies such as reclamation. For example, the numerous distributaries of the River Niger that empty into the Atlantic Ocean with a significant amount of sand are the main barrier to the construction of seaports in Nigeria (Ogunsanya & Olawepo, 2004). In addition, larger vessels are needed to achieve economies of scale and ports are anticipated to meet these demands, which the country cannot achieve. Similar or related challenges also confront container truck drivers on Nigerian roads, such as multiple tolls by unauthorized persons that mount roadblocks at short distance intervals in the guise of collecting revenues, resulting in long waiting times and traffic gridlocks, as well as avoidable mishaps such as accidents and disruptive service delivery to the consumers.

Southeast Nigeria is regarded as a hub of commercial and industrial activities compared with other parts of the country, with a high number of importers and exporters, especially in Onitsha (Anambra State), the largest commercial nerve center east of the Niger, Aba (Abia State), which hosts the first free trade zone east of the Niger, among others, coupled with a large volume of containerised cargoes or freights transported to the areas frequently by road from Lagos seaports. A recent publication by Vanguard News (online) and Shipping Position (online) dated September 29, 2022, and September 30, 2022, respectively, reported that, according to Dr. George Moghalu, the former Managing Director of Nigeria Inland Waterways Authority (NIWA), 65% of the seaborne containers received through the Lagos and Tin Can Island seaports has its final destination in the southeast cities, especially Onitsha and Aba. This has become more compelling, considering the proposed development of Onitsha River Port, which can serve as an inland waterway to convey containerised cargos from Lagos seaports to the river port and, subsequently, connect to the proposed inland container depot (dry port) at Amansea through rail or road, thereby minimising the cost of transportation, reducing waiting time, reducing damage to road infrastructure in the area, etc. Another consideration in terms of location is the impact of high taxation and high labor costs, as well as the recent socioeconomic and politically-motivated discrimination and attacks on the businesses and livelihood of those classified as non-indigenes, especially southeast business owners and operators in the southwest coastal state of Lagos, as a fallout of the 2023 post-election reactions.

Drivers of bulk dry ports and their impacts on seaport efficiency and competitiveness

Space availability remains one of the key drivers and determinants of seaport effectiveness and competitiveness due to the large volume of containerised cargo throughput in the Nigerian seaports, especially since the post-concession era. The inadequate space capacity at the seaports shown in this study can be traced to the limited seaport expansion capacity of the Nigerian major seaports of Lagos and Tin Can Island, resulting from the challenge of dealing with the geological barriers for physical developments in the coastal areas, where distributaries of the River Niger transport significant quantity of sediment into the Atlantic Ocean, as reported by Ogunsanya and Olawepo (Ogunsanya & Olawepo, 2004). The main geological barrier here is the considerable cost and the complex technical processes involved in land reclamation to enable seaport space expansion. Limited space capacity at container seaports generally constitutes serious operational challenges, such as prolonged waiting and service time, high demurrage costs, congestion, low economies of scale for customers, etc. This study shows that inadequate seaport space capacity has generated a need for dry port developments in the hinterland or inland area. A related study by Jeevan, Chen, and Cahoon (Jeevan, Chen & Cahoon, 2019) in Malaysia demonstrated the significant contributions of dry ports in terms of enhancing container seaport competitiveness by reducing waiting time and congestion, among others. This has proven consistent with the motivating factor behind the Wiri Inland Port in New Zealand, which assisted in managing delayed containers transported from the seaport, thereby reducing the demurrage charges at the seaport (Frost, 2010). Thus, dry ports' space capacity increases the number of clients who approach them with minimal cost and time implications while providing seaports with additional space for operations.

This study shows that flexible cargo or container distribution/supply chains can enhance seaport efficiency and competitiveness, constituting a measure of seaport quality performance. However, the participants' disagreement with the importance of cargo or container/supply chain flexibility suggests their inability to understand its ability to motivate dry port development, particularly in southeast Nigeria. Flexible cargo or container distribution/supply chain can have an advantageous effect on identifying customers' requirements and, consequently, fulfilling their demands. Brazilian dry ports, for instance, have implemented new measures to improve customer service, such as suspending duty payments, expediting customs clearance procedures, allowing immediate container unloading to prevent demurrage, having inspection agents on duty at all times, reducing the risk of cargo loss and damage, allowing partial cargo imports and exports based on business requirements, and suspending duties for foreign companies (Robles, 2013).

Effects of dry ports on seaport efficiency and competitiveness

From the participants' responses, this study shows the significant effect of a dry port as a means of expanding seaport-inland transportation networks, seaport efficiency, and competitiveness. A related study conducted by Jeevan, Chen, and Lee (Jeevan, Chen & Lee, 2015) on the role of Malaysian dry port in the container seaport system confirmed that the four dry ports sampled, including Padang Besar Cargo Terminal (PBCT), Ipoh Cargo Terminal (ICT), Nilai Inland Port (NIP), and Segamat Inland Port (SIP), contributed to improved seaport-inland transportation networks by providing multimodal transportation system, thereby enhancing container delivery time and economies of scale for shipping lines and shippers. This is also confirmed by a study in India, which showed that the flow of containers from manufacturers to the Chennai ports and the Inland Container Depots (ICD) is significantly increased by the combination of road and rail transportation (Hanaoka & Regmi, 2011). Moreover, Nguyen et al. (Nguyen et al., 2021) developed a conceptual framework to enable the evaluation of the role of a dry port in the port-hinterland setting in the context of the Vietnamese dry port, using multi-criteria and multi-stakeholder approaches from seaport and dry port user's perspectives. Nguyen et al. (Nguyen et al., 2021) found that a dry port enhances seaport-inland transportation networks by reducing the cost of transportation, merging and demerging consignments, and promoting the use of containers and transportation modes between the seaport and hinterland.

On the other hand, the efficiency of seaport-inland transportation connectivity can be constrained when dependence on a particular component of the connectivity system is disproportionately higher compared with the others. A dry port provides an opportunity for seaport-inland space expansion, especially for containerized cargo, which includes one of the primary criteria for assessing seaport efficiency and competitiveness. This study demonstrates strong participants' perception of the impact of dry ports in providing adequate space capacity to mitigate the space inadequacy at the Nigerian seaports due to limited land space for expansion. As a result, developing a dry port at Amansea, southeast Nigeria, will absorb the land-consuming activities at the seaports, thereby enabling the seaports to concentrate more on handling shipments, which enhances seaports' efficiency and competitiveness by reducing pressure from space-demanding seaport activities. This is consistent with findings from other studies reported by Roso and Lumsden (Roso & Lumsden, 2009), Notteboom and Rodrigue (Notteboom & Rodrigue, 2009), Rosa and Roscelli (Rosa & Roscelli, 2009), Caballini and Gattorna (Caballini & Gattorna, 2009), Bask et al. (Bask et al., 2014), and Jeevan et al. (Jeevan et al., 2019). The seaport-inland space expansion created by dry ports also enables the expansion of seaport facilities, which the study participants strongly agreed with. This finding corresponds with Jaržemskis and Vasiliauskas (Jaržemskis & Vasiliauskas, 2007), Notteboom and Rodrigue (Notteboom & Rodrigue, 2009), Rodrigue et al. (Rodrigue et al., 2010), Cullinane and Wilmsmeier (Cullinane & Wilmsmeier, 2011), Bask et al. (Bask et al., 2014), UNESCAP (UNESCAP, 2014), and Jeevan, Chen, and Cahoon (Jeevan, Chen & Cahoon, 2019).

A dry port provides value-added services to the seaports and hinterland customers, such as customs clearance, offices for customs, immigration, and quarantine services (Jeevan, Chen & Lee, 2015), as well as warehousing for packing, repacking, relabeling, sorting, mixing, blending, bar-coding, maintenance, and repair of containers (Robles, 2013; Nguyen et al., 2021). These value-added services, which enable the decongestion of seaports, can enhance Nigerian seaports' efficiency and competitiveness.

Conclusions

This study evaluates the implications of dry port developments in Nigeria in the context of potential opportunities, specifically in the southeast zone of the country. On the performance indicators of the existing seaports in Nigeria, concerning seaport efficiency and competitiveness, we conclude that the capacity utilisation of the existing seaports is not fully realised, considering the growing trade demands. The need is to meet the increasing container flow, high-quality service, efficient container handling operations, improved inspection procedures, improved waiting and service times, well-trained and skilled personnel, and seaport accessibility. This study demonstrates the high frequency of the readiness of the stakeholders to embrace dry ports as complementary facilities that can drive the Nigerian seaport's logistical efficiency and regional competitiveness, particularly in the southeast zone. On the drivers of dry port developments, we conclude that space inadequacy, congestion, and challenges in handling high cargo volumes are primary factors driving the consideration for dry ports in Nigeria and the southeast zone. In evaluating the effects of dry port on seaport efficiency and competitiveness, the study indicated that dry port development could enhance seaport-inland transportation networks, improve seaport-inland access, provide adequate space for containerised cargo, expand seaport facilities to the hinterland, extend customer and value-added services inland, improve seaport flexibility and reliability, reduce inland distribution costs, and increase ship call frequency in Nigeria and the southeast zone, in particular.

Recommendation

This study relates to an emerging topical research area in the maritime sector, applying qualitative and quantitative data collection, analysis, and interpretation approaches to expand the limited scholarship on a dry port concept in developing contexts such as Nigeria. To achieve improved capacity utilisation of the Nigeria seaports, we recommend that a strategic regulatory and policy commitment be made to mainstream dry port development and operations in the country's multimodal hinterland infrastructural design and implementation. Moreover, for dry ports to realise their full capacity utilisation and potential, more efforts are needed to ensure seamless connectivity between inland and coastal logistics systems, thereby enhancing seaport operations' overall efficiency and competitiveness. Toward achieving the former and latter, there is a need to forestall the challenges generally associated with the successful implementation of dry ports, including inadequate funding, lack of government commitment, inadequate rail infrastructures, inadequate manpower and technical capabilities, and unfavorable land tenureship and ownership systems.

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Risk assessment in maritime autonomous surface ship long-distance voyage planning

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Abstract

Rapid technological progress in the field of autonomous surface ships (MASS) has outpaced international regulations concerning the safety of their operation and various research centers and classification societies, which independently conduct work on requirements of MASS safety. The implementation of "remote" risk management during MASS voyages, with the support of remote operations center (ROC) operators, is generally recognized as key to safety in MASS operations. This paper presents issues related to the operation of MASS in the context of long-distance voyage planning, taking into account the risk management process. The factors initiating hazards in MASS operation are described with the background of current requirements for the crewed ships. The voyage plan and route selection are presented using the example of a bulk carrier sailing from Gdynia to Miami in the winter season. A MASS casualty accident probability model related to the hazards occurring at individual stages of the ship's voyage, based on the Poisson distribution, is proposed.

Introduction

The Maritime Safety Committee (MSC) of the International Maritime Organization (IMO), in its 108th session in May 2024, agreed to the revised road map for the development of the Maritime Autonomous Surface Ship (MASS) code, including the adoption of non-mandatory MASS Code in 2025 and considering a new chapter of the International Convention of Safety at Sea (SOLAS) in 2026, then adoption of the mandatory code in 2030 and entry of the code into force in 2032 (IMO, 2024).

The rapid development of MASS-related technologies has outpaced international regulations and caused various institutions, including research centers and classification societies, to present their own risk analyses to be carried out at the design and operation stages (DNV-GL, 2020; MEGURI2040, 2024). Most of the MASS applications are currently at various stages of sea trials. According to the interim guidelines for MASS trials (MSC.1-Circ.1604) (IMO, 2021), MASS should meet at least the same degree of safety since it is now provided by SOLAS for the crewed vessels. The guidelines address the risk associated with the trials, appropriate risk reduction measures, and ROC operator competencies, qualifications, and experience. However, they do not address specific indicated procedures.

The Det Norske Veritas (DNV) classification society, contracted by the European Maritime Safety Agency (EMSA), has developed the risk-based assessment tool (RBAT) (RBAT, 2023) for harmonization of the analyses and approvals of the MASS preliminary designs. The generally agreed upon key to the safety of MASS voyages was the risk management carried out by the MASS remote operation center

(ROC) operators. The first competence standard for the operators has been introduced by the DNV in collaboration with Kongsberg Maritime, Wilhelmsen Maritime Company, the University of South-Eastern Norway, and the Norwegian Maritime Authority (DNV, 2021).

Comparing the voyage planning for MASS and a crewed vessel using advanced planning tools, the differences are mainly related to human situational awareness. The methods used in traditional voyage planning are qualitative, based on experts' opinions and IMO resolutions on voyage planning (IMO Resolution A.893(21), 1999), weather routing (IMO Resolution A. 528(13), 1983), and Convention on the International Regulations for Preventing Collisions at Sea (COLREG) convention. In the development of MASS, effective route planning is additionally based on system and human situational awareness, including control and inference systems, reducing the impact of human error.

In 2023, the Korean Register (KR, 2023) presented "Guidance for Autonomous Ships." The guidance introduced in the "risk-based approval" chapter includes the emergency procedures to be applied in case of autonomous system failure. They included requirements for considering the operator's response in the event of an autonomous system failure at the early stage of ROC systems design.

Li and Yang (Li & Yang, 2023) presented a literature study on different route planning methods using the optimization of selected objective functions, e.g., the cost and benefit or inventory costs and emissions. They proposed the use of an AIS data-based machine learning for the MASS voyage planning. Wu et al. (Wu et al., 2021) and Yun et al. (Yun et al., 2024) developed the route planning method for MASS, which is based on a multiscale visibility graph. Ohn and Namgung (Ohn & Namgung, 2023) presented the requirements for optimal local route planning for MASS based on COLREG and navigation practices. The algorithms used in autonomous systems can be based on the determined parameters assigned to the rules. The rules of COLREG are of a qualitative nature and need to be interpreted before they are applied in practice. Therefore, the parameters have to be developed and verified.

Tao et al. (Tao et al., 2024) presented a literature review on hazard identification and risk analysis of MASS, including the influence of human factors and ship-related technological and environmental parameters. They provided potential future research directions, moving from human-oriented risk drivers to increased awareness of autonomous systems, combining perception and decision-making based on data sources, communication, and ship control technologies.

Various generally accepted risk assessment methods are usually combined and modified by researchers. Fan et al. (Fan et al., 2024) proposed a risk matrix based on a fuzzy analytic hierarchy process (AHP) for navigation risk assessment. Primarily based on expert opinions, they provide the basis for future quantitative analyses. Supervision and bridge resource management were identified as the main risk factors related to ship management.

In the MASS operation, a risk assessment can be defined as the analysis of potential hazards that cause disruption to the safe operation of the vessel and the remote operation center. This is a process of identifying, assessing, controlling, and monitoring hazards to minimize a combination of their frequency and the severity of their consequences. Hazards, defined by the IMO as potential threats to human life, health, property, or the environment (Formela, Neumann & Weintrit, 2019), when related to a MASS voyage should be defined as potentially harmful situations occurring in conditions of uncertainty.

This paper presents the factors initiating hazards in MASS operation and the implementation of risk analysis in the MASS voyage planning process. The probability model of hazards occurring at specific stages of the voyage, based on a Poisson distribution applied to long-distance planning, is introduced.

Factors initiating hazards in MASS operation

In the human-machine-environment systems (HME), many factors, jointly or separately, in the form of a sequence of events can cause unfavorable changes in the operational and technical states of the system. They can result in accidents. In maritime transport, they are defined in the casualty investigation code (Resolution MSC.255(84)) as events with the following consequences:

- death or serious bodily injury,
- missing from the ship,
- disappearance, intentional disappearance, or abandonment of the ship,
- damage to the ship,
- ship stranding, disablement, and collision,
- damage to infrastructure that threatens the safety of the ship,
- environmental pollution or potential hazard of pollution caused by damage to the ship.

The number of casualty events can be reduced when there is no crew onboard. The factors initiating hazards are dependent on the systems onboard MASS, communication systems, remote management systems, and ROC operator response. Autonomous technology transforms the role of a human from an active to a passive operator supervising the safety of the whole system, ready to take over the functions of an autonomous system in an emergency. Therefore, the usually considered human-related risk factors, including human situation awareness, have an impact on operational MASS safety. They should be considered at the early stages of the design of system architectures (KR, 2023).

The factors initiating hazards in the operator–MASS–environment system in normal operation include operational and technical parameters, loading conditions and cargo characteristics, navigational and weather conditions, and factors related to ROC, including human factor and ROC systems. They should be considered in MASS long-distance voyage planning. The dependencies between the factors are presented in Figure 1.

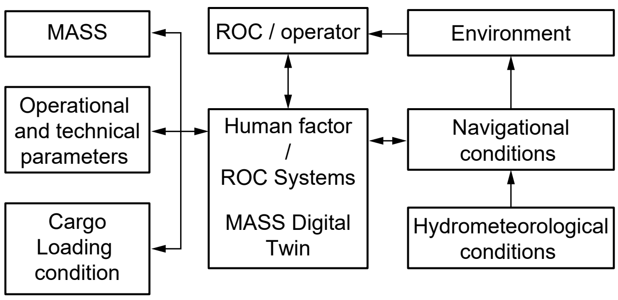

Figure 1. Factors initiating hazards in the operator–MASS–environment system in normal operation

Long-distance MASS voyage planning

Before commencing the voyage, ROC operators who plan the route should adopt an appropriate risk management method to identify, assess, and manage hazards. The method, based on a list of potential adverse events at individual voyage stages, enables the identification and assessment of hazards. They can be of a sudden nature, caused by external or internal factors, e.g., failure of systems, mechanical equipment, or hull girder during the voyage. The list of created hazards should enable their assessment and correction in sufficient time to prevent or limit the consequences of possible accidents. The flowchart of the MASS voyage planning, including the risk management process, is presented in Figure 2.

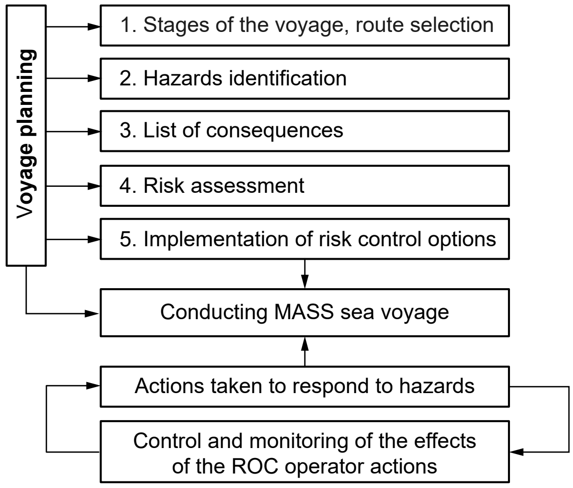

Figure 2. MASS voyage planning included a risk management process

Stages of the voyage, example of route selection

The following example of route selection, which can be used at the preliminary stage of voyage planning, is based on the experience of previous voyages of a bulk carrier sailing from Gdynia to Miami in the winter season. The voyage plan is prepared by taking into account all the possible parameters and variants of the voyage stages relating to possible hazards. The example of a Gdynia–Miami bulk carrier voyage allows us to consider both the southern and northern routes.

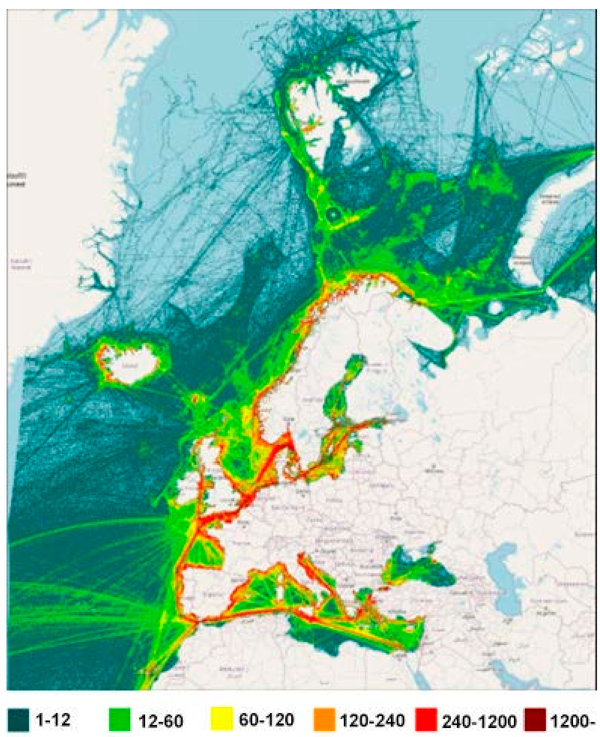

Figure 3. Vessel traffic density observed in 2022 in European waters (EMSA, 2023)

The voyage plan is calculated by a team of practitioners, specialists, and consultants, including navigators, chief engineers, meteorologists, cargo experts, and shipowner representatives, using available navigation publications. The coordinating person of the team is the ROC operator, who remotely manages the MASS. The level of hazards depends on the stage of the voyage, e.g., navigation in open waters, restricted water areas with heavy traffic (such as the English Channel and the Baltic Sea), approaches to ports, anchorages, hydrometeorological conditions, and operational parameters of MASS. An example of vessel traffic density observed in 2022 in European waters (EMSA, 2023) is presented in Figure 3.

The first step of planning is to determine the voyage stages and sailing times for individual route variants. Each variant is characterized by different intensities of hazards related to the season, hydrometeorological conditions, and navigation areas. The stages of the voyage on the Gdynia–Miami route are presented in Table 1, while the route variants are presented in Table 2 and illustrated in Figure 4. In addition, an example of a barometric situation along the routes is presented in Figure 5.

Table 1. Voyage stages on the Gdynia–Miami route

Stage of the voyage	Route	Distance [NM]	Time [h]	Assumed speed/route
A	Gdynia–Kiel	346	23.0	15 knots
B	Gdynia–Skagen	410	27.5	15 knots
C	Kiel–Brunsbuttel	52	10.0	According to the vessel traffic
D	Skagen–Dover	527	35.0	15 knots
E	Brunsbuttel–Dover	348	23.0	15 knots
F	Dover–Quessant	308	20.5	15 knots
G	Quessant–Miami	3740	249.5	15 knots northern route
H	Quessant–Miami	4507	300.0	15 knots southern route
I	Skagen–Orkney	430	29.0	15 knots
J	Orkney–Miami	3757	250.5	15 knots

Table 2. Options of the Gdynia–Miami route

Route variant		Stages of the voyage	Distance	Time	
			[NM]	[h]	[days]
1	1.1 northern	A, C (Kiel Canal), E, F, G	4794	326	13.6
	1.2 southern	A, C (Kiel Canal), E, F, H	5561	376,5	15.7
2	2.1 northern	B, D, F, G	4985	332,5	13.8
	2.2 southern	B, D, F, H	5752	383	16.0
3		B, I, J	4597	307	12.8

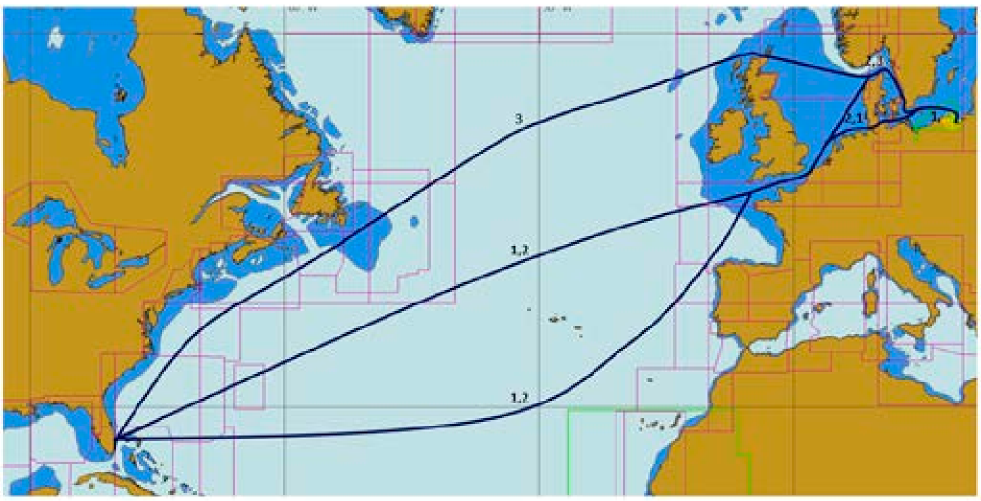

Figure 4. Gdynia–Miami route variants

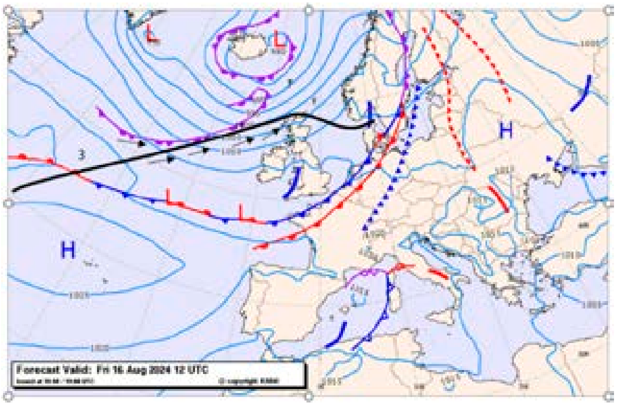

Figure 5. An example of a barometric situation (August 16, 2024). The wind directions opposite to the MASS courses on the Gdynia–Miami route are marked in black for variant 3 of the routes (KNMI, 2024)

Hazards at individual stages of the voyage

Identification of hazards at individual stages of the voyage is the basis for proper risk assessment. Missing a hazard has a much greater impact on the overall risk assessment than adopting an inappropriate consequence model or assuming an incorrect frequency of occurrence. Therefore, the goal is to develop a complete list of hazards. To analyze the hazards, a list of accidents should be agreed upon, starting with accidental events. According to EMSA 2023, "an accident event is an event that is assessed to be inappropriate and significant in the sequence of events that led to the marine casualty or incident," and "a casualty event is an unwanted event in which there was some kind of energy release with impact on people and/or ship including its equipment and its cargo or environment." These definitions are applied to ships with a crew on board. The "non-accidental events are not considered as marine casualties or incidents are not covered by the scope of the Accident Investigation Directive (2009/18/EC)."

Identification of hazards involves developing possible accident scenarios based on historical data of the accidents that occurred in the examined area, data on accidents in similar areas, and expert opinions (Burciu, 2011; EMSA, 2023). The probability of hazards leading to property and environmental losses is related to the operational status of MASS, navigational and hydrometeorological conditions, and ROC operator decisions.

The hazards for particular variants of MASS sea routes are as follows:

- winter season,
- restricted visibility,
- heavy ship traffic,
- adverse wind direction, currents, and tides,
- navigation in restricted waters, canals, and narrow passages,
- navigation in ice-covered waters and icing on the ship.

Tides and sea currents may have a significant impact on the MASS voyage and should form the basis of route planning. Hazards identified for individual route variants in the winter season are presented in Table 3. The MASS voyage hazards matrix for the winter season is presented in Figure 6.

Based on the constructed matrix, the hazards and the priority of actions aimed at preventing or minimizing the risk can be assessed, including actions planned to avoid hazards. The selection of a route option can be based on minimizing the risk of the planned MASS voyage due to the duration of the voyage, i.e., variant 3 (12.8 days), or minimizing hazards, i.e., variant 2.2 (despite it being the longest route time, namely, 16 days). When selecting route variant 2.2, it is necessary to assess the probability of failure and the degree of its impact on safety. Hazards that should be considered for route option 2.2 are restricted visibility and navigation in restricted water areas with heavy traffic.

Table 3. Hazards for individual route variants in the winter season

Route variant			Restricted visibility	Ship traffic	Wind direction	Narrow passages, canals	Ice-covered waters
European waters		1.1 1.2	Max	Max	Divergent	Restricted traffic	Min
		2.1 2.2	Max	Max	Divergent	Restricted traffic	Min
		3	Max	Max	Divergent	Restricted traffic	Min
Atlantic	Orkney–Miami	3	Max	Min	Favorable	No traffic restrictions	Medium
	Northern route	1.1 2.1	Medium	Min	Adverse	No traffic restrictions	No ice-covered waters
	Southern route	1.2 2.2	Min	Min	Weak	No traffic restrictions	No ice-covered waters

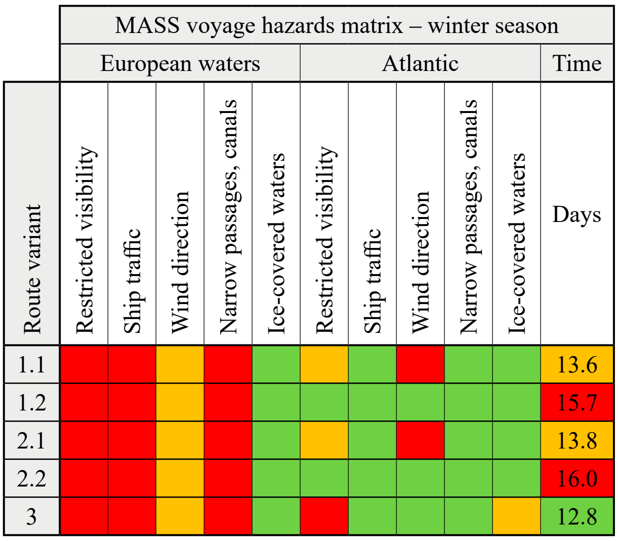

Figure 6. MASS voyage hazards matrix. The levels of hazards are marked in green for minimum, yellow for medium, and red for maximum probability

Implementation of risk analysis in MASS voyage planning

The risk of an accident is defined as the probability of the occurrence of a specific dangerous event, which may cause damage, combined with the consequences associated with this event (PN-IEC 300-3-9). In a traditional approach (Fan et al., 2024), the combined probabilities and consequences of hazards are presented within a risk matrix. The risk assessment of a MASS accident should be carried out systematically by the system supervised by the ROC operator in order to determine whether the identified hazards can be reduced or eliminated and what actions should be taken.

In MASS navigation, the same adverse events as those mentioned for a crewed ship should be considered. They are classified as capsizing/listing, collision, damage to equipment, grounding/stranding, fire/explosion, flooding/foundering, hull failure, loss of control (i.e., total or temporary loss of the ability to operate or maneuver the ship), failure of electric power, and release of harmful substances on board. In restricted waters, with the possibility of heavy ship traffic, accidents mainly relate to contact, collision, allision, and grounding. In the risk analysis relating to MASS voyage planning, all these types of accidents should be considered. Therefore, their consequences and the related reduction options should be included in the analysis.

When planning a voyage through multiple areas, the probability of hazards occurring at specific stages of the trip can be estimated using the Poisson process. Namely, an approximate model of probability that the assumed number of accidents can occur in a designated area, proposed by Grabski and Jaźwiński (2009) and Burciu (2011), can be applied. To describe the number of marine accidents of specific types of vessels in the area, if the following component processes arise

$$\{X_1(t);\ t \geq 0\},\ \ldots,\ \{X_n(t);\ t \geq 0\} \tag{1}$$

we find that

$$\{X(t);\ t \geq 0\} \tag{2}$$

describes the total number of accidents in this area.

If the component processes mean the numbers of possible accidents with different intensities in separate areas, then the Poisson process describes the number of marine accidents in the entire area, i.e.,

$$P(X(t) = k) = \frac{(\lambda t)^k e^{-\lambda t}}{k!} \tag{3}$$

where $k = 1,2,3,\ldots$ is the number of events, $\lambda = \gamma\mu$ is the intensity of marine accidents, μ is the intensity of ship traffic in the area, and $\gamma = \lambda/\mu$ is the marine accident rate. The distribution function, variance, and standard deviation are given, respectively, as follows:

$$F(X(t)) = \lambda t \tag{4}$$

$$V(X(t)) = \lambda t \tag{5}$$

$$\sigma(X(t)) = \sqrt{\lambda t} \tag{6}$$

For example, the probability that the number of possible marine accidents is less or equal to 10 in the time interval [0, t) for the particular sea area can be expressed via:

$$P(X(t) \leq 10) = \sum_{k=0}^{10} \frac{(\lambda t)^k e^{-\lambda t}}{k!} \tag{7}$$

Approximating this Poisson distribution with a normal distribution, we can then obtain:

$$P(X(t) \leq 10) = P\left(\frac{X(t) - \lambda t}{\sqrt{\lambda t}} \leq \frac{10 - \lambda t}{\sqrt{\lambda t}}\right) = F\left(\frac{10 - \lambda t}{\sqrt{\lambda t}}\right) \tag{8}$$

where F is the distribution function of the standard normal distribution.

The team of experts and practitioners responsible for the implementation of preventive and mitigating actions must make decisions on the implementation of the MASS voyage plan, react to existing hazards, undertake the appropriate actions, and monitor their effects.

Conclusions

This paper presented a discussion on the problems relating to the risk assessment of the MASS voyage planning and the important role of the ROC operator. Man, Lundh, and Porathe (2014) presented a study on the human factors relevant to shore-based unmanned ship handling. They stated that the most important difference is that the watch officer is not onboard the ship and, thus, there is a lack of physical perception of the ship's movements and environmental conditions. The "feelings" that the watch officer perceives onboard by looking outside of the window allow for a reduction in stress. In contrast, stress can be reduced in unmanned ship handling via a team of advisors supporting the ROC operator. Namely, hazards should be identified along with the associated risk and, if the risk exceeds acceptable levels, the warning system alarm should be activated.

The current ongoing MASS-related projects confirm the importance of further research on reliable models that can be implemented in the design of automatic systems, including a risk analysis that lowers the ROC operator error threshold. Automatic systems can eliminate the human factor in voyage planning. However, they do not eliminate human responsibility. A growing problem related to MASS voyage planning is the operational autonomy of port infrastructure (Abramowicz-Gerigk et al., 2024). The ROC operator, fully aware of the MASS voyage plan in many dimensions, including navigation, port operations, and system performance-related hazards, will be able to make decisions that enhance safety and efficiency. The designation of an appropriate operator, who is not only well-trained and experienced but physically and psychologically fit for work under high tension, can considerably reduce the risk of accidents.

Acknowledgment

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Impact of the protection of critical infrastructure facilities on the management of public transport and tourism economy on the example of Świnoujście

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Abstract

Critical infrastructure facilities, especially those located close to urban agglomerations, can cause serious difficulties for tourists. An example of such a situation is Poland's only sea-land LNG terminal located in one of Poland's three seaports of strategic importance to the national economy, Świnoujście. This port is located in the center of the city, which borders Germany, and is a very popular sea resort for both compatriots and foreign tourists. On the basis of a critical analysis of the literature, a comparative analysis, and the method of inductive-deductive reasoning, the authors point out a research gap in the field of transportation problems in critical infrastructure areas. The purpose of this article is to present current transportation problems resulting from the introduction of a closed transportation zone within critical infrastructure. In this article, the authors focus on presenting the effects of the aforementioned restriction on the tourism economy. One of them is a reduction in the ability to reach important historical sites and, thus, a significant decrease in interest in these monuments. The authors, with the help of observations, interviews, and a comparative method, analyzed possible solutions to transportation problems and proposed the most favorable solution. The proposed scenarios include three modes of transportation: road, rail, and water. Currently, the only possible solution is water transport. Consequently, the authors proposed an innovative and inviting means of transport for tourists, which is electric water cabs. An analysis of the effectiveness of such boats is made, and their additional added value for the environment and the image of the city and port as nature-friendly are pointed out.

Introduction

Critical infrastructure plays a key role in the economic and social well-being of regions and countries (Kopiika et al., 2025). Since water covers 71% of the Earth's surface and is essential for all known forms of life, modern economies and societies are fully dependent on maritime infrastructure (Bueger & Liebetrau, 2023, p. 2; Fošner et al., 2024, p. 2; Balta et al., 2025). The increasing number of crises, including natural disasters and armed conflict, underscores the importance of critical infrastructure in terms of security, especially in urban areas and port areas (Henriques et al., 2023, p. 1–2; Gebhard et al., 2025, pp. 2–3). Critical infrastructures provide essential services for the needs and functioning of society, enabling not only safety, security, and health but also economic prosperity, social well-being, and economic development (Nick et al., 2023, pp. 2–3). In addition, well-functioning critical infrastructure in cities contributes to all sorts of activities; for example, public transportation systems increase access to employment and services, thereby reducing social exclusion and improving the overall quality of life in cities (McAlister et al., 2024). Identifying critical infrastructure is also an important step for governments in order for them to better assess the threats to which they may fall victim. By creating a list of their critical sectors, governments can optimize the use of their resources and better recommend comprehensive national policies, regulations, and implementation plans that best combat the threats most likely to disrupt or destroy their critical functions (Davis, Bace & Tatar, 2024).

Economic activities carried out in seaports take place on many levels. The functions they perform, i.e., transport, industrial, commercial, logistics, or regional, make seaports a key factor in the economic growth of the country and regions. On their territory, there are many infrastructure facilities that, from a regulatory point of view, belong to the country's critical infrastructure and are included in emergency management policies. Critical infrastructure is the basis for the safe functioning of the country and its citizens. The Crisis Management Act of April 26, 2007, defines critical infrastructure as "systems and their constituent functionally related facilities, including construction facilities, equipment, installations, services that are key to the security of the State and its citizens and that serve to ensure the smooth functioning of public administration bodies, as well as institutions and businesses. Critical infrastructure includes systems (Journal of Laws, 2023):

a. supply of energy, energy resources, and fuels,
b. communications,
c. data communications networks,
d. financial,
e. food supply,
f. water supply,
g. health care,
h. transportation,
i. rescue,
j. ensuring continuity of public administration,
k. production, storage, and use of chemical and radioactive substances, including pipelines of hazardous substances."

From the above definition of critical infrastructure, it can be seen that the vast majority of the systems listed are located in seaports. First and foremost, port infrastructure serves the supply of energy resources, fuels, food, and storage of chemicals; it has pipelines with hazardous substances and is an important component of the transportation system in global supply chains. Critical infrastructure, as defined by the European Commission, means "a component, system, or part of infrastructure located in the territory of the Member States, which is essential for the maintenance of essential social functions, health, safety, security, material, or social well-being of the population and the disruption or destruction of which would have a significant impact on the Member State concerned as a result of the loss of these functions" (Official Journal of the European Union. 2008). All these components are reflected in seaports. Accordingly, the Directive of the European Parliament and of the Council on Enhancing Port Security pays special attention to the protection of persons, infrastructure, and port facilities from security incidents and their possible destructive effects (Official Journal of the European Union, 2005). At this point, it should be noted that the links that exist between seaports and the cities in which they are located and their economic hinterland affect the socioeconomic processes in the seaport but, most importantly, the development processes of the region and the country, which means that hundreds of thousands of people are directly and indirectly affected (Tubielewicz, Forkiewicz & Kowalczyk, 2010). The international environment and the geopolitical situation of the country and the region have a particular impact on potential security risks at ports. Therefore, taking measures to ensure security, especially of the supply economy, should be an elementary step in planning the strategic development and infrastructure investment of countries.

Reviewing the literature on the critical infrastructure of seaports, it can be noted that it refers to the whole area of the ports and to securing security in ports as a whole, placing particular emphasis on identifying threats and developing methods to prevent them. Wróbel and Kustra include port and maritime infrastructure as an element of the critical infrastructure of the entire State. In their work, they deal with possible risks, their consequences, and the State's readiness to counter them (Wróbel & Kustra, 2021). Similarly, the study of Ighravwe and Mashao, who deal with the critical infrastructure of seaports, conducted an extensive review of the literature on risk management methods in ports and proposed an effective method for estimating possible risks in seaports (Ighraywe & Mashao, 2023). On the other hand, the works of Tubielewicz, Forkiewicz, and Kowalczyk deal primarily with crisis management in seaports, framing them as the critical infrastructure for the entire State. In their deliberations, they point out how strategically important seaports are for economic and social development, and the need to ensure their security as a key link in the global transport chains (Tubielewicz et al., 2010a, 2010b, 2010c; Tubielewicz & Forkiewicz, 2011). In addition, they point out the need to pay attention to the planning of infrastructure investments in seaports so that the security of both residents and the entire state economy is ensured. The study of Żywucka-Kozłowska and Broniecka provided a direct reference to the current geopolitical situation, which affected the restriction of access around the sea-land LNG terminal in Świnoujście and the importance of making such a decision. In their paper, they point out the real threat to the security of the flow of goods through seaports that, in the face of Russia's aggression against Ukraine in 2022 (which continues to this day), becomes even more relevant today. Particularly because Poland, as a neighboring state, is in the first line of exposure to various types of attacks. This is confirmed by successive reports by Polish intelligence on the detention of citizens of the Russian Federation and Belarus suspected of espionage activities against the Republic of Poland. One of the interventions occurred in the West Pomeranian province, where the LNG terminal is located. The detentions resulted in court decisions on temporary detention; this indicates the high social harmfulness of the acts committed by these foreigners (Żywucka-Kozłowska & Broniecka, 2024).

In the case of carrying out transport processes, a negligible part of the undertaking of a given topic in the security of port areas has been carried out. The available literature notes an important research gap in relation to the absence of studies on transportation problems in port areas, particularly within critical infrastructure. The source analysis made it possible to detail several methodologies for conducting transportation infrastructure risk assessments. One of them is the recommended security guidelines for facilities, which have been used to conduct risk assessments of ports in the United States. It has also been used in other countries, especially countries in the Americas that have significant trade relations with the United States. Another example is SECUREPORT, which was developed by the State Ports of Spain specifically for this sector. The Hazard and Risk Analysis Matrix, developed by the International Labor Organization (ILO) and the International Maritime Organization (IMO), has been used to conduct risk assessments at ports around the world (Romero-Faz & Camarero-Orive, 2017). Based on a critical analysis of the literature, the authors also recognized that there is a lack of research relating to transportation itself in the critical infrastructure area. An assessment was made of the interdependencies between inland port infrastructure and the surrounding supply chain, where it was shown that environmental factors have the greatest impact and organizational factors, including transportation, have the least impact on port disruptions. Ports around the world are often affected by natural disasters, such as storms and flooding, and less affected by organizational problems, such as labor strikes and insufficient resources (Hossain et al., 2020).

The analysis of the literature has identified a certain research gap in the form of a lack of translation of the effects of locating investments of strategic importance to the national economy in seaports for residents and users of the land around these facilities in general, as is the case with the Świnoujście seaport in Poland. Naturally, the huge positive development impact of the regions has been pointed out. However, this is not analyzed in micro terms, pointing out certain limitations and risks for the residents of port cities. The port of Świnoujście is one of three Polish ports of strategic importance to the national economy, which is the only one with a modern sea-land terminal for handling and storing liquid LNG. The terminal is a critical infrastructure component, as it is used to supply energy resources or fuels. It has been located in a very favorable location in terms of international exchange; however, it is unfavorable in terms of tourism and culture. It is located on an island, next to historical tourist sites and not far from the city beach. The location of a critical infrastructure facility in this place has caused some complications for tourism. The present article deals with these problems.

Methodology

This article presents a literature review related to port critical infrastructure, which showed a certain research gap in the area of the lack of impact of locating strategic investments in tourist destinations. In particular, the lack of research on transportation constraints and their socioeconomic effects on the region was noted. An analysis was made of the problem of introducing a protection zone around the LNG terminal and its effects on local residents. The focus was on existing and new transportation solutions in the areas of port facilities covered by the critical infrastructure zone. On this basis, assisted by descriptive analysis and the method of deduction, three potential scenarios were identified that could solve the transportation problem in the area of the protection zone in the city of Świnoujście. The essence of the research becomes the introduction of the possibility of further development of tourism on the right-hand side bank of the city, which has been drastically minimized by the lack of free transportation to key tourist facilities (i.e., Fort Gerhard and The Lighthouse). Previously, access to The Lighthouse and Fort Gerhard was provided by Line No. 1 of the Świnoujście bus service and the possibility of direct access to the destination by private transport. A scenic bicycle path, part of the West Pomerania Bicycle Route, was a popular route.

In order to find the most optimal solution to confirm the transportation possibilities in the study area, three modes of transport were selected: road, rail, and water. The analysis was carried out on the basis of materials made available by the City of Świnoujście and the Szczecin and Świnoujście Seaport Authority, as well as available ordinances contained in the Journal of Laws and independent field research. For each solution, the transportation system was described by taking into account the feasibility of its implementation and considering the restrictions currently in place.

The port city of Świnoujście

The city of Świnoujście is located on the Baltic Sea, on the western coast of Poland. In addition to being a popular seaside resort, it is home to a naval port and one of Poland's three seaports of strategic importance to the national economy. The commercial port is universal in nature; however, it stands out from others in that it offers the largest number of ferry connections between Poland and Scandinavia. The location of the ferry terminal is exceptionally favorable for international trade and transport, as the city of Świnoujście borders Germany. The Świnoujście port is also home to Poland's only sea-land LNG terminal. In addition, there are few terminals of this type in the Baltic Sea Region and northeastern Europe in general, which is clearly illustrated in Figure 1. The map shows land and water LNG handling terminals (Analytical Solutions and Products, 2024).

In the face of an energy crisis and Russia's potential military threat to NATO countries, the LNG terminal has become a very important critical infrastructure facility. However, this causes some complications for tourism, especially for historical tourist sites nearby. Figure 2 shows a screenshot from the Google Maps application with a view of the city and the seaport.

Using the Google Maps application, the most popular attractions of the city of Świnoujście are marked. Meanwhile, the city's main beach, which is also the most popular destination for sunbathing tourists, is marked manually with a blue square. The yellow and red ovals mark the seaport and LNG terminal, respectively. It should be noted that just above the seaport and close to the waterline are two tourist attractions. These are some of the oldest structures in the city, including The Lighthouse, which is now the highest point on the Baltic coast, and Fort Gerhard from the 17th century, which was part of the city's military fortifications. In addition,

Figure 1. Map of LNG terminals (Analytical Solutions and Products, 2024)

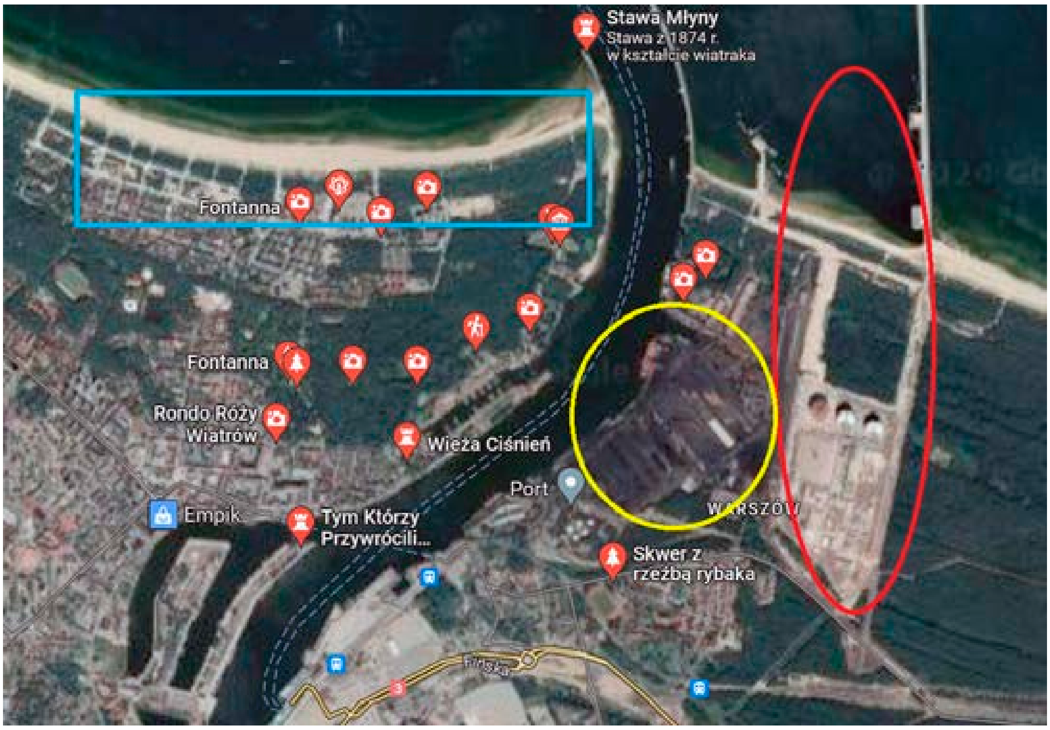

Figure 2. Screenshot showing the city of Świnoujście (Google Maps)

on the right-hand side of the LNG terminal is another city beach. It is an important tourist spot, as the other main beaches are located on the other side of the city and can only be accessed in a limited way via water ferries and from the German border, where traffic volume is generally at a high level resulting in frequent congestion in the entrance area. Despite the tunnel under the Świna River connecting the islands of Wolin and Uznam, which was built in 2023, access to the sites remains difficult due to high traffic and a lack of parking spaces on the island. The aforementioned attractions are the basis for further discussion as, after Russia's aggression against Ukraine on February 24, 2022, a decree was introduced on April 12, 2022, which established a protection zone around critical infrastructure, resulting in significantly restricted access to these tourist attractions.

As a result, the number of tourists visiting these facilities has dropped to almost zero. According to the gazette relating to the designation of the protection zone area, they apply to (Journal of Laws, 2024, Art. 121):

- only the area that directly includes the specified zone;
- the area directly covered by the protection and the intermediate area.

Due to restrictions on the movement of vehicles in the areas of protection zones, there is a lack of opportunities for innovation in public transportation. In view of this situation, the authors have attempted to explore possible solutions to this problem.

Research results: Case study

Road transport

The most optimal solution for residents and tourists of the city of Świnoujście is public transportation provided by land in the form of their own vehicles or public transport. On April 12, 2022, an ordinance was introduced, based on which a protection zone was designated, which prevented such access. Prior to the introduction of the zone, the city offered access to the route by public transportation, covering the stops that are presented in Figure 3 in the area of the Warszów district. The terminal stop (closest to the beach and the mouth of the Świna River) was the lighthouse, located in the vicinity of the fort.

Currently, while driving along the container terminal along Barlickiego Street, one may encounter point infrastructure elements that prevent further travel to the LNG terminal site (Figure 4).

In Figure 4, the street affected by the barricade has been marked in red on the right-hand side. The existing safeguards were created on the basis of decisions by the Port Authority, which stated that the possibility of providing an overland access road to the tourist facilities raises the risk of a situation threatening the port facilities and the container terminal itself.

Figure 3. Route of Line 1 (based on Google Maps and Komunikacja autobusowa, 2025)

Figure 4. No access to the LNG Terminal

Analyzing all the considerations in this scenario, the possibility of introducing road transportation must be rejected.

Rail transport

The proposed solution addresses the possibility of introducing a railroad line leading from the train station to both attractions. Railroads are a branch of transport characterized by low operating prices, which distinguishes them from other solutions in the economic area. In addition, it is another attraction for visitors to Świnoujście, as they can visit the right-hand side bank of the city in this way. By choosing such a solution, the city authorities would also not have to face increasing traffic congestion, as rail transportation would ensure a reduction in the number of private drivers in the area. The authors focused on planning a well-connected route for both tourists and city residents, as presented in Figure 5.

Figure 5. Proposed Route 1 and 2 for rail transport (based on Materials of the City of Świnoujscie)

The first proposed form, as shown in Figure 5 (marked in yellow), of the crossing would run along the Świna River on the land road, where the rail line used to transport goods is carried out. The introduced rail line would end with the designated infrastructure, that is, at the site of The Lighthouse. Unfortunately, it will not be possible to organize public rail transportation at this location, as cargo ships dock along the coast. A lot of transshipment operations take place there using the port suprastructure. It would be highly dangerous to transport people to this location. In addition, freight trains often stand at this location waiting to load or unload, which would cause difficulties for passenger trains. Another alternative would also involve the participation of rail transportation with its proposed route requiring a crossing at Nowoartylerska Street so that the destination stop would be at the intersection with Ku Morzu Street. The proposed crossing is marked in purple on the map. Unfortunately, the second proposed route, in addition to consisting of a section above the shoreline, is also located in a protection zone, which makes it off-limits to public use. Therefore, the scenario that includes the introduction of a rail line to the fort and lighthouse must also be rejected.

Water transport

Currently, the only way to reach both tourist sites is by water transport. A license to provide transportation by water has been obtained by the German shipowner Adler Schiffe, whose offer includes a cruise to both attractions. It is worth noting that the current price of the cruise already includes entries to both attractions. The operator allows the cruise from three marinas, namely, (1) Adler Schiffe, located at Władysław IV Street, (2) Warszów (Dworcowa Street), and (3) GPK Wharf, located at Fort Gerhard. The ferry route is shown in Figure 6.

Unfortunately, the new way of accessing the attractions is not bringing the expected turnover.

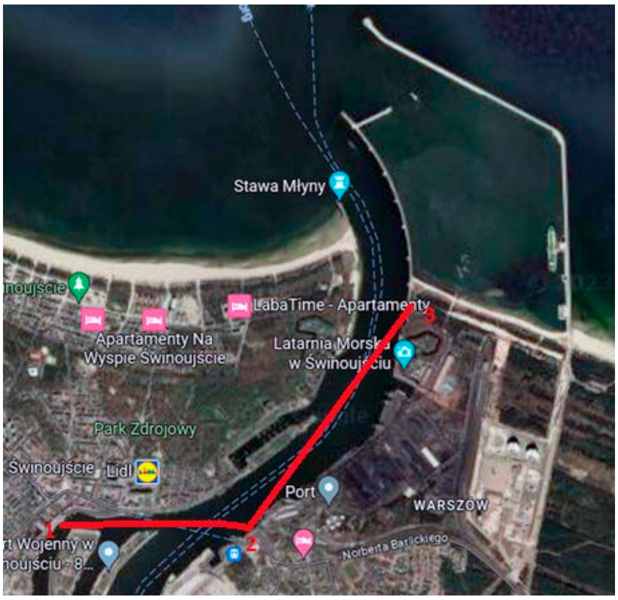

Figure 6. Route of the Fort Gerhard and Lighthouse tour (based on Google Maps and information from the company Adler Schiffe)

Under the influence of the current changes, both the owners of the fort, lighthouse, and the city are incurring large losses financially and in terms of tourism. From an interview that was conducted with the staff of Fort Gerhard, information was obtained that the current financial losses of both attractions amount to about 80–90% per year compared with previous years when the protective zone was not designated. Undoubtedly, limited access to the site will have a direct impact on the attractiveness of the city to tourists.

An additional possibility that provides a more efficient transportation option is the introduction of water streetcars and small vessels that would transport customers to the fort and lighthouse. It is worth noting that similar cruises on the port waters of Szczecin are very popular among tourists, which could be an additional attraction when visiting the monuments. In addition to the aforementioned means of transportation, another solution to attract consumer attention could be the expansion of the Border Inspection Post (GPK) Wharf, in order to improve the image and quality of service.

In addition, the city could introduce a new transportation system based on water cab travel. This is an innovative means of transportation that, due to its prosperity, greatly facilitates the functioning of transport systems of port cities. In Venice, for example, the most popular public transport vehicle is the vaporetti or water streetcars. Their routes include areas along the main thoroughfare (Canal Grande) and between the islands belonging to the city, especially the Lido, Giudecca, Murano, Burano, and Torcello. Water cabs, delivery boats, and motorboats are also in use (Nowakowski, 2014).

Another example of promoting water transportation in cities is Szczecinek, which was provided with Dutch water cabs as part of the CITIVAS project (Figure 7). The route of the cabs was designed to help residents move from one end of the city to the other in a short period of time across Lake Trzęsiecko (Wach-Kłosowska & Rześny-Cieplińska, 2018).

Figure 7. Water cab in Szczecinek (Ośrodek Sportu i Rekreacji, 2024)

In addition, in Poland, a plan to introduce water cabs to cities such as Szczecin, Gdańsk, Wrocław, and Warsaw is increasingly being developed. Recently, work on the design of such cabs has been started by Verne and mPower, who want to introduce unmanned cabs to the market. Verne's cab transport process would then have a built-in GPS module, which would send real-time location information to a central unit. Based on this data, the route traveled by the unit would be determined. With the help of laser radar (LIDAR), infrared sensors, and vision systems, the boat would continuously analyze the surrounding world and build its own model for responding to situations on the course (Portal Morski, 2024).

The scenario described above fits into the existing port operations of the City of Świnoujście and does not interfere with the introduced protection zone in the LNG terminal area. Maritime traffic management would not be a problem in this case, given the existing transport operations introduced before the establishment of Adler Schiffe locally – the change would be the frequency of similar courses or the introduction of additional water cab courses. For the sake of comparison, a comparative analysis of the two transport solutions, as shown in Table 1, has been made. The example of the PARKER 900 RS boat, which operates as a water cab in the Tri-City

Table 1. Comparative analysis of the capabilities of the two offered transport solutions (based on Vessel Finder, 2024; Odkryj Pomorze, 2024)

Analysis area	Water cab offer	Adler Schiffe offer
Availability	Possibility of daily transportation	Days of the week selected by the shipowner
Capacity of rolling stock	12 people	19 people
Velocity	Up to 100 km/h	7.4 kn (about 14 km/h)
Service cost	About 60 PLN	35–45 PLN
Dimensions (L×W)	9×7.86 m	33×8 m

area, was used to determine the technical parameters of water cabs.

Both offers are the most feasible transportation options. Despite the higher price, the availability of water cabs is definitely a more comfortable and faster option that allows for personal transportation to the designated destination.

Also of note is the fact that countries are focusing on switching to hybrid or all-electric powertrains for water transportation. Environmental aspects are also gaining importance in Poland, with Polish transport companies planning to convert their water transport vehicles to green energy in the future. The use of electric propulsion on seagoing vessels can bring a number of environmental benefits, such as minimizing noise in seaports, reducing emissions of hazardous chemicals into the atmosphere, creating opportunities for the use of renewable energy sources, developing environmental education and social change, and popularizing maritime transport as an environmentally friendly mode of transportation characterized by the ability to carry large volumes of cargo at low prices (Kaśkosz, 2021). Therefore, an excellent solution for transporting passengers to tourist attractions would be the introduction of electric water cabs. An example of such a cab is the Watertaxi 30 XL operated in the Netherlands, whose parameters are compared with the PARKER 900 RS, which is used as a cab on the Tri-City–Hel route. The authors performed a detailed comparative analysis between the diesel and electric engines, which is presented in Table 2.

Both water cabs are designed to transport passengers within seaports. However, it is the Watertaxi 30 XL that demonstrates a more sustainable solution due to its zero emissions of hazardous chemicals. Moreover, comparing the parameters of the two vehicles, the Alumax operator also has a significant advantage in terms of carrying more passengers. The distance

Table 2. List of technical parameters of the Watertaxi 30 XL and PARKER 900 RS (Alumax, 2025; Parker ribs, 2025)

Parameter	Measurement	
Name	Watertaxi 30 XL	PARKER 900 RS
Country	Netherland	Poland
Type	Passenger	Passenger
Operator	Alumax	Taxi Boat–Water Taxi
Route	Within the Port of Rotterdam, Netherlands	Tri-City–Hel
Length	12.17 m	9 m
Width	3.15 m	3.3 m
Moulded depth	0.66 m	0.8 m
Number of passengers	40	18
Maximum speed	15 km/h	80 km/h
Engine type	Electric	Diesel
Power of main engine	114 kW/h	QSD 4.2 350 KM max.
Weight	4000 kg	1000 kg

between the city center and the wharf of the Border Control Post, where tourist ships currently stop, is approximately 3 km. To calculate the efficiency and frequency of both water cabs, a simple mathematical formula for speed (V) with decision variables $V(s,t)$ is as follows:

$$V = s/t \tag{1}$$

where s is distance expressed in kilometers and t is time (in hours).

Table. 3. List of parameters for transportation to the studied attractions

Parameters	Watertaxi 30 XL	PARKER 900 RS
V (km/h)	15	22
s (km)	3	3
t (h)	0.2 (12 min)	0.14 (8.5 min)
Person	200	126

The Watertaxi 30 XL is able to make five trips and take a total of 200 people (1 trip = 12 min), while the PARKER 900 RS, over the same time period, would make seven trips and take 126 people (1 trip = 8.5 min). It should be remembered that, despite the great advantage of the maximum speed achieved by the PARKER 900RS vehicle in port areas, regulations limit the speed to a maximum of 12 knots (22 km/h). Given that the Polish maritime industry plans to switch its water transport vehicles to green energy in the future, the Alumax operator's solution is the most optimal choice for the situation. Given the current pro-environmental policies of the European Union, as well as of port authorities and city managers, the use of electric vehicles is an added advantage that fits in with environmental neutrality.

Conclusions and recommendations

The guiding element of the analysis and research carried out was the identification of the effects of enacting an ordinance to impose a temporary ban on a specific area in Świnoujście. As a result, a huge research gap was noted in the area of the negative effects of locating strategic infrastructure investments near urban facilities. In view of this, an important recommendation for the future for both the authorities and residents is to think meticulously about the location, taking into account all the possible risks, even those remote at the moment. The decision to build an LNG terminal in Świnoujście was made in 2006, and the terminal has been in operation since 2016. At the time, there was no indication of escalating conflicts among Poland's neighbors. The LNG terminal had even been an item of tourist interest up to that point. However, if the possible threat to the security of the State had been taken into account at the time, the LNG terminal could have been located a few kilometers away and would not have interfered with the tourist economy of the sea resort. In addition, a detailed analysis of the literature and our own research revealed the following conclusions:

- specifics of the designated protection zone hinder the operation of the city's key attractions located on its right-hand side bank;
- The Lighthouse and Fort Gerhard have recorded financial losses of about 80–90% per year in the last year compared with previous years, to which the introduction of the protection zone directly contributes;
- current transportation solution limits the frequency of visits to the sites, minimizing them to only three transports per day (with a limited number of ship passengers);
- proposed scenarios emphasize that, despite all efforts, it is significantly hampered to enter tourist facilities due to protection zone;
- of the three proposed scenarios, it is clear that the most optimal and only possible solution is the proper management and expansion of the waterway transport branch.

The solutions indicated by the authors will increase the profits of the owners of The Lighthouse and Fort Gerhard due to the renewed interest in the facilities resulting from the introduction of innovative means of water transportation and the corresponding quality of the services provided. In addition, the implemented restrictions and solutions proposed by local and national authorities contribute to the development of water transport, which is crucial in both the economic and tourist spheres for the city of Świnoujście.

The proposal to introduce an innovative solution will be forwarded to the city's authorities. The authors sincerely hope that their proposal will be positively received and the city will be able to implement the project of introducing electric water cabs running to The Lighthouse and Fort Gerhard. Then, it will be possible to realistically verify the popularity of this type of transportation and also to compare the number of visitors who are reluctant to visit historical sites due to transportation complications.

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Optimization system for workforce allocation for the ship hull section assembly process

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Abstract

This article presents a decision-support system developed for optimizing workforce allocation within production processes, specifically addressing the challenge of assigning employees to individual workstations during the assembly of ship hull sections. The proposed methodology integrates discrete-event computer simulation and evolutionary optimization techniques to accommodate the inherent complexity and stochastic nature of the analyzed manufacturing tasks. The objective is to assess the effectiveness of the proposed optimization system in determining optimal workforce allocation to workstations within stochastic production models.

Introduction

Effective employee allocation directly influences productivity, quality, and timely task completion. Matching employees to tasks based on their skills, experience, and availability is crucial. Optimal human resource management ensures efficient personnel utilization, minimizes downtime, and reduces production costs. Welding processes, such as hull section assembly, are influenced by numerous random factors affecting task durations. Unlike deterministic scenarios, real-world conditions – employee skill variability, atmospheric factors, and technological variations – cause execution-time fluctuations. The complexity of welding tasks and variable working conditions require appropriate workforce allocation to avoid bottlenecks that disrupt production flow. Thus, a decision-support system for assigning employees to workstations is essential, particularly one that incorporates welding plans, joint sequences, and randomness.

This study aims to develop a simulation-based decision-support tool for staffing management at prefabrication workstations in shipyards, utilizing production data specific to welding operations. A literature review identifies potential methods for modeling random variability in production processes and workforce allocation. Subsequently, the system's assumptions are defined, and its applicability to complex probabilistic processes is examined. The system for assembling a complex welded structure is evaluated. The results provide insights into future research directions. Given the explorative character of this study, economic factors such as production and labor costs are not included in the current optimization analysis, but their integration remains a critical area for future development.

Literature review

Computer simulation for modeling probabilistic processes

Computer simulation is a method used to analyze system behavior and conduct experiments using models that replicate real systems or processes. Currently, numerous software tools are available for creating simulation models. For example, one vendor has provided a comprehensive comparison of the most popular simulation programs (AnyLogic, 2024), while other authors have evaluated and highlighted their practical applications (Mourtzis, Doukas & Bernidaki, 2014).

Most real-world production processes exhibit uncertainty regarding activity durations, delivery times, and equipment reliability. The human factor significantly contributes to this uncertainty, as task durations vary with employee behaviors, health conditions, atmospheric influences, and other external random events. Therefore, simulation models should reflect reality as closely as possible. Many available software packages enable modeling with random variables and uncertainty.

One approach to capturing human-related randomness is the use of probabilistic input parameters (Ruediger & Hagen, 2017). Complex production processes are typically divided into subprocesses and tasks, each with specific durations varying according to employee performance. Task durations in the simulation model can, thus, be represented as random variables. Statistical distributions, such as exponential, Gaussian, normal, gamma, or beta, are commonly utilized for modeling input variability. The selection of an appropriate distribution depends on data characteristics and simulation requirements. Methods for fitting statistical distributions and generating random samples have been extensively discussed in the literature (Kuhl et al., 2009; 2010).

Workforce scheduling and allocation

Allocating workers to workstations is a critical component of production management, directly influencing operational efficiency, productivity, and quality. To optimize such allocations, simulation-based methods and heuristic approaches informed by managerial expertise are often applied. For example, a heuristic method for short-term workforce planning on truck assembly lines achieved significant savings (Gronalt & Hartl, 2003). Metaheuristic techniques, notably genetic and evolutionary algorithms, have also gained attention. Modern technologies, including big data, artificial intelligence, and cloud computing, further enhance workforce allocation by dynamically assigning workers to production bottlenecks (Tu & Zhang, 2023). Additionally, many enterprises employ enterprise resource planning (ERP) systems for integrated resource management (Zhao & Tu, 2021; Tuli & Kaluvakuri, 2022) despite associated licensing, implementation, and training costs.

Hybrid optimization methods combining various heuristic and metaheuristic techniques often yield superior workforce allocation results. For instance, Su and Xie (Su & Xie, 2019) developed a combined heuristic-genetic algorithm for scheduling under variable human resources. Gu, Lam, and Zinder (Gu, Lam & Zinder, 2022) addressed scheduling problems involving multiple resources and random task durations using a hybrid genetic algorithm and sample average approximation. Similarly, Miao et al. (Miao et al., 2023) proposed a progressive Pareto algorithm for production scheduling, although without explicitly accounting for real-world disturbances. Derkinderen, Bekker, and Smet (Derkinderen, Bekker & Smet 2023) optimized workforce assignments in warehouse environments through a metaheuristic algorithm integrated with discrete-event simulation.

The literature review revealed numerous methods for optimizing workforce allocation. However, they pertain primarily to industrial sectors that differ significantly from the specifics of welded structure production. While various optimization approaches, including heuristic and metaheuristic methods (e.g., ant colony algorithms and simulated annealing), have been widely used, this research specifically employs genetic algorithms integrated with computer simulation. Genetic algorithms were selected due to their proven effectiveness in handling complexity, variability, and uncertainty – features typical of ship hull section assembly processes. Although comparative studies with alternative optimization methods are valuable, performing such detailed comparisons was beyond the scope of this work and has been identified as a potential area for future research.

A distinctive feature of shipbuilding production is the significant variability of tasks performed at individual workstations, alongside specific ergonomic and organizational conditions. Workstations frequently operate simultaneously and in proximity, resulting in mutual interactions, such as vibrations, sparks, and heating of components. Ergonomic factors, particularly welding positions (i.e., flat, horizontal, vertical, and overhead), strongly influence the complexity of equipment operation, physical workload, and the resulting quality and precision of welds. Moreover, open production environments expose the processes to external environmental conditions such as humidity, sunlight, and dust, which further affect joint reliability and quality. Due to these specific industry conditions, tasks at each workstation must be defined in detail, and a precise welding sequence plan must be developed (Mandal, 2017). Such planning involves dividing the structure into sections, subsections, and individual joints, thus facilitating optimal scheduling and resource allocation (Iwańkowicz, 2016). Proper weld sequencing reduces deformation risks, thereby significantly contributing to improved productivity.

Nevertheless, the Optimization System for Workforce Allocation (Skibińska & Iwańkowicz, 2024), originally developed for deterministic processes, requires modifications to better address the unique challenges presented by shipyard production. Specifically, the current system does not fully account for complex interdependencies between subprocesses, variability in task durations, and changing working conditions. Therefore, the present study expands this method, adapting it to better reflect shipyard-specific factors. Given these initial limitations and the complexity of incorporating factors such as production costs and detailed ergonomic aspects, these have been identified as essential components for future research rather than being the focus of the current work.

Assumptions of the optimization system for workforce allocation

In the proposed method, the first step is identifying the current state of the real system, thereby obtaining the assumptions and data necessary for building the simulation model. In this step, the process must be divided into tasks performed according to a designated order, known as the process sequence. The studied process is divided into subprocesses (comprising m prefabrication workstations), and within these subprocesses, the n tasks required to complete the prefabricate in each subprocess are identified. Sequences are established both at the subprocess level and for the entire process. The technology of welding large-scale structures includes a sequence **S** for executing construction prefabricates at prefabrication workstations. Sequence **S** is represented by the following binary matrix:

$$\mathbf{S} = \left(s_{i,j}\right)_{m \times m}, \quad s_{i,j} \in \{0,1\} \tag{1}$$

where $s_{i,j} = 1$ indicates that the ith subprocess at a given workstation must be completed before initiating the jth subprocess at the next workstation.

Sequence **S** forms the basis for the simulation model, defining the relationships between workstations and the flow of components. For each subprocess (in the prefabrication workstation), it is necessary to determine the sequence of welding joints depending on the number of workers assigned to the workstation. Based on observations of the production process, the boundary staffing of each workstation is established, that is, the minimum and maximum number of workers $[x_{\min}, x_{\max}]$. The values within this range depend on the type of prefabricate, the number of joints to be executed, and the available space within the prefabricate for workers performing the joints. One worker performs a single welded joint, and its execution time is assumed based on actual time measurements in shipyards. Due to the human factor, the time to execute one joint is modeled using a normal distribution, with an expected value and standard deviation assigned for each task. Using the PERT method, the duration of subprocesses and deviations for each workstation are estimated for assignment variants within the range from $x_{\min}$ to $x_{\max}$. The expected times obtained for each workstation are represented by the vector $\mathbf{T'_i}$:

$$\mathbf{T'_i}\left[x_{\min}, x_{\max}\right] = \left(t'_i\left(x_{\min}\right), \sigma_{t'_i}; \ldots; t'_i\left(x_{\max}\right), \sigma_{t'_i}\right) \quad i = 1, \ldots m \tag{2}$$

where t'_i ($x_{\min}$) and t'_i ($x_{\max}$) are the expected times for the ith workstation depending on the assigned staffing within the range $[x_{\min}, x_{\max}]$ and $\sigma_{t'_i}$ is the standard deviation for the determined time t'_i.

After determining the necessary data, a simulation model is built using selected software. In this procedure, the *FlexSim* program is utilized, allowing for the introduction of vectors **T'** for all the workstations and modeling them using a normal distribution. The number of workers p assigned to the process is determined based on observations of the production system. Workers are allocated to prefabrication workstations, forming a staffing configuration represented as the initial vector:

$$\mathbf{X} = \left(x_i\right)_m, \quad x_i \in \mathrm{N}_+, \quad \sum_{i=1}^{m} x_i = p \tag{3}$$

where x_i is the number of workers assigned to the staffing of the ith workstation. The total number of workers remains constant, meaning that increasing the staffing of one workstation necessitates decreasing the staffing of another.

By introducing a Table with the determined vectors **T'** for each workstation and vector **X**, it becomes possible to run simulations and randomly generate the execution times of each subprocess. The obtained execution times for the subprocesses, depending on the assigned number of workers according to vector **X**, are represented by the vector **T(X)**:

$$\mathbf{T}(\mathbf{X}) = (t_i(x_i))_m \tag{4}$$

where $t_i(x_i)$ is the randomly generated execution time of the ith subprocess based on the number of workers assigned to that subprocess.

The efficiency of the workstations was utilized to evaluate the quality of the staffing decisions. The program determines efficiency by dividing the execution time of the subprocess at a workstation by the production cycle time; this indicator is expressed as a percentage. The cycle time is the time required to complete the entire construction. For each prefabrication workstation, an efficiency indicator is obtained, and the results can be recorded in the form of a vector, i.e.,

$$\mathbf{Y}(\mathbf{S}, \mathbf{T}(\mathbf{X})) = (y_i(\mathbf{S}, \mathbf{T}(\mathbf{X})))_m \tag{5}$$

where y_i is the efficiency of the ith workstation.

For the efficiency vector **Y**, the overall efficiency of the process can be determined, which serves as a criterion for evaluating the quality of decision **X**:

$$\overline{\mathbf{Y}}(\mathbf{S}, \mathbf{T}(\mathbf{X})) = \frac{1}{m} \sum_{i=1}^{m} y_i(\mathbf{S}, \mathbf{T}(\mathbf{X})) \tag{6}$$

where $\overline{\mathbf{Y}}$ represents the collective efficiency of the process.

If the process efficiency does not meet the set objectives, it is possible to reallocate production capacities. The procedure for optimizing workstation staffing is conducted using the *Optimizer* module, which automatically adjusts parameters and executes scenarios by employing various optimization techniques. It requires defining an objective function; in the proposed procedure, this is the maximization of the total process efficiency. The module modifies the staffing of each workstation according to the previously assumed execution times of the prefabricate. By appropriately modeling the process, it is possible to consider the maximum staffing p during the optimization. After performing the calculations, vector **X*** is obtained, representing the optimal assignment of workers to workstations.

Example analysis

Characteristics of the studied process

The hull construction process, including its sections and subsections, is a unique endeavor due to the non-repetitive nature of the projects. Consequently, meticulous planning and scheduling of the production process are particularly important to ensure its efficiency and accuracy. Effective planning minimizes the risk of delays, errors, and unnecessary costs, which is crucial given the unique nature of shipbuilding projects.

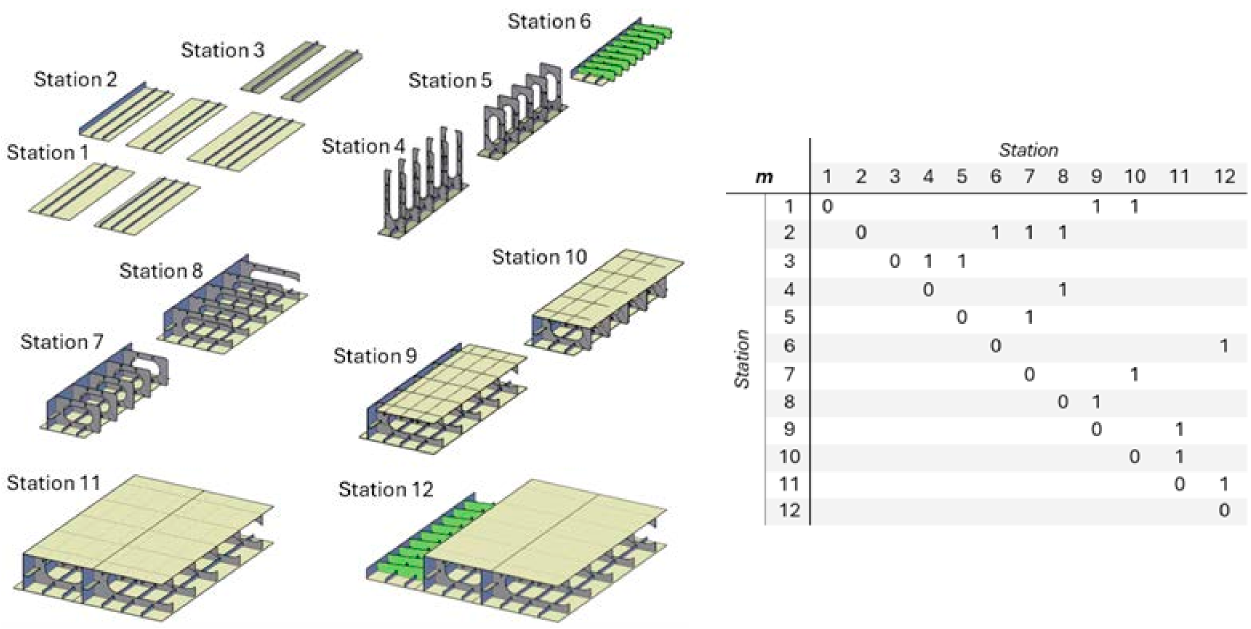
Sequencing the assembly process is essential for ensuring the efficiency and fluidity of the entire production workflow. The topic of assembly sequence optimization was thoroughly analyzed by Iwańkowicz (Iwańkowicz, 2016), where he presented methods for optimizing the order of operations in assembly processes. Building upon his research, the issue of optimizing workforce allocation for the structure he studied – a fragment of a double hull with a cargo hatch coaming – was addressed. This structure consists of elements such as inner and outer plating, stiffeners, frames, and transverse coaming stiffeners.

The assembly of the given structure was divided into subprocesses, referred to as prefabrication workstations. In the studied structure, 12 such workstations were identified and are presented in Figure 1(a); the sequence of workstation operations is shown in Figure 1(b). At the first three workstations, the prefabrication of the basic structural elements takes place, including the arrangement of the outer and inner plating and the preparation of transverse stiffeners. The subsequent workstations (4, 5, and 6) execute the connections of frames and transverse stiffeners of the coaming. To minimize deformations and stresses in the structure during welding, the welder should employ an appropriate sequence and technique, starting from the central frames and proceeding symmetrically toward the outer edges to ensure an even distribution of forces.

Workstations 7 and 8 assemble previously prefabricated inner plating with frame components. Workstations 9 and 10 are responsible for assembling outer plating to the prepared inner structure. Workstation 11 integrates previously assembled elements into a coherent unit and Workstation 12 completes the final connection and securing of the structure. Proper welding sequences, especially at initial workstations, significantly reduce deformation, ensuring structural integrity and strength.

Effective personnel allocation is crucial for the smooth execution of the assembly process, especially in the context of complex structures such as hull sections. Optimizing workforce assignments improves resource utilization, enhancing production efficiency and quality.

The analyzed workforce p consisted of 20 welders, all equally qualified to perform welds using the MIG/MAG method. Task durations depended



(a) (b)

Figure 1. (a) Division of the process into subprocesses and (b) the sequence matrix of the process

Table 1. Input parameters for the simulation

	$t'(1)$	$\sigma(1)$	$t'(2)$	$\sigma(2)$	$t'(3)$	$\sigma(3)$	$t'(4)$	$\sigma(4)$	$t'(5)$	$\sigma(5)$	$[x_{min}, x_{max}]$
Station 1	600	20	360	12	240	8	240	8	120	4	[1,5]
Station 2	787	25	399	13	291	9	205	7	194	6	[1,5]
Station 3	240	8	120	4	–	–	–	–	–	–	[1,2]
Station 4	100	5	60	3	40	2	–	–	–	–	[1,3]
Station 5	100	5	60	3	40	2	–	–	–	–	[1,3]
Station 6	288	9	160	5	96	3	–	–	–	–	[1,3]
Station 7	135	5	81	3	54	2	–	–	–	–	[1,3]
Station 8	215	10	129	6	86	2	–	–	–	–	[1,3]
Station 9	210	5	126	3	84	2	–	–	–	–	[1,3]
Station 10	330	9	168	4	126	3	120	4	–	–	[1,4]
Station 11	265	10	217	8	193	7	–	–	–	–	[1,3]
Station 12	129	11	101	7	87	5	–	–	–	–	[1,3]

on joint types, plate thicknesses, welding methods, parameters, and individual welder performance. In the studied structure, all the welds were manually performed using MIG/MAG welding, and the workers had uniform skill levels. Inner hull plating and longitudinal frames had a plate thickness of 10 mm, while the remaining structural elements had a thickness of 12 mm. Both butt and double-sided fillet welds were present.

Based on observations and measurements of individual welded joints, the expected times for completing the prefabricate at each workstation were determined using the PERT method. For each variant of worker assignment, the degree of uncertainty, represented by the standard deviation, was also established. Through field studies, staffing limitations for each workstation were determined, along with the initial staffing vector **X** = (2,2,2,2,2,2,2,2,2,1,1,1,1). The input data are presented in Table 1.

Simulation model for the studied process

The simulation model was developed in the *FlexSim* environment using the 3D object library and *ProcessFlow* (Figure 2). A simulation was conducted using the initial workstation staffing vector **X**. The process efficiency index obtained from the simulation was 15.57%.

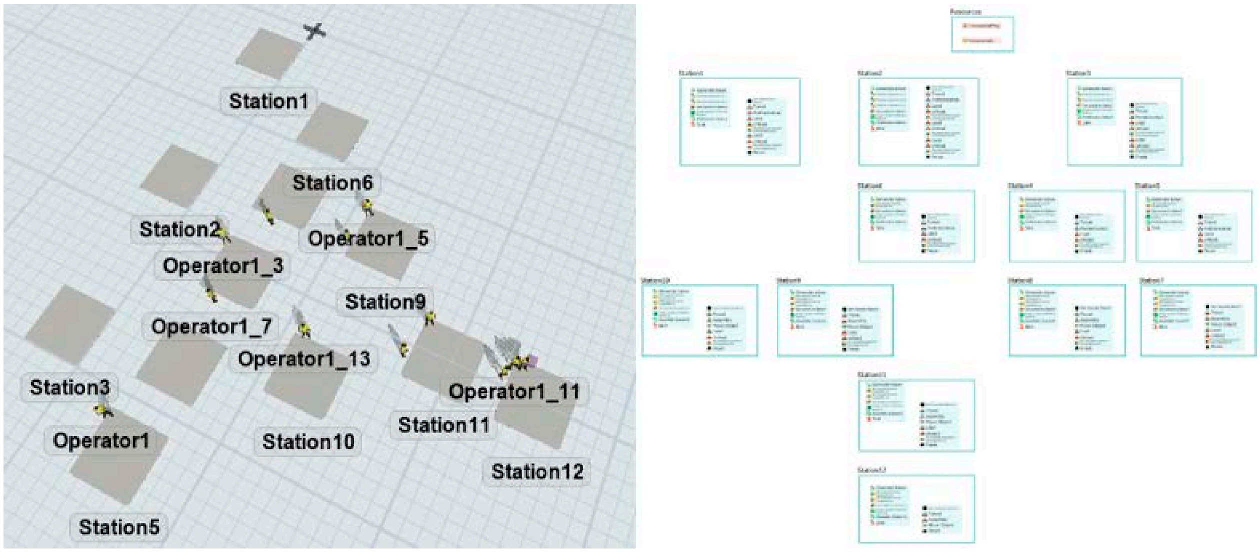
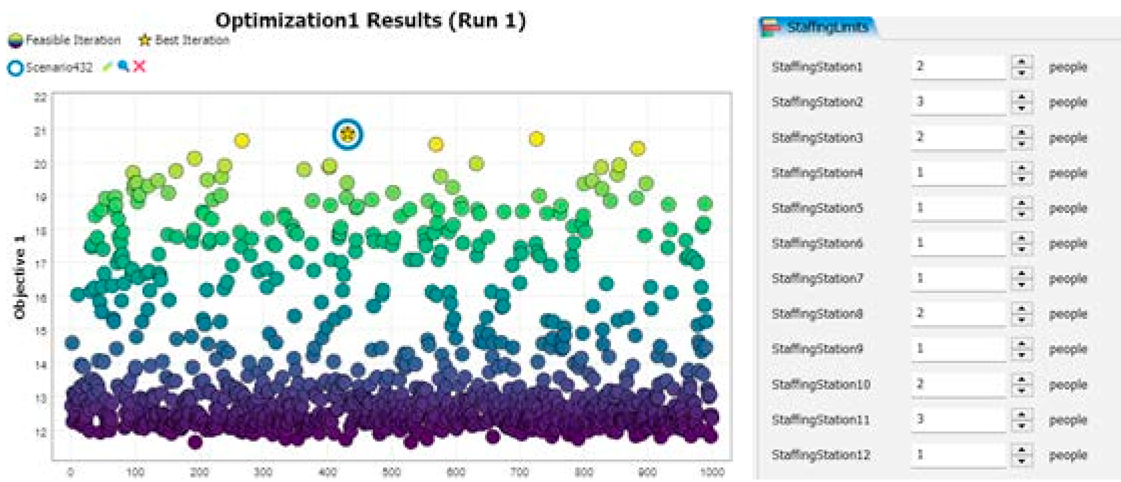


Figure 2. Constructed model in FlexSim



a. b.

Figure 3. (a) Algorithm optimization iteration chart and (b) optimal staffing X*

Optimization of workforce allocation

The Optimizer module implemented in FlexSim was utilized to optimize the allocation of workers. The module performed 1000 iterations, evaluating possible scenarios. The results of each iteration, with the best solution highlighted, are presented in Figure 3(a). The optimal staffing **X*** obtained is shown in Figure 3(b). For the best scenario, a cumulative efficiency of 20.84% was achieved.

Discussion

After conducting the study, the Optimization System for Workforce Allocation proved to be an effective decision-support tool for allocating workers to workstations in the assembly process of ship hull sections. The application of the developed system led to an increase in overall process efficiency, as confirmed by an improvement in cumulative efficiency from 15.57% to 20.84%. Achieving the optimal allocation of human resources resulted in a reduction of process duration and minimization of downtime.

The graph presented in Figure 4 illustrates the variability of efficiency in relation to the randomly generated subprocess durations for the optimized workstation staffing. It was observed that the variability in subprocess durations has a significant impact on cumulative efficiency. This indicates a considerable sensitivity of the process to this variable, which greatly influences the outcomes achieved. Despite the high variability in measurements, the median efficiency remains relatively stable at 20.84%.

Gantt charts were generated for the two scenarios under study: Scenario 1, representing the initial

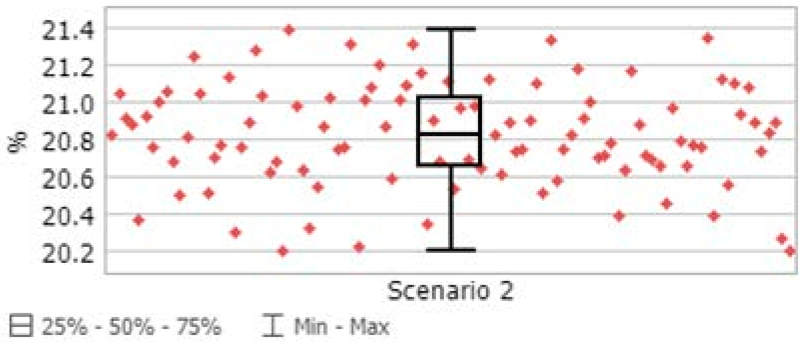


Figure 4. Performance variability for the optimized scenario

staffing allocation, and Scenario 2, signifying the staffing allocation after optimization. These charts are presented in Figure 5 to facilitate comparison. For each station, the start and end times of work on the respective prefabricated components were determined and indicated on the chart. Additionally, the assigned workers at each workstation are marked.

The total duration of the entire process is significantly longer in Scenario 1, amounting to 1,197 minutes, whereas in Scenario 2, it is 962 minutes. In both scenarios, no downtime occurs during the process. Due to the diversified staffing allocation in Scenario 2, several subprocesses have shorter durations compared with Scenario 1, indicating higher efficiency in operational time utilization in Scenario 2. Adding one additional worker to prefabrication stations 1–3 in Scenario 2 allows for earlier commencement of work on stations 4–6. This is attributable to the nature of tasks at the initial stations, where fundamental structural elements can be assembled simultaneously. Such an allocation enables earlier completion of work on stations 4 and 5, even though their durations are longer than in Scenario 1. Scenario 2 also exhibits better synchronization between stations, particularly among stations 1–10, where tasks can be performed concurrently. This avoids situations where only one station is operational while others await its completion – a scenario observed in Scenario 1 when stations 6–8 wait for the completion of work on station 2.

The differences in schedules result from the staffing allocations to individual stations. Scenario 2, with the optimized solution, demonstrates a more efficient organization of the process, leading to a shorter total execution time. Based on the obtained Gantt charts, workload intensity graphs were generated, illustrating the cumulative number of workers at all the stations as a function of process duration. Figure 6 presents the graphs for Scenario 1 (left-hand side) and Scenario 2 (right-hand side).

In Scenario 1, the workload intensity is more variable, with distinct peaks of activity (up to eight

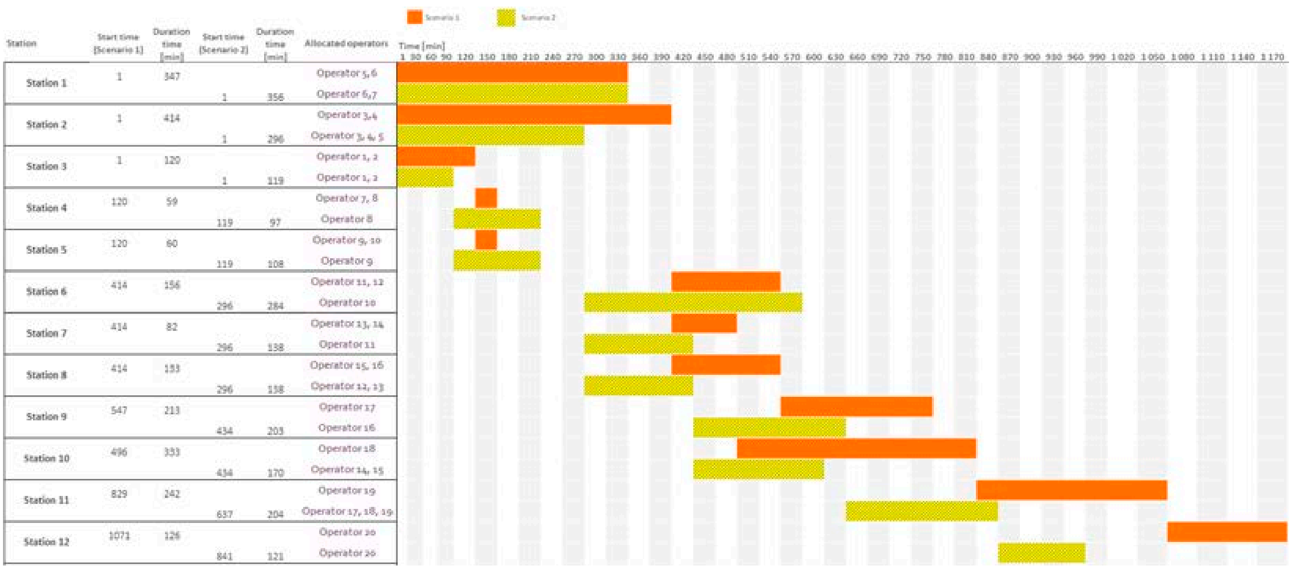


Figure 5. Comparison of the Gantt schedules for the two scenarios

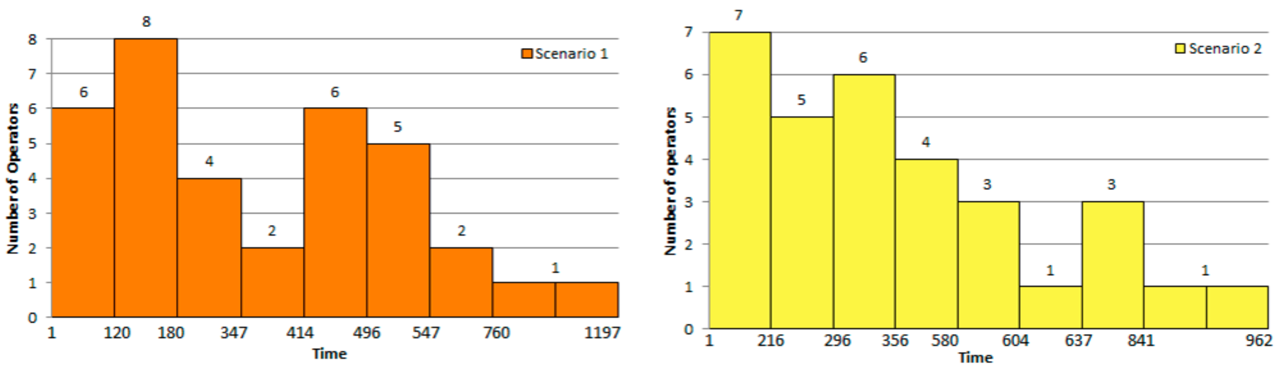


Figure 6. Work intensity chart

workers) followed by sharp declines in the number of active operators. This uneven distribution can lead to downtimes and periods when human resources are not fully utilized. In Scenario 2, the workload is more evenly distributed over time. The maximum number of workers is seven, and subsequent workload periods exhibit a smoother decline, indicating a better temporal distribution of tasks and more effective resource management.

In Scenario 1, there are periods where the number of workers drops to 1 or 2, indicating less efficient continuity between subprocesses. In Scenario 2, such abrupt decreases are less frequent, suggesting improved coordination between successive workstations and a smoother workflow. The more consistent workload intensity in Scenario 2 implies better utilization of human resources, preventing situations where only one worker is engaged while others remain idle. The task distribution indicates an optimal personnel allocation in Scenario 2, ensuring continuity of the production process and minimizing downtime.

Conclusions

The Optimization System for Workforce Allocation is an advanced decision-support tool for human resource management in production environments. A key advantage of the system is its flexibility, enabling dynamic assignment of workers to workstations based on current production demands and available resources. Accounting for the uncertainties and variabilities typical of the analyzed processes significantly enhances the practical applicability of the system in rapidly changing industrial conditions. Consequently, simulation results derived from probabilistic models become increasingly valuable to managers responsible for overseeing production processes.

The developed method demonstrated a substantial improvement in production efficiency, reducing the total process duration by approximately 20%, which confirms its effectiveness in optimizing workforce allocation. The system's performance was further validated by an increase in cumulative process efficiency by nearly six percentage points, a particularly significant outcome in the context of unit production. The possibility of iterative analyses and automated staffing optimization facilitates adjustments aimed at maximizing efficiency, which is critical given changing production parameters and the specific demands of custom manufacturing. Moreover, the optimized scenario improved synchronization among workstations, effectively minimizing downtime and ensuring a more balanced workload distribution.

However, it is important to acknowledge that the analysis presented here was limited to a single hull structure, restricting the direct generalization of results to other ship hull designs. Nonetheless, the methodology is readily adaptable to other structures, provided that the necessary adjustments in input data are made. A comprehensive empirical validation of the simulation model using broader datasets remains an essential area for future research. Ergonomic and organizational aspects, though not explicitly considered in this study, significantly impact overall production efficiency and should, therefore, be incorporated into future analyses to ensure a comprehensive evaluation of workforce optimization strategies.

Future research could also explore adapting the proposed optimization system to mass production environments, in which subprocesses are executed repeatedly under varying conditions and durations. Under such conditions, worker assignments would need frequent updates during production. Decomposing processes into elementary operations, each influencing subprocess durations, would necessitate developing an automated database to support real-time updates of input parameters. Additionally, integrating economic aspects, particularly labor costs per hour, into future optimization models would enable more advanced strategies, balancing both operational efficiency and economic effectiveness. Incorporating these financial parameters would further enhance the system's versatility, allowing it to better adapt to dynamic production conditions and economic realities.

Expanding the system's functionality to include real-time performance and quality monitoring modules would allow rapid identification and elimination of production bottlenecks. Such integration would empower managers to make informed decisions, fostering continuous improvements and enhancing enterprise competitiveness. In summary, further development and broader industrial implementation of the Workforce Allocation Optimization System have the potential to significantly increase operational efficiency, flexibility, and economic viability, which are particularly crucial in the context of growing market variability and uncertainty.

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