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Autonomous shipping – a stochastic model of the process describing the safety of MASS operation

Zbigniew Burciu[1], **Teresa Abramowicz-Gerigk**[2]✉

[1] https://orcid.org/0000-0001-5171-1943
[2] https://orcid.org/0000-0002-0477-3161

Faculty of Navigation, Gdynia Maritime University
81-87 Morska St., 81-225 Gdynia, Poland
e-mail: [1]z.burciu@wn.umg.edu.pl, [2]t.gerigk@wn.umg.edu.pl
✉ corresponding author

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Abstract

The main interest in introducing maritime autonomous surface ships (MASS) is centered on communication, autonomous navigation, and collision avoidance systems. This paper presents a more comprehensive approach, accounting for selected issues relating to navigation safety, ship operation, maritime rescue, and decision support systems for the MASS remote managing operator. The technical solutions for improving the safety of MASS operation are described, and the decision support system (DSS) for the MASS operator, based on the stochastic model of the process describing the safety of MASS operation, is proposed. The presented analysis can be used to build a computer program and an integrated decision support system that increases the safety and reliability of the MASS operator's decision-making process.

Introduction

The introduction of maritime autonomous surface ships (MASS) creates new challenges that have not been encountered so far with manned vessels. Advanced communication, navigation, and collision avoidance systems (Pietrzykowski et al., 2022) are currently at the center of interest for autonomous shipping. However, the complex approach towards autonomous integrated transport infrastructure (Łebkowski, 2018; Gerigk & Gerigk, 2019; Gerigk, 2022) needs to take into consideration all the aspects of autonomous shipping (Idzior, 2022; Wrobel et al., 2023).

Currently, all the legal standards and applicable regulations relating to the safety of maritime transport, having references, among others, to the maritime code, expressed, for example in cargo documentation, refer to the ships with the crew on board, and they are carried out in accordance with the principle of "good maritime practice" – a motto relating to the ship's crew. The legal term "good maritime practice" includes codified regulations such as the International Law of the Sea and the Convention on the International Regulations for Preventing Collisions at Sea.

The introduction of remotely operated, unmanned units MASS gives this motto a new meaning and changes its scope when covering the current meaning. It will be necessary to change the current approach to assessing the safety of maritime transport. One of the possible stages of the MASS mission may be participation in a SAR operation, which may be a difficult decision for the unmanned unit or the operator. The proposed decision support system using the semi-Markov process enables the operator to make a decision knowing the new reliability/safety probability of the transition from the MASS voyage stage to the SAR participation stage. The introduction of maritime autonomous surface vessels and environmentally friendly transport reduces the impact of the human factor, which is the cause of approximately 90% of accidents at sea, as well as reduces the number of injuries, fatalities, property damage, and environmental pollution.

This paper focuses on technical solutions, a comprehensive approach ensuring the reliability and operational safety of the MASS units and the idea of a decision support system for the MASS remote managing operator.

International Maritime Organization activities in the field of autonomous shipping

The proposed levels of autonomous navigation, according to the International Maritime Organization (IMO), have become a roadmap for the development of maritime transport and the introduction of maritime navigation into new directions. Currently, navigation in its entirety is associated with the safe operation of the ship and is based on the crew on board.

According to IMO, ship management takes place depending on the level and degree of autonomy, starting with units that will be crewed – level I, partly crewed – level II, remotely managed – level III, and fully autonomous – level IV.

Depending on these levels, the ship's crew changes (i.e., between fully manned, semi-manned, unmanned – remotely controlled, and fully autonomous). The manning of the crew also depends on the situation at sea, for example, the emergency situations such as rescue operations, cyberattacks, navigation with maritime piracy present in a given area, or during selected operations, such as a MASS approach to internal waters or port area, port maneuvers with the pilot, and berthing and mooring procedures. One of the examples is sailing a vessel in stormy conditions. For practitioner seafarers who are on board, the crew's "feeling" regarding the ship's motions in waves is already a parameter for assessing the ship performance and safety of the ship, crew, and cargo. This "feeling" will not occur for the supervised or remotely controlled unit operator, who will be able to assess the situation "at a distance". This will be one of many elements that will be a challenge for the operator of the MASS.

As a result of the lack of crew on board and the implementation of navigation by the remote operator, we will be dealing with a new situation with respect to ship operation, which involves assessing the safety of the ship and cargo. Currently, the IMO and the EU are working to develop and implement regulations governing the safe navigation of MASS units. This work covers the relationship between human responsibility and the automation of processes responsible for the safety of navigation. In 2022, work began on regulations and the implementation of the program on MASS units. The MASS Code developed by the IMO comes into force on January 1, 2028. Classification societies and maritime administrations are also working on the standards that MASS units should meet.

The MASS Code will regulate technological, legal, and safety issues, including navigational hazards resulting from the operation of MASS, monitoring, reliability of technical systems, rescue of people at sea, legal aspects, and cooperation of MASS with other units. MASS units will be managed by remote operational centers and operators that should be supported by decision support systems (DSS).

Selected safety issues in the aspect of autonomous navigation

There are several legal problems that will be encountered with regard to, for example, the maritime code (Maritime Code Journal of Laws, 2023) regarding the ship master and crew not being present on board. In all activities relating to the operation of the MASS unit, the operator in the remote operational center supported by DSS systems operates the MASS unit, which should be technologically adapted to activities in the field of maritime safety, including search and rescue (SAR) operations. The reliability of the MASS operation should, therefore, cover a wide spectrum of areas, including the "ship on the way".

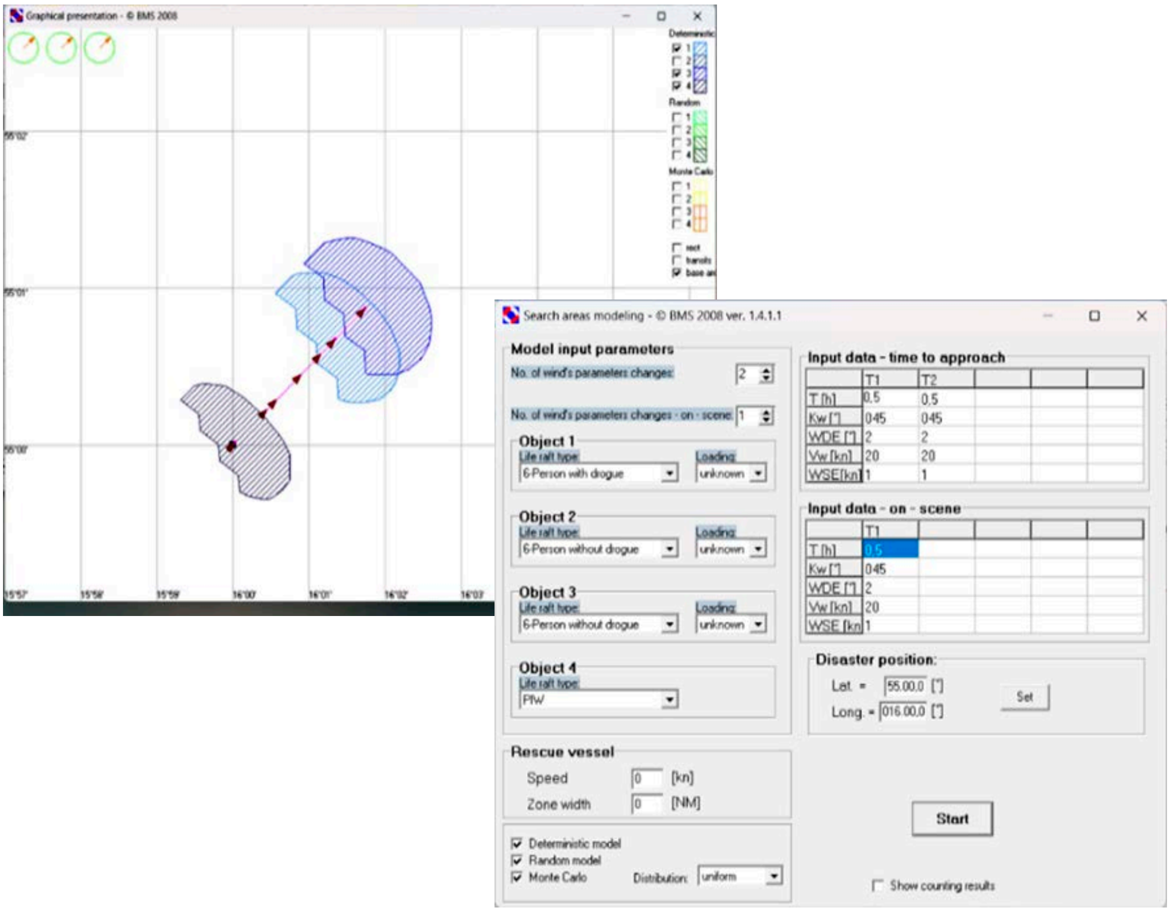
The selected issues of MASS reliability relate to ship operation safety, technical operation, cargo, maritime rescue, and emergency procedures in the event of a collision. These issues can be formulated as follows:

- reliability of complex technical systems – ship safety,
- cargo – an obligation to supervise the cargo directly,
- rescue of life at sea – duty to provide assistance,
- rendering assistance to a ship in distress,

- event of a collision when there is no crew on board.

The preparation of the DSS systems requires a new development of the algorithms with a new formulation of the problem. At the same time, the equipment of the unmanned ship should enable the remote operator to control and act in various areas of the ship's operation, i.e.:

- **Cargo**
  Bulk and liquid cargoes, general cargo, and containers – in case of remote control over the cargo, the safety status for each of these cargoes requires a different "remote" handling during the sea voyage.
- **Rescue of life at sea, participation of an unmanned unit in the SAR action**
  The operator of the vessel, being in the vicinity of the distressed vessel position, knowing the current hydrometeorological conditions and having the DSS system for determining search areas, will be able to direct the unmanned vessel to the position of the accident. An example of visualization of a decision support system – determining search areas during the SAR action – is presented in Figure 1 (An IT system supporting the action of saving human lives at sea. Report of the Target Project co-financed by Committee for Scientific Research, No. 2288/C.T12-9/98. Gdynia Maritime University, 2001).
- **Behavior of the remote operator during the rescue action at the position of the rescued vessel**
  The SAR operation begins when the MASS operator receives a signal. The IMO Committee is considering equipping MASS units with a rescue boat operated by an operator. The question is whether appropriate technical solutions enabling the operator to help people in danger exist. The proposed solution is to install a remotely controlled rescue platform on board ships. An example of a prototype of a remote platform for picking up people and life rafts from the water via MASS is presented in Figure 2 (Construction of a rescue platform for picking up people and life rafts with people in danger of life at sea in extreme hydro-meteorological conditions. Report of the Target Project co-financed by the Committee for Scientific Research No. 2711/C.T12-9/2000, Gdynia 2001. UMG).



Model input parameters

No. of wind's parameters changes: 2

No. of wind's parameters changes - on - scene: 1

Object 1: Life raft type: 6-Person with drogue; Loading: unknown

Object 2: Life raft type: 6-Person without drogue; Loading: unknown

Object 3: Life raft type: 6-Person without drogue; Loading: unknown

Object 4: Life raft type: PIW

Input data - time to approach

	T1	T2			
T [h]	0.5	0.5			
Kw [°]	045	045			
WDE [°]	2	2			
Vw [kn]	20	20			
WSE[kn]	1	1			

Input data - on - scene

	T1				
T [h]	0.5				
Kw [°]	045				
WDE [°]	2				
Vw [kn]	20				
WSE [kn]	1				

Disaster position:

Lat. = 55.00.0 [°]

Long. = 016.00.0 [°]

Rescue vessel

Speed 0 [kn]

Zone width 0 [NM]

☑ Deterministic model

☑ Random model

☑ Monte Carlo Distribution: uniform

☐ Show counting results

Figure 1. An example of a visualization of a decision support system for search area determination

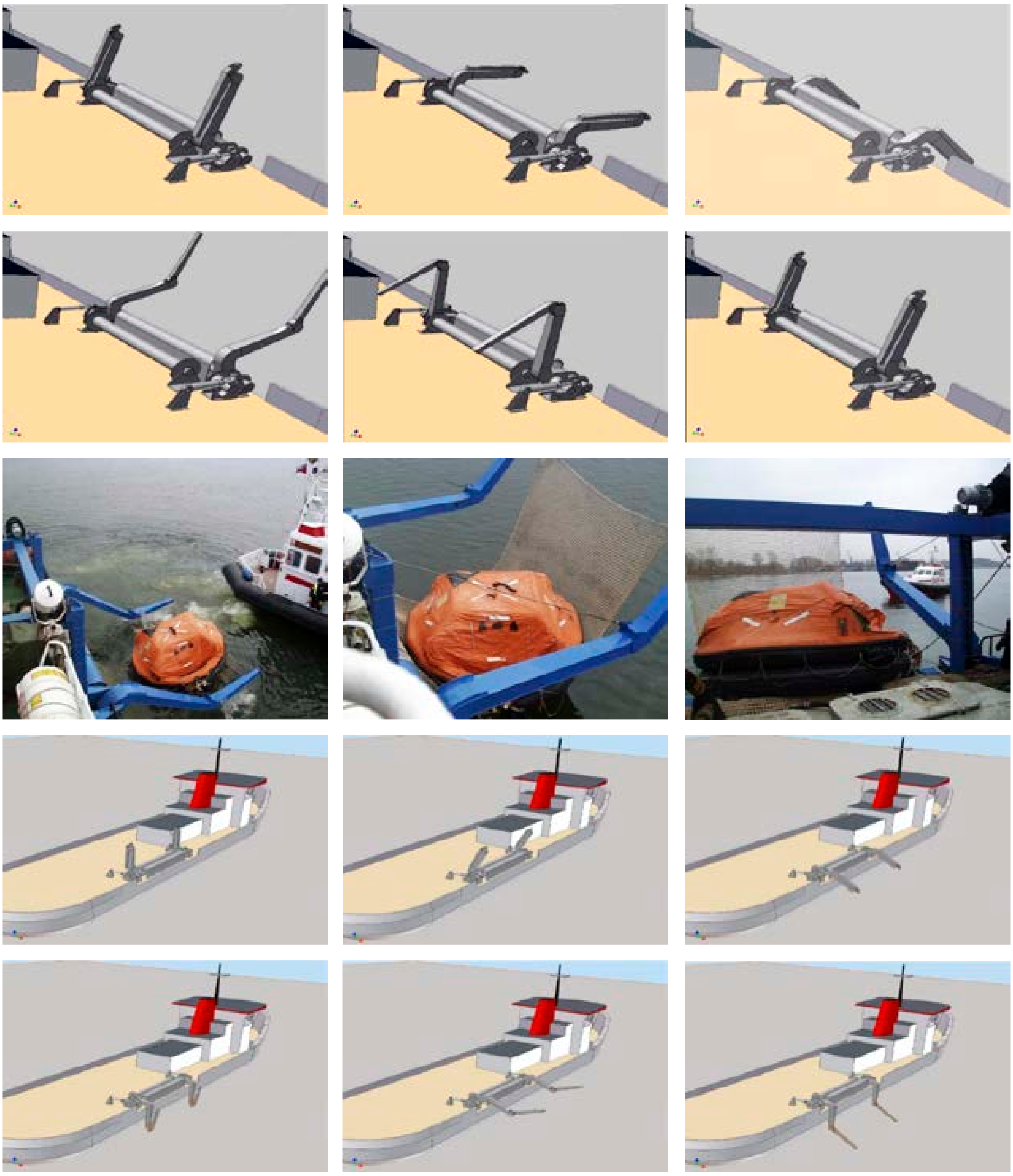


Figure 2. An example of a remote platform prototype for picking up people and life rafts with people inside from the water via MASS

Safety assessment of the MASS remote operation

During the voyage of the remotely operated MASS (IMO level III), the operator will need to keep up-to-date information on the safety status of the environment and ship, including complex technical systems (ZST). The operator's actions and decision-making will be reduced to minimize the risk and maintain the ZST reliability level by avoiding, reducing, transferring, and accepting particular risks (Steward & Melchers, 1997).

Reliability assessment based on semi-Markov model – an example of MASS operating states

A digital twin of the MASS is introduced to control the operation of complex MASS systems.

The digital twin is a virtual representation of a real MASS unit, created to supervise the safety and reliability of operation in order to make optimal decisions in the area of safe operation of the ship and reliability of complex technical systems (Łukaszewski, 2018; Barnard, 2023).

The digital twin makes it possible to evaluate the work of the integrated complex system and will be an element of the decision-making system built on the basis of a stochastic model of the process describing the safety of MASS operation. It presents the operational parameters of the MASS and the ZST, enabling the operator to make the optimal decision necessary to complete the mission.

When creating a stochastic model of the process describing the safety of MASS operation at sea, it is necessary to determine the possible operating states of the unit, including information on the possible intentional states at a specific moment and information on the reliability and safety of the unit (Grabski & Jaźwiński, 2009; Burciu, 2012).

$$S_{ijk} = (i, j, k) \qquad (1)$$

where S_{ijk} signifies the state of the unit, i is the intentional state of operation of the unit, j is the reliability state of the unit, and k is the safety state of the unit.

A rescue operation may occur in any of the defined intentional states. The necessary information for creating a reliability model of the MASS unit involves combining the following elements: destination port, distances, existing sea areas with varying traffic intensity, hydrometeorological conditions, narrow passages, and reliability characteristics. The concept of a random process with a discrete set of states and a continuous set of parameters will be used in the creation of the model. The proposed states of the MASS unit and the MASS safety conditions are as follows:

- Intentional states of MASS:
  - $i = 1$ – end of port operation, readiness of the vessel to go to sea,
  - $i = 2$ – exit maneuvers, pilot's opinion, end of maneuvers,
  - $i = 3$ – start of a sea voyage in port waters,
  - $i = 4$ – the sea voyage – implementation of the operational task,
  - $i = 5$ – port approach, piloting, port maneuvers, mooring,
  - $i = 6$ – port operations.
- Reliability states of MASS at sea:
  - $j = 0$ – unsuitability of the unit,
  - $j = 1$ – partial suitability state of the unit,
  - $j = 2$ – state of suitability of the unit.
- MASS safety conditions:
  - $k = 0$ – state of threat to the safety of the unit (safety of the unit during performance of the task is completely at risk),
  - $k = 1$ – state of relative safety threat (in some situations, it may occur as a threat to the safety of the individual),
  - $k = 2$ – state of safety (the execution of the task by the unit is safe, not threatening her safety).

For example, status S_{321} = (3,2,1) means that the unit carrying out the task, starting the sea voyage in port waters, is in a state of suitability and a state of relative hazard to safety. Note that the set of all states S of the examined unit in this case consists of $6 \times 3 \times 3 = 54$ elements. Such a number of states for a single unit is too large to build a macro-model of the process for carrying out a sea operation. Therefore, it is necessary to aggregate the states by creating disjoint subsets.

Model of the MASS sea voyage process – tasks of the MASS unit

Subsets Z_0, Z_1, ..., Z_{12} of the defined states are assumed to be the states of the MASS unit task implementation process (Burciu, 2012). The following states of the sea voyage process can be distinguished:

0 – complete inability of the unit to perform the operational task – the sea voyage;

1 – the end of the port operation, preparation for an incomplete technical suitability of the ship to go to sea, or (and) with a threat to its safety;

2 – port maneuvers of a MASS unit with a pilot, with incomplete technical suitability, or (and) with a threat to safety;

3 – pilot leaving the ship, end of maneuvers, start of the MASS voyage – (nautical propeller revolutions order) with incomplete technical suitability, or (and) with a threat to safety;

4 – sea voyage to the next port, performance of the operational task by the unit with incomplete technical suitability, or (and) with a threat to safety;

5 – port approach (maneuvering propeller revolutions), pilot on board, port maneuvers, berthing, mooring, commencement of port operations by the unit with incomplete technical suitability, or (and) with a threat to safety;

6 – end of port operation, end of voyage, waiting for the task to be accepted by the unit with incomplete technical suitability, or (and) with a threat to safety;

7 – end of port operation, preparation for the vessel's departure to sea at full suitability, and in a state of complete safety;
8 – port maneuvers of a MASS unit with a pilot by a fully technically operational unit with full suitability, without any threat to its safety;
9 – pilot leaving the ship, end of maneuvers, start of the MASS voyage – (nautical propeller revolutions) carried out by a fully technically operational unit with full suitability, without any threat to its safety;
10 – sea voyage to the next port, performance of the operational task by the unit with full technical suitability, without any threat to its safety;
11 – maneuvering propeller revolutions, port approach, pilot on board, port maneuvers, berthing, mooring, and commencement of port operations, carried out by a vessel with full technical suitability, without any threat to its safety;
12 – end of port operation, end of voyage, waiting for the task to be accepted and carried out by a unit with full technical fitness, without any threat to its safety.

Figure 3 presents a graph of changes in the state of a sea voyage process carried out by a MASS operator. When constructing the sea voyage process – an operational task – the directed arcs of the graph should be assigned probabilistic characteristics generating the implementation of this process. The arc (i, j) corresponds to the probability of changing the state from i to j, which is denoted by the symbol p_{ij} and the distribution function $F_{ij}(x)$ of the random variable t_{ij} denoting the duration of state i, provided that the next state is j. The function presenting the probability of a state change from i to j in time $t \geq 0$ is in the form (2):

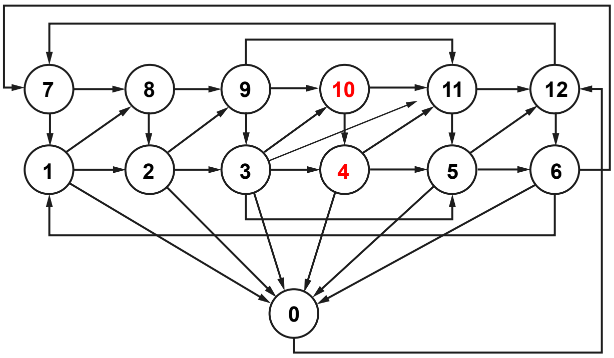


Figure 3. Graph of changes in the state of the MASS navigation process

$$Q_{ij}(t) = p_{ij}(t) \cdot F_{ij}(t), \quad t \geq 0 \tag{2}$$

The graph of changes in the state of the MASS navigation process is presented in Figure 3.

For example, the probability of a state change from 1 to 8 in time t is written as:

$$Q_{18}(t) = p_{18} F_{18}(t), \quad t \geq 0 \tag{3}$$

In this way, the functional matrix $Q(t)$ – a matrix of transition probabilities from state i to state j – will be determined as (4).

The defined process of the operational task performed by the MASS unit allows the use of semi-Markov processes (Grabski & Jaźwiński, 2001; 2009) to analyze the safety and reliability of the implementation of the operational task – the sea voyage. The theory of semi-Markov processes (SM) shows that a sequence of random variables $\{X(\tau_n): n = 0, 1, 2,..\}$, where τ_n, $n = 0,1,2,..$ are moments of state changes, is a Markov chain with a matrix of state transition probabilities given as (5), (6):

$$P = [p_{ij} : i, j \in S] \tag{5}$$

$$Q(t) = \begin{bmatrix}
Q_{00}(t) & 0 & 0 & 0 & 0 & 0 & Q_{06}(t) & 0 & 0 & 0 & 0 & 0 & Q_{012}(t) \\
Q_{10}(t) & 0 & Q_{12}(t) & 0 & 0 & 0 & 0 & 0 & Q_{18}(t) & 0 & 0 & 0 & 0 \\
Q_{20}(t) & 0 & 0 & Q_{23}(t) & 0 & 0 & 0 & 0 & 0 & Q_{29}(t) & 0 & 0 & 0 \\
Q_{30}(t) & 0 & 0 & 0 & Q_{34}(t) & Q_{35}(t) & 0 & 0 & 0 & 0 & Q_{310}(t) & Q_{311}(t) & 0 \\
Q_{40}(t) & 0 & 0 & 0 & 0 & Q_{45}(t) & 0 & 0 & 0 & 0 & 0 & Q_{411}(t) & 0 \\
Q_{50}(t) & 0 & 0 & 0 & 0 & 0 & Q_{56}(t) & 0 & 0 & 0 & 0 & 0 & Q_{512}(t) \\
Q_{60}(t) & Q_{61}(t) & 0 & 0 & 0 & 0 & 0 & Q_{67}(t) & 0 & 0 & 0 & 0 & 0 \\
0 & Q_{71}(t) & 0 & 0 & 0 & 0 & 0 & 0 & Q_{78}(t) & 0 & 0 & 0 & 0 \\
0 & 0 & Q_{82}(t) & 0 & 0 & 0 & 0 & 0 & 0 & Q_{89}(t) & 0 & 0 & 0 \\
0 & 0 & 0 & Q_{93}(t) & 0 & 0 & 0 & 0 & 0 & 0 & Q_{910}(t) & Q_{911}(t) & 0 \\
0 & 0 & 0 & 0 & Q_{104}(t) & 0 & 0 & 0 & 0 & 0 & 0 & Q_{1011}(t) & 0 \\
0 & 0 & 0 & 0 & 0 & Q_{115}(t) & 0 & 0 & 0 & 0 & 0 & 0 & Q_{1112}(t) \\
0 & 0 & 0 & 0 & 0 & 0 & Q_{126}(t) & Q_{127}(t) & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \tag{4}$$

$$P=\begin{bmatrix}
p_{00} & 0 & 0 & 0 & 0 & 0 & p_{06} & 0 & 0 & 0 & 0 & 0 & p_{012}\\
p_{10} & 0 & p_{12} & 0 & 0 & 0 & 0 & 0 & p_{18} & 0 & 0 & 0 & 0\\
p_{20} & 0 & 0 & p_{23} & 0 & 0 & 0 & 0 & 0 & p_{29} & 0 & 0 & 0\\
p_{30} & 0 & 0 & 0 & p_{34} & p_{35} & 0 & 0 & 0 & 0 & p_{310} & p_{311} & 0\\
p_{40} & 0 & 0 & 0 & 0 & p_{45} & 0 & 0 & 0 & 0 & 0 & p_{411} & 0\\
p_{50} & 0 & 0 & 0 & 0 & 0 & p_{56} & 0 & 0 & 0 & 0 & 0 & p_{512}\\
p_{60} & p_{61} & 0 & 0 & 0 & 0 & 0 & p_{67} & 0 & 0 & 0 & 0 & 0\\
0 & p_{71} & 0 & 0 & 0 & 0 & 0 & 0 & p_{78} & 0 & 0 & 0 & 0\\
0 & 0 & p_{82} & 0 & 0 & 0 & 0 & 0 & 0 & p_{89} & 0 & 0 & 0\\
0 & 0 & 0 & p_{93} & 0 & 0 & 0 & 0 & 0 & 0 & p_{910} & p_{911} & 0\\
0 & 0 & 0 & 0 & p_{104} & 0 & 0 & 0 & 0 & 0 & 0 & p_{1011} & 0\\
0 & 0 & 0 & 0 & 0 & p_{115} & 0 & 0 & 0 & 0 & 0 & 0 & p_{1112}\\
0 & 0 & 0 & 0 & 0 & 0 & p_{126} & p_{127} & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \tag{6}$$

where the boundary values of the transition probabilities between states are:

$$p_{ij}=\lim\nolimits_{t\to\infty} Q_{ij}(t) \tag{7}$$

In reliability models, the parameters and characteristics of the SM process translate into the parameters and characteristics of the reliability of the modeled object – the MASS. The important process characteristics include the transition probabilities defined as conditional probabilities, i.e.:

$$P_{ij}(t)=P\{X(t)=j|X(0)=i\},\ \ i,j\in S \tag{8}$$

As a result of further mathematical developments, we can present an analysis of the states of a sea operation and an analysis of their durations, which

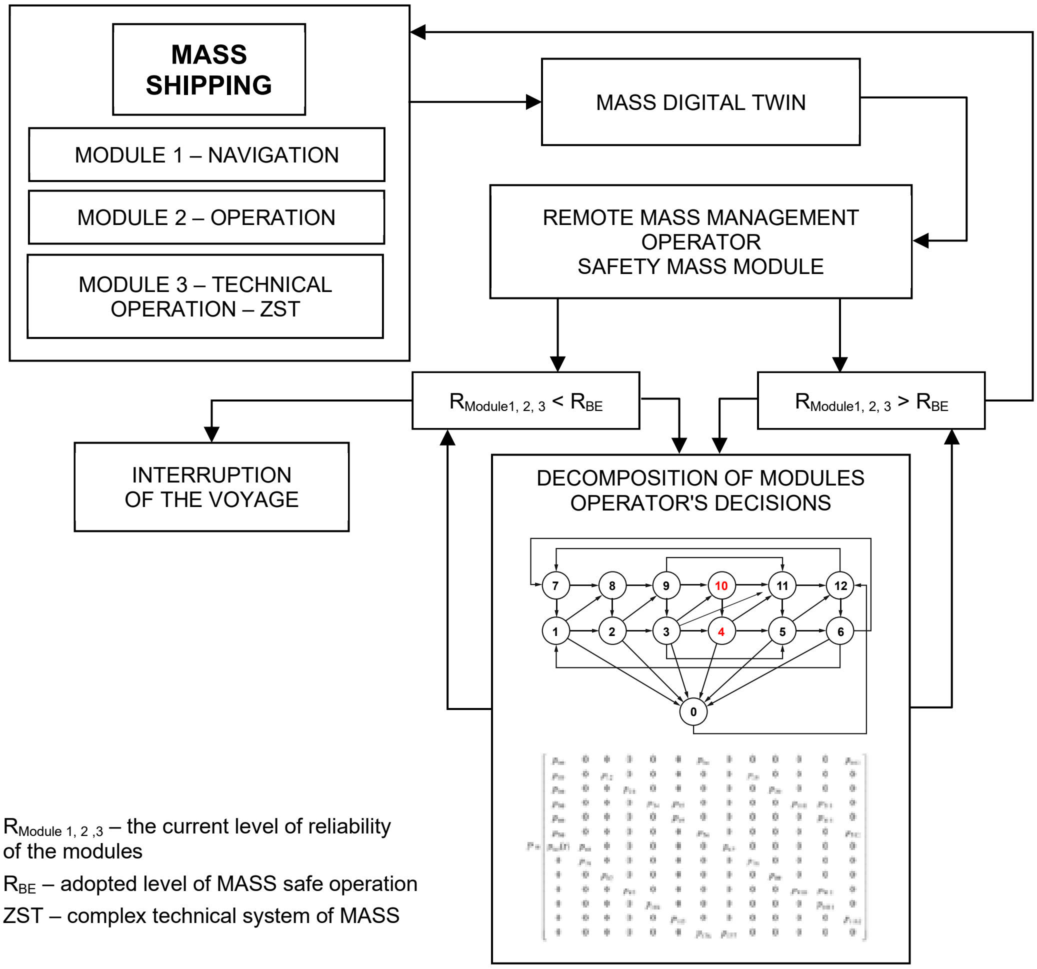


Figure 4. General scheme for the DSS, including the SM process and the MASS digital twin

creates an opportunity for the operator of the MASS to make rational decisions.

The analysis presented above can be the basis for building a computer program and integrated decision support system regarding the safety and reliability of the decision-making process of the MASS operator. The scheme of the proposed DSS, including the SM process and the MASS digital twin, is presented in Figure 4.

Conclusions

To control the operation of complex MASS systems, a digital twin of the MASS is introduced. The digital twin is a virtual representation of a real MASS unit, created to supervise the safety and reliability of operation in order to make optimal decisions in the area of safe operation of the ship and reliability of the complex technical systems.

This article presents possible critical states relating to SAR at sea and the reliability states of the MASS unit that may occur during the voyage. Since the implementation of the MASS voyage was assumed to be remotely managed by the operator, the authors presented concepts of technological solutions that the operator will be able to use in emergency situations.

The proposed rescue platform for picking up survivors from the water can be remotely controlled when the unmanned MASS is close to the distress position, either for a man in the water or a life raft with people on board. The proposed DSS for the search area determination may enable the MASS to undertake a quick search and rescue operation, for example, thanks to the MASS “knowledge” of the current hydrometeorological conditions.

The presented analysis can become the basis for building a computer program – an integrated system relating to MASS safety and a reliability and decision-making process for the MASS operator.

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