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The Construction of Seaports in the Arctic: Prospects and Environmental Consequences

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Abstract: The Arctic zone of the Russian Federation is of strategic importance for the country. Considering the fragility of Arctic ecosystems, special attention needs to be paid to the sustainable development of transport and related infrastructure within the framework of the "blue economy" concept, which is relevant for Arctic waters. At the same time, it is necessary to identify the main factors and tasks of creating transport and port infrastructure, building a modern fleet, and organizing fisheries and tourism in an environmentally sound manner. The purpose of the study is to consider the problems of anthropogenic influence for seaport facilities and to create a conceptual model of an environmental risk management system. The existing problems of Arctic ports and infrastructure are analyzed and existing business processes are considered, taking into account the peculiarities of their functioning in Arctic conditions. To systematize environmental assessments and establish dependencies between the main indicators describing the impact of port activities on elements of the natural environment, ontological domain engineering is proposed. It systematizes the basic terminology used within different subject areas of ecology and risks and allows one to visualize the relationships between elements of the natural environment, objects, port systems, their parameters and impact factors to assess the impact of the seaport on the natural environment. The results of ontological engineering (design and development of ontologies) in the field of risk management are presented. Future research will be aimed at developing the applied aspect of applying the results of ontological engineering in terms of specific engineering studies related to the assessment of anthropogenic load on the Arctic territory using simulation modeling.

Keywords: "blue economy"; seaports; Northern Sea Route (NSR); environmental safety; anthropogenic factor; anthropogenic pollution; ontological engineering; risk management system

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1. Introduction

The Russian Arctic zone is among the key directions in the development of the Russian national economy, contributing to the development of mining and transportation of minerals, accessibility and autonomy of remote settlements, international cooperation, and the national image. Russian Federation has the largest Arctic sector among the countries that have an outlet to the Arctic Ocean, a result of which is that it has a leading role as a developer of the Arctic development strategy [1]. It is assumed that the Northern Sea Route (NSR), which is a major transport corridor in the Arctic area, will operate uninterrupted and year-round by 2030 according to the Arctic development plan [2]. The freight turnover of the NSR is growing annually, and it is planned that in 2024 its volume will reach 80 million tonnes [3]. Currently, the coastal infrastructure in the Arctic region is formed by 18 seaports—12 ports in the Western Arctic and 6 ports in the Eastern Arctic. Despite the large number of ports, all of them have a lot of equipment wear, and many ports in the Eastern Arctic were built back in 1940–1950 [4]. Despite the complexity of the structure and features in the Arctic region, port infrastructure needs to be significantly modernized and upgraded, and the safe and sustainable functioning of port infrastructure needs to be ensured. For these purposes, technologies for the transition to a "smart port" should be used, including the creation of a risk management system. Digital transformation and modernization of the infrastructure in the Arctic Basin create great advantages for the development of the region. The Fourth Industrial Revolution and digitalization are changing the structure of the Russian region's economy, requiring a change in technological structure, the use of modern solutions using the Internet of Things, edge computing, and data mining.

A major problem of the Arctic is environmental threats. In this regard, the most important tasks of providing ecological stability during NSR's development are identification and monitoring of the key contamination factors of the Arctic seas ecosystems and developing a system for managing the safety of maritime operations and ecological safety in the Arctic. Currently, the Russian Federation has accumulated and annually updates a large body of knowledge about the Arctic seas, which should become the basis for making informed environmental decisions. So, from 1 January 2020, global requirements were put into effect to reduce the sulfur content from 3.5% to 0.5% in all types of marine fuel [5]. In connection with the introduction in 2020 of the requirements of the International Maritime Organization (IMO) prohibiting the use of traditional marine fuel-oil, the rationale for shifting to alternative environmentally friendly fuels becomes apparent.

In this sense, assessing the long-term vision of the development and environmental impact of complex organizational and technical systems and facilities, which include seaports, is undoubtedly an urgent problem.

Arctic port infrastructure development policy should take into account that the new economic paradigm of the XXI century is the concept of the "blue economy", which was presented to the Club of Rome by Gunther Pauli in 2009 [6], designating a term that has been further developed in scientific research. The term "blue economy" has caused a significant paradigm shift towards the study of the ecology of oceans and coastal areas in connection with the development of ocean and sea management strategies, which together determine whether the use of oceanic and marine resources is sustainable. However, the "blue economy" of the Russian Arctic should be based on business development in the following areas:

- Marine technologies for the safe use, operation and protection of the Arctic marine ecosystem;
- Marine food systems represented by value chains in fisheries, aquaculture and seafood trade;
- Marine biotechnology and bio-products;
- Application of scientific and engineering principles to the processing of materials by marine biological agents for the provision of goods and services;
- Maritime transport via the NSR, which increases the stability of navigation through the use of modern Russian icebreakers.

The growth of the "blue economy" notion in the Russian Federation could potentially play a significant role in advancing its overall economy. Simultaneously, establishing eco-friendlier supply chains is a crucial aspect of cultivating the "blue economy" idea within the Russian Arctic region.

Within the framework of the Sustainable Development Goals set out in the UN General Assembly resolution, all aspects of the "blue economy" based on natural "blue capital" are defined. One of the most important is "Conservation and rational use of oceans, seas and marine resources for sustainable development" [7], which highlights and solves the oceans' problems and defines specific modern aspects of the concept of the "blue economy". A risk management system (RMS) is needed to address the challenges of sustainable development and utilization of port infrastructure. It will allow the most efficient organization of the activities of the seaport in accordance with its characteristics.

Given the above, the purpose of this paper is to construct an RMS within the concept of a "blue economy" for the exploration of Russia's Arctic waters. This goal determines the outcome of the following tasks:

1. Analysis of the development of Russian seaports in the Arctic;
2. Identification of anthropogenic threats and ways to ensure environmental safety for the Arctic seas;
3. Ontological engineering of the subject area for the purpose of developing an RMS.

The contribution of this study lies in the presented results of an analysis of the existing problems of the Arctic ports and their infrastructure, existing business processes, taking into account the peculiarities of their functioning in the Arctic conditions. As part of the creation of a risk management system conceptual model and to systematize environmental assessments and establish dependencies between the main indicators describing the impact of port activities on elements of the natural environment, ontological engineering of the subject area was carried out. It systematizes the basic terminology used within different subject areas, such as ecology, as well as risks and allows for visualization presenting the relationships between elements of the natural environment, objects and systems of the port, their parameters and impact factors to assess the impact of the seaport on the natural environment. The results of ontological engineering (design and development of ontologies) in the field of risk management are presented.

2. Literature Review on Port Infrastructure Development: Logistics, Ecology, Risks

Maritime transport is included in logistics chains around the world; therefore, both the transportation processes themselves and port activities are of concern, since it is in ports that there is a large accumulation of ships and other types of transport, which, with irrational planning, creates many problems. [8]. The exploration of the Artic is connected to the growth of cargo traffic through the NSR, thus requiring the developing of port facilities. Thus, understanding and managing the global and local implications of environmental degradation of the Arctic requires scientific and practical co-operation. Russia has been developing its capabilities to regulate and support the NSR along its Arctic coast for decades. This route can save up to 40 percent of the time and fuel needed to cross to Europe from Asia via the Suez Canal. This chapter presents the results of studies of port activities in various countries, both in terms of processes and risks arising from this. The possibilities of applying the existing experience to developing Arctic ports are being studied.

2.1. Logistics, Process Management

The NSR has the potential to significantly reduce the distance between the Far East and Europe, influencing both the shipping industry and the environment. In order to reduce the environmental consequences, it will be necessary to get rid of oil sludge, garbage and sewage, including the managing of ballasts. Research [9] has explored the primary threats to the Arctic environment from pollutants and the possibility of implementing pollution control methods in the region. Environmental concerns stem mainly from accidental and industrial contamination.

In [10], authors evaluate the current ecological state of the Russian Federation's Arctic zone as a promising area for active industrial development. The authors stress the need to consider environmental safety requirements in the Arctic region for all economic and other activities, given the unique susceptibility of Arctic ecosystems and the region's climate-forming significance for the planet. Anthropogenic factors pose substantial environmental risks, which, if ignored, could result in global consequences.

The authors of [11] assessed 1300 of the world's key ports for global supply chains and economies to identify crucial cross-border infrastructure dependencies for some landlocked and island countries that depend on specific ports beyond their jurisdiction. This approach allows for analyzing trade flows at the port level and the utilization of specific transport routes for trading goods between pairs of countries.

The T and E report [12] recommends three priority steps to reduce the adverse effects of Arctic shipping: lowering marine black carbon emissions, which contribute to regional ice melting; banning fuel oil usage by ships in Arctic waters due to toxic air pollution and potential catastrophic consequences for ecosystems following an oil spill; and requiring ships to operate at reduced speeds to minimize the risk of accidents and enhance safety and environmental protection.

Study [13] demonstrates that the latest and largest container ships can effectively decrease vehicle emissions and conserve energy, while emissions reductions can also cut down ship docking times. Docking times are influenced by hub port efficiencies, including terminal operations. These vessels can also enable hub ports to receive increased transshipment from Asian or Middle Eastern ports. Besides fuel type, vessel speed is crucial in lowering emissions. Large container ships can decelerate when entering or exiting ports to lessen the impact of their emissions on port air quality and nearby cities. Employing the newest and largest container ships on primary Far East–European routes can reduce operating costs and promote environmental sustainability.

2.2. Tourism

Cruises are a maritime activity that has been constantly growing for more than three decades, and therefore cruise seaports are becoming increasingly important, the direct and indirect impact of which extends to marina towns or nearby touristic locations, since the travel business requires special services for ships and travelers. A chapter of [14] extensively explores two categories of factors that render "green" development a strategic priority for cruise ports, along with crucial considerations for ensuring their sustainable growth.

One prime cruise destination is the Baltic Sea region, where managing cruise ships and passengers poses several logistical challenges related to both water and land. Article [15] aims to investigate service offerings for the cruise industry within the framework of environmental demands and sustainable logistics in port cities, encompassing both ports of call and turnaround ports for cruise ships. Maritime tourism increases the need for urban infrastructure, such as streets, roads, city facilities, shopping centers and entertainment complexes. Ground services for passengers, particularly transfers between terminals, centers, airports and railway stations at turnaround ports, impact urban mobility and may contribute to congestion. Port authorities are formulating environmental policies to mitigate the adverse effects of shipping on the environment by implementing measures to decrease emissions, pollution, noise from cruise ships and waste disposal.

In recent years, the Arctic region has become increasingly important in terms of the number of cruise liners and passengers, as well as all over the world. As tourism activity in the region expands, the likelihood of environmental pollution increases. The influence of cruise tourism on Arctic environmental pollution is studied in [16]. The authors grouped the following identified factors into four main categories and showed them on the "fish skeleton" diagram: geography, industry, infrastructure and legislation. It is shown that there are both controlled factors (rules, infrastructure, operation of ships) and uncontrolled factors (weather and sea conditions). The use of heavy diesel fuel primarily has a negative impact on the Arctic environment. The excessive amount of waste generated on cruise liners is another important factor of possible pollution, since there are no facilities for inspection and reception of waste in remote Arctic ports. The lack of infrastructure can also be a key factor in the event of an oil spill or other spills when considering adverse weather and sea conditions in the region, which can multiply the consequences of such incidents. Reducing the impact of the identified factors can be achieved only with the multilateral cooperation of cruise companies, managing states in the Arctic, international regulatory bodies and intergovernmental organizations.

2.3. Power Consumption in Ports

In [17], the authors, using a multi-level perspective (MLP), explore the socio-technical impacts of three Norwegian ports actively working towards becoming zero-emission energy centers. The study emphasizes the ports' active participation in the transition to sustainable development. The paper examines the factors influencing the transformation of ports towards sustainable energy and the development of different concepts of 'zero-emission energy hubs' adapted to relatively small ports, taking into account their constraints and potential. Energy and transport systems are being transformed and complicated, which is accompanied by a transition from one or more key technologies (for example, fossil fuels) to mixed ones.

Russia has a number of floating power plants along its Arctic coast. The reconstruction of the Far Eastern ports is planned. It is also planned to build at least 15 floating nuclear power plants along the Northern Sea Route [18].

The authors of [19] devised a model for determining the exhaust emissions of vessels maneuvering within port areas. The findings indicate that reduced speeds and utilizing shore power can decrease local air pollution, contributing to a sustainable future. The study reveals that small ships generate the most greenhouse gas emissions in the port vicinity, and emissions increase as navigation speed rises. Therefore, slower speeds and shore power connections can help mitigate local air pollution.

Continuous monitoring of energy consumption in seaports is essential for controlling escalating energy costs, as seen in the growing demand for fuel. Fishing, an energy-intensive activity in seaports, becomes increasingly significant due to the sharp rise in global fish consumption. Document [20] established a roadmap for transforming fishing ports into carbon-free ports and reducing their reliance on the national grid through local solar energy generation. This developed roadmap will facilitate the creation of a carbon-neutral fishing port ecosystem by incorporating sustainable energy practices, including evaluating the quality of energy utilized within the fishing port.

2.4. Port Emissions, Environmental Risks

The port industry often faces the need to comply with regulatory requirements, including safety, protection or environmental requirements. The results of one study [21] show that, although there is still no clear "economic justification" linking "environmental efficiency" with the direct competitiveness of the port, improving this efficiency should be a priority as a means of meeting current needs and as a supportive condition for the development and improvement of environmental indicators to gain a competitive advantage.

Article [22] highlights that, while ports play a crucial economic role, they also negatively affect the environment through local air and water pollution, greenhouse gas emissions, noise and air pollution, traffic congestion and extensive sediment contamination. As public awareness of environmental concerns increases, efficient environmental management in port operations becomes essential. To address growing social and economic demands and environmental challenges, port authorities need to continually implement strategies to enhance environmental performance and guarantee the sustainability of port operations.

Annually, global shipping activities emit 938 million tons of carbon dioxide, surpassing the emissions of the eighth largest-emitting country. One study [23] suggests a methodology for the distribution of intercontinental responsibilities between trading pairs and ships. Based on the model inventory of emissions from shipping, itself based on satellite observations of the activities of ships, emissions from ships related to trade and their impact on human health are estimated.

The analysis of shipping's impact, alongside international trade databases, reveals a multifaceted relationship between trade, shipping, air quality, and health effects. The quantitative assessment showed that U.S.–China bilateral trade represents 2.5% of global CO_2 emissions from shipping and 4.8% of worldwide premature deaths due to ship-related air pollution.

Article [24] offers an in-depth review of current technologies and ideas that support and advance the decarbonization of seaports, such as smart grids and virtual power plants for energy management. The study emphasizes the need for a tailored energy regulation landscape. It identifies three primary factors that directly and indirectly influence the environment: fossil fuel consumption, elevated energy usage of power systems and insufficient professional resource management in seaports.

One study [25] is aimed at assessing the emissions associated with ports and their impact on the environment, since air pollution is caused by the burning of diesel fuel by container ships and port equipment.

Terminals situated near residential areas cause higher levels of pollution in the atmospheric air along major urban roads compared to other locations, with port-related emissions most significantly impacting areas close to these roads where container cargo traffic occurs. The authors suggest promoting a comprehensive "green ports" policy in Shanghai by optimizing cargo delivery systems from the port to the city, improving the energy structure within the port, and incorporating real-time monitoring systems to manage energy consumption and atmospheric pollutant emissions.

Seaports substantially contribute to the pollution of the waters in which they are located. Document [26] seeks to categorize the environmental issues arising from shipping and port activities, focusing on the east coast of peninsular Malaysia. The study identifies key issues like waste dumping, air pollution, maintenance waste, dust, noise pollution, bilge water, dredging and oil spills. The authors recommend several strategies for mitigating these environmental problems.

3. Analysis of Research on Smart Ports, New Technologies and Development Prospects

3.1. Port Sustainability and Efficiency through New Technologies

In order to ensure sustainability and comply with the methods of Industry 4.0 and digitalization, seaports should turn into intelligent ports to solve socio-economic and political problems by taking into account environmental factors. One study [27] offers a comprehensive review of the research literature regarding the new concept of smart ports. The authors proposed 11 characteristics of intelligent ports grouped into seven business areas.

The transformation to a smart port necessitates prioritizing the implementation of cutting-edge technologies and management strategies in line with the unique challenges and limited resources available to address current and future hurdles, ensuring a seamless transition to an intelligent port system.

One study [28] explores the digitalization progress in ports by examining smart ports and Port 4.0 within three primary domains—automation, sustainability and collaboration—focusing on cargo operations, traffic management, safety, cybersecurity, energy, environmental concerns, stakeholder services and partner cooperation and innovation. The logical following step is to methodically gather feedback on scenarios to appreciate their relevance and boundary conditions and elucidate their mechanisms.

Ports are aiming to adopt innovative technologies to manage the consistently rising transportation demand while minimizing environmental impacts. Though Digital Twin (DT) technology has been successfully integrated into various industries, its adoption within complex systems like ports is still in its early stages. One article [29] finds that a port's DT is closely analogous to complex systems such as smart cities and supply chains. By utilizing real-time sensor input and historical data, users can pinpoint patterns causing inefficiencies and model "what-if" scenarios for future conditions.

The NSR offers significant economic and strategic potential. However, numerous challenges and obstacles exist, including the underdeveloped transport and logistics infrastructure, as well as the inadequate digitalization of essential services for secure navigation in Russia's challenging Arctic region. One study [30] aimed to devise approaches, techniques and tools that facilitate the digital transformation of Arctic shipping. It separately examined infrastructure components such as Arctic ports and icebreakers and shipping-related services. Additionally, the research explores the creation of sophisticated geoservices, integrating various geoinformation systems, which are typically employed within decision support systems for territorial and maritime management. This helps analyze cargo movement, transport and logistics infrastructure, coastal economic activities and shipping along the Russian Federation's northern coastlines.

Approximately 90% of global trade occurs by sea, making operational efficiency vital for ports. Industry 4.0 and Internet Plus facilitate the shift toward digital, automated and intelligent operations. Huawei and Shanghai Zhenhua Heavy Industries Company (ZPMC) plan to collaborate with leading telecommunications companies to build efficient and eco-friendly smart ports [31] powered by 5G connectivity. These communication systems must ensure low latency, high throughput, and high reliability for processing control data and multi-channel video data of port equipment. The adoption of 5G technology is anticipated to address these needs. In the future, the construction and management of smart ports will be essential for the port industry, with operations evolving alongside trends like device automation, intelligent planning and data visualization. Huawei's 5G technology is expected to become a vital driving force for providing more efficient solutions to port customers through the use of AI, cloud computing, big data and IoT.

3.2. Smart Port Management

One approach to improving the responsiveness of port infrastructure is the "smart port" concept, which allows automation of existing processes. A "smart port" combines the collecting, storing and exchanging of information to manage operations at all stages of port operation, including integration with the surrounding "smart territory" and intelligent transport structure. This approach reduces the processing time of port operations, reduces costs per operation performed, improves the quality of decisions made and reduces transit time.

A "smart port" is a combination of a central port system in which big data is processed and an IoT platform. Incoming data from the environment and port infrastructure enters the IoT platform, and then data is exchanged between the central port system and the IoT platform. Such exchange between systems allows for the monitoring and management of the operations of port services, as well as predicting the likelihood of emergency situations.

The "smart port" model, taking into account the characteristics of the Arctic region, is presented in Figure 1.

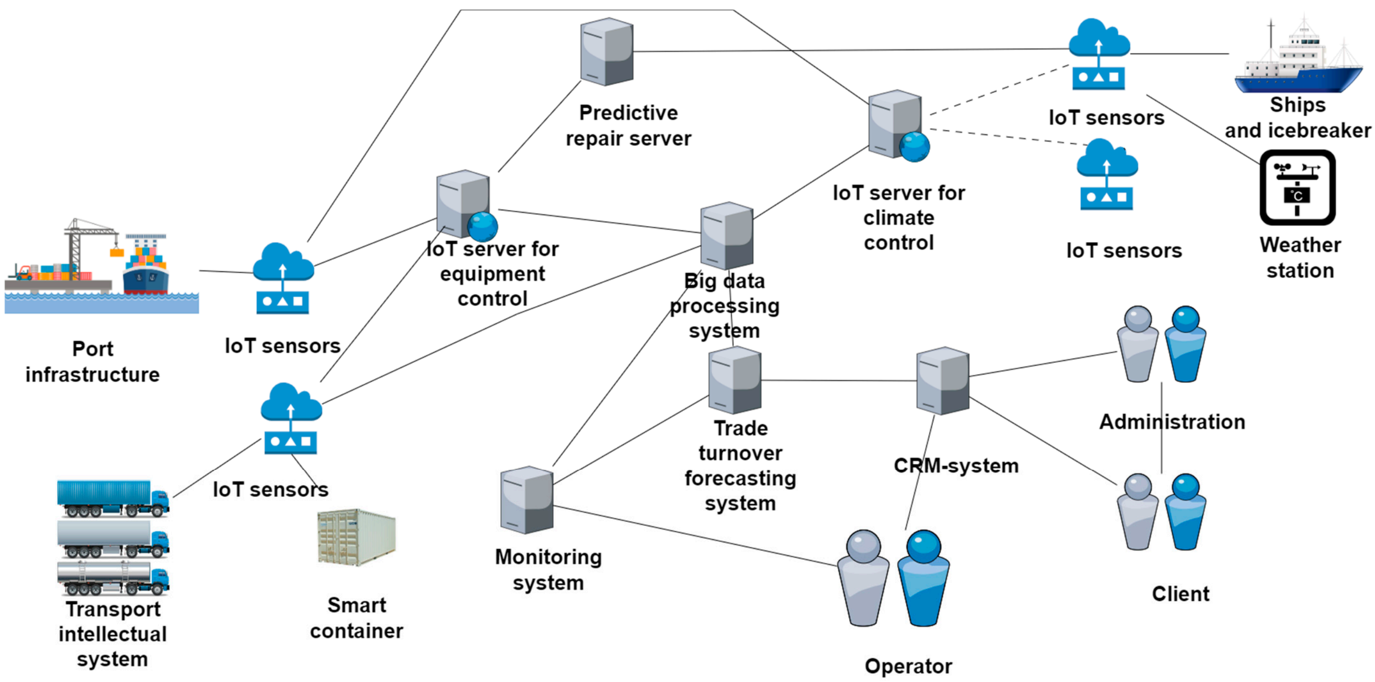

Figure 1. Smart port model.

Figure 1 shows five systems and two data transfer servers. The big data system collects, stores and processes information received from various smart IoT sensors; for example, data on climate conditions is transmitted through the "IoT Climate Server" from weather stations, infrastructure adjacent to ports, ships and icebreakers. After processing, the received data is transferred to the monitoring system, which determines the degree of influence on the functioning of the port and the likelihood of emergency situations occurring. If there is a high probability of risks occurring, responsible persons are notified.

Using IoT tools, we can monitor not only environmental conditions and the location and condition of cargo, but also the normal functioning of port infrastructure equipment, which will allow one to predict the likelihood of equipment failure and minimize the risk of delays in cargo processing.

Shipping in this direction is just developing and, accordingly, there is not enough information about ship accidents. As aforementioned, one approach to improve the responsiveness of port infrastructure is to apply the concept of a “smart port”. One of the scenarios for the operation of a “smart port” is the collection of information from sensors of port infrastructure facilities, which enters the software and hardware complex in real time, on the basis of which monitoring and assessment of the condition of infrastructure facilities is carried out. When unusual values are recorded or those that go beyond acceptable limits, the probability of equipment breakdown is assessed, after which a notification is issued about the need for predictive repairs. System diagnostics can be assessed at several levels: planned, abnormal and critical. The situation is planned when the values from equipment sensors are within acceptable limits. An emergency situation is characterized by a number of conditions and circumstances in which the values differ from the given norms and regulations, leading to the occurrence of an emergency situation. A critical state is characterized by events that cause emergency situations and lead to the risk of a chain reaction associated with the destruction of infrastructure facilities.

This system will reduce the risk of serious equipment breakdown, mechanical failures or other incidents that could lead to negative consequences and oil spills in particular.

A smart port has parts of transactions and shipping that are tightly interconnected with each other via different networking. It is the most advanced model for managing the business processes of a seaport. According to the authors of [32], some sea cargo ports of Croatia can be considered “developing ports”, where they are seeking ways to facilitate business operations through the development of port community systems and a national “single window”. Smart technological innovations enable ports to enhance their information management. Subsequently, the objective is to incorporate suitable smart technologies, which can result in faster cargo processing, among other benefits. Each seaport has its own unique obstacles and prospects, making the shift a potentially extensive and intricate procedure. As such, Croatian ports should aim to adopt a wide range of intelligent technologies to reap numerous benefits, such as expediting cargo handling.

In one article [33], the authors delve into the idea of a smart port, which represents an evolution of traditional ports augmented by technologies like IoT. The authors propose an intelligent port architecture and introduce the CLASSE project, a significant stride in transforming Le Havre’s port into a “smart” facility. The project primarily utilizes Automatic Identification System (AIS) data. This vast influx of daily data turns the project into a big data endeavor, accompanied by several challenges such as handling, processing and storing vast data files. Despite these challenges, the project offers promising applications, including the following: ship punctuality in ports compared to shipping schedules; effects on land-based logistic chains; and modeling traffic conditions in busy seas. Furthermore, the authors present two use cases involving ship classification based on their TEUs and terminals, which holds interest for port authorities, shipping firms and other stakeholders, offering insights into the port’s operations.

One study [34] proposes a system designed to issue electronic licenses for ships and seafarers utilizing blockchain technology, which requires developing a website to register inland vessels and seafarers, followed by granting user access to their data. The suggested system aids in creating a data collection portal and allows remote access to the stored information. The database will also maintain records of inland navigation vessels and their owners, as issued by the Ministry of Port Shipping and Waterways. Consequently, this system assists in registering ships, generating certificates using a range of parameters, ensuring data encryption and integrity and implementing restrictions on data modifications via blockchain technology.

Monitoring goods, containers and vehicles in ports is complicated due to the typically remote locations of seaports and their limited network capabilities. Current solutions employ a mix of RFID tags and wireless sensor networks (WSNs). One article [35] assesses the efficacy of LoRa (Long Range) radio technology, an emerging favorable option among other low-power wide-area networks (LPWAN), for geolocation and tracking in harbors using ns-3 as a use case. Harbors, known for their harsh industrial settings with metallic elements and surfaces, can negatively impact wireless network performance. The results presented in the paper show that the configuration of the LoRa infrastructure is applicable in the harbor environment for GNSS data transmission for tracking and geolocation purposes.

One article [36] shows that the construction of an intelligent port can contribute to the development of intelligent shipping. For incoming vessels, a reasonable allocation of berth resources can reduce the time the vessel stays in port, improving the overall efficiency of the terminal and the overall competitiveness of the port. The use of intelligent algorithms to rearrange berths in the port is only one aspect of reducing pressure in the port. The port is a highly integrated unity of several subsystems; therefore, it is important to integrate the resources of various subsystems to make their work coordinated and efficient in order to ensure the smooth running of port operations. However, new swarm intelligence algorithms, such as Lion Swarm Optimization (LSO), have obvious problems, such as the possibility of falling into a local optimal solution and the presence of a central trend, which must be eliminated to facilitate the practical application of LSO.

There is a clear need to invest in the UK's port infrastructure; however, deciding how to govern the emerging sector that relies heavily on digital information and communication technologies poses a challenge. Smart ports can offer local, national and global advantages by reducing greenhouse gas emissions, enhancing air quality, streamlining supply chains and promoting safe working environments. Nevertheless, they introduce new safety risks and vulnerabilities that traditional management methods often struggle to handle. The authors of [37] examine the digital transformation of seaports in both Rotterdam and Singapore, the smart port leadership of which can inform the UK's innovation and digitalization implementation within its new maritime strategy. Recommendations for further action are outlined, as well. As the UK develops smart ports, it must ensure the involvement of suitable support agencies, encompassing cybersecurity, national infrastructure safety, environmental protection and standardization authorities.

3.3. Energy Efficiency SP

The authors of [38] highlight the challenges faced by seaports in enhancing energy efficiency, embracing technological innovations, reducing their carbon footprint and adhering to regulations aimed at lessening the environmental impact of the maritime industry. In response, seaports are working to become smart energy hubs, with extensive electrification being a critical component. The growing electricity consumption of seaports, driven by operational, regulatory and environmental factors, makes intelligent energy networks an attractive solution. Future seaports will comprise refrigeration units, shore-to-ship power supplies, electric vehicles, energy storage systems, cranes, etc. Intelligent power and energy management systems will enable optimization of operations in terms of cost and efficiency. The implementation of ideas such as microgrids, smart grids, distributed control and more will offer dependable solutions to operational issues emerging from the complexities of a future seaport's power system.

The focus on energy-efficient operations is increasing among maritime operators and regulators as they move towards sustainable smart ports. The authors of [39] propose a framework to analyze and evaluate sustainability efforts related to land terminal operations within the maritime sector. The authors present a structure and methodology for gathering and assessing energy sustainability measures at various marine terminals in their transition to smart ports. Four primary evaluation parameters were considered: transparency (i.e., measurements), technologies, best practices and management policies. Through this framework, marine terminal operators can evaluate their own operations' energy efficiency, learn from other sustainable ports, and enhance their energy consumption practices.

Integrating renewable energy into maritime systems, like port microgrids, substantially enhances energy efficiency while decreasing the reliance on environmentally harmful fossil fuels. The authors of [40] present a comprehensive review that offers current insights on seaport electrification and infrastructure, considering factors such as environmental aspects, energy efficiency advancements, incorporation of renewable energy sources and legislative and regulatory requirements. Furthermore, an infrastructure scheme has been introduced to boost energy efficiency in modern ports, encompassing port microgrids and smart seaport microgrids. In the future, there is considerable potential for improving energy efficiency in port terminal operations through the utilization of energy storage systems (ESS) and emerging technologies like the Internet of Things (IoT).

To mitigate air pollution and noise in seaports, there is a growing trend toward using electric ships and shore-based charging stations, also referred to as cold ironing infrastructure (CI). The authors of [41] introduce an enhanced CI system with improved electricity quality (PQICI) through a refined charging mechanism to address this issue. This novel PQICI system is inherently versatile, enabling it to supply various forms of energy to different types of vessels, including AC power, DC power, 50 Hz frequency, 60 Hz frequency, single-phase, three-phase, three-wire networks, four-wire networks, five-wire networks and diverse AC and DC voltages. Moreover, the PQICI supply system can concurrently service four vessels. The developed solution's capabilities were tested on various ship and vessel types using a simulation platform and experimentally, yielding satisfactory outcomes.

The authors of [42] suggest an ideal management approach for a "smart port" that includes renewable energy generation and features an electrified berth using cold ironing (CI) and a hydrogen-based berth that accommodates zero-emission ships. One battery-based energy storage system and one hydrogen-based energy storage system are utilized to manage renewable energy sources, catering to vessels powered by electricity and hydrogen. The control algorithm incorporates uncertainties in renewable energy generation through stochastic optimization. The efficiency of this method is being evaluated on a prospective smart port outfitted with wind and solar power generation.

In the case of the experimental site analyzed in [43], namely in the Norwegian port of Borg, local generation implies the possibility to reduce its electricity costs by increasing its own demand and escaping price costs during the peak periods of demand. The estimation results show that the effect of providing shore power to multiple ship-to-shore profiles increases the local renewable energy utilization in the system. The modeling conducted examines the cost benefit of expanding local RS production in the Norwegian port of Borg, as well as the prospective effect of supplying the vessel with shore-side power.

3.4. Self-Driving Vehicles in SP

Future seaports will enable autonomous trucks to enter the terminal and seamlessly interact with on-site autonomous loading and unloading vehicles and equipment, considerably enhancing transport efficiency compared to present capabilities. The authors of [44] introduce a secure, portable, decentralized and user-controlled identification system for authenticating trucks. The advancement of autonomous vehicle technologies contributes to the realization of the "smart port" concept, where incorporating autonomous vehicles will fully automate container terminal operations. Nevertheless, engaging with the transport ecosystem in seaports presents a significant safety challenge for all parties involved in managing containers from origin to destination. The article proposes a method for setting up a secure communication channel between two entities, followed by mutual authentication. The system employs a user-centric decentralized identification approach, utilizing HI tools to generate secure identification for each device, encrypt and decrypt data and verify identity proofs.

The foundation of a future eco-friendly and cost-efficient transportation system consists of innovative transportation modes. The authors of [45] offer a feasibility analysis of a door-to-door use case that combines route development and infrastructure definition for cargo transport in southwest England and south Wales. The suggested system employs novel, adaptable and environmentally sustainable vehicles, including electric vertical take-off and landing aircraft and electric autonomous zero-emission vessels. To examine the safety and feasibility of a multimodal transport system powered by electricity, as well as to assess the overall energy requirements, a digital twin is proposed.

The authors of [46] showcase an evaluation of wireless ultrasonic berth occupancy sensors, examining the precise and imprecise detection of berth occupancy and the sensors' performance under different berth conditions while emphasizing the primary reasons for false alarms. The findings reveal that the predominant factors contributing to inaccurate berth occupancy detection include sea currents, improper sensor placement, damaged sensors, excessive distance between the boat and sensor, ropes from adjacent berths and surrounding vegetation and mooring of a catamaran-type vessel.

In [47], an ITCA algorithm is proposed for managing vessel movement in challenging shallow water conditions, influenced by wind and waves, by combining the Nomoto model and sliding mode control. Additionally, the authors considered the effects of wind and wave disturbances, transforming them into an equivalent steering angle generated by the ship. The feasibility of this ITCA was tested through experiments modeling real ships in two distinct scenarios. The suggested ITCA model can facilitate automatic mooring both with and without disturbances, significantly lowering labor expenses. The outcomes demonstrate that the vessel can be stably moored at the optimal heading angle without interference, and the maximum deviation of the heading angle under disturbances does not surpass 4%.

3.5. Safety in SP

At present, ports have transitioned from analog to digital systems to leverage IT tools for streamlining processes, particularly in the administrative domain. The Terminal Operating System (TOS) serves as the central element in these operations. Consequently, integrating IoT into TOS is an essential move towards the development of intelligent ports. In [48], expanding the concept of IoT in other intellectual fields to consider them in the paradigm of intelligent ports, such as intelligent buildings, intelligent networks, intelligent environmental monitoring, etc., is proposed. The authors argue that LTE/4G is the most suitable technology for establishing private networks within smart seaports.

The authors of [49] explore various options for the design and implementation of a ZigBee/RFID smart occupational safety system to safeguard workers, pedestrians and the surrounding marine environment at seaports, specifically at the port of Bar (Montenegro). A brief overview of RFID, ZigBee and ZigBee/RFID system features is provided. Furthermore, several experiments involving modeling in the OPNET environment using the ZigBee/RFID network at the physical level are conducted, and relevant conclusions are drawn. To enhance the safety of port workers and pedestrians, two models are examined: (i) utilizing active RFID ID tags for tracking and controlling access to hazardous areas, and (ii) installing RFID readers on forklifts to detect nearby workers/pedestrians, trigger audible/visual alarms and decelerate the vehicle as needed. These two RFID subnets function as end nodes and moving routers (respectively) within the ZigBee communication protocol, configured by the XBee module to accommodate RFID technology requirements.

The authors of [50] discuss and study possible sustainable schemes for the operation of intelligent business ports based on IoT and blockchain technologies. Despite international trade ports being integral to global logistics, there is a scarcity of research on the application of IoT in port operations, particularly in empirical studies. Setting up fully automated terminals and deploying smart IoT equipment necessitates substantial investments. Often, IoT technology is combined with AI and big data to maximize its impact, particularly in AIS for ships, allowing managers to precisely assess shipping dynamics and cut costs. This research seeks to identify the primary factors contributing to the development of smart ports. Terminal operators are used as a reference to inform future advancements in intelligent port evolution.

One of the aspects of increasing interest is the impact of the activities of seaports, which play a significant role in climate change, on the environment, as well as how they affect the health of the population of neighboring regions. The authors of [51] discuss various environmental aspects that can be taken into account when monitoring smart seaports, as well as communication methods that can be used for data collection, if there are three levels of network categories: narrowband, LPWA (known for its large coverage) and broadband mobile solutions. The design of communication layers that support this broad spectrum of intelligent applications must satisfy a range of functional requirements and service quality standards. In certain situations, such as fire scenarios, high reliability (ultra-reliable communication—URLC) is also of significant importance.

The cyber resilience of intelligent ports is crucial to avert potential disruptions in the economic supply chain, particularly as there has been a significant rise in reported cyber-attacks on ports in recent years. The authors of [52] explore the potential of a cutting-edge hybrid cyber range to educate and train individuals about cyber risks in ports, emphasizing critical port infrastructure threats, risks, consequences and solutions. The pilot demonstration revealed that, while various Cyber-MAR components detected the attack, the speed of the assault made it impossible to halt once the intruder obtained administrative access to the organization's network. Proactive and adaptive prevention and response measures are essential to block the initial attack vector and impede its spread throughout the network infrastructure.

4. Materials and Methods

Any management activity is more or less associated with risks. This is due to the multifactorial dynamics of management and the external environment, as well as the presence of an anthropogenic factor in the process of making and implementing management decisions. Risk is closely related to security, whether physical, economic, informational or environmental. Based on the value of the risk level, decisions are made that apply strategies to ensure necessary safety levels. The activity related to the assessment of the level of risk and the development of solutions to reduce it has been called risk management. At the same time, each specific industry or scope of risk management has its own specific features.

The creation of a risk management system should begin with an analysis of the business processes of port activities and, accordingly, with the identification of those operations this can have a negative impact on the environment—on the air, on the water and on the land. Based on this, the difficulties of taking into account the risks of port activities, as well as risk management, may be due to various factors. Thus, port operations are carried out using a broad variety of vehicles, often powered by diesel, which leads to the emission of harmful substances and greenhouse gases, affecting climate change.

Furthermore, seaports, due to their proximity to the coast, face potential hazards from severe weather occurrences, with flooding being the most prominent threat. This can result in harm to electrical substations and ground-level electric motors of docking cranes and pumps, as well as causing damage to or loss of goods.

Harbor activities can substantially affect the quality of water and the well-being of aquatic organisms. Debris from vessels and additional port-related actions may result in the deterioration or destruction of environments, while also harming marine plants and animals. Recognized consequences of port functions consist of the following:

- Waste water: Vessels occasionally release waste water, sewage and bilge water, which typically contains oil contamination. These discharges are controlled by national, regional and local agencies, encompassing harbor authorities as well.

- Vessel paint: The release of hazardous paint substances intended to hinder shell adherence to ships may damage aquatic organisms.
- Storm drains: Rainwater drains gather contaminants from the port's hard surfaces and release them into the water, frequently circumventing treatment centers.
- Nitrogen: As the primary contributor to eutrophication in oceanic environments, nitrogen results in proliferating algae that deplete the water's oxygen, leading to the demise of fish and shellfish populations.
- Oil spills: Pollution from oil can encompass persistent contamination due to runoff, discharge from bilge, oil tanker transfers and substantial spills that occur from tanker overflow or breaches in ship hulls.
- Dredging: The process of eliminating sediment to expand navigational routes may heighten water cloudiness, disturb contaminated sediments, harm or demolish crucial habitats for wildlife and disturb or annihilate vulnerable and threatened species.
- Foreign species: Marine creatures may hitch a ride on ships through ballast water, utilized for stabilizing vessels, and subsequently be introduced to foreign environments, posing a risk as invasive species that disrupt the equilibrium of native ecosystems.

Environmental risk assessments usually relate to one of two areas:

- Human health.
- Ecosystem status.

Environmental hazards can be viewed as the likelihood of detrimental impacts on human well-being or ecological systems due to exposure to an environmental stressor. A stressor represents any physical, chemical or biological entity that can provoke negative consequences for an individual or an ecosystem. Stressors may have adverse effects on specific natural resources or entire ecosystems, encompassing flora and fauna along with their surrounding habitats. Hazards can be linked to distinct chemical pollutants, like mercury, or combinations of numerous chemicals, such as those found in oil spills. Additional stressor types consist of harmful microbial pathogens or unfavorable conditions like anoxia (oxygen deficiency) in surface waters. The Environmental Protection Agency conducts risk evaluations to ascertain the types and severities of threats to human health or different population segments, encompassing both juveniles and adults, and also appraises hazards to environmental receptors, such as vegetation, avifauna, other wildlife and aquatic plants and creatures.

The risk management process consists of several stages that are repeated (Figure 2).

After the planning and scope stage, at which point the purpose and scope of the risk assessment are determined, the risk assessment process usually begins with the collection of measurements characterizing the nature and degree of danger in the surrounding area. For instance, the levels of chemicals in the ground can be assessed near the origin of the leakage. Additionally, data required for forecasting the potential actions of contaminants can be gathered.

Grounded on the findings from the planning and scaling phase, the risk evaluator examines the occurrence and intensity of potential effects on people and the environment. To estimate the prospective repercussions of exposure to a contaminated setting, both in the present and future scenarios, numerous proofs are used, such as the nature and degree of the stressor's impact on people or ecosystems, on the basis of which one can predict the likelihood, nature and magnitude of possible adverse consequences.

Evaluating risks must rely on a robust foundation of knowledge. As it is crucial to comprehend the transport and destiny of substances, microorganisms or other environmental elements, dependable and comprehensive information regarding the nature and extent of contamination or the presence of additional stressors is required. In other words, data that establishes a quantifiable connection between the severity and occurrence of human and environmental impacts and adverse consequences is needed. In real life, however, all risk assessments involve uncertainty, as risk assessors often have to use judgment to calculate risks.

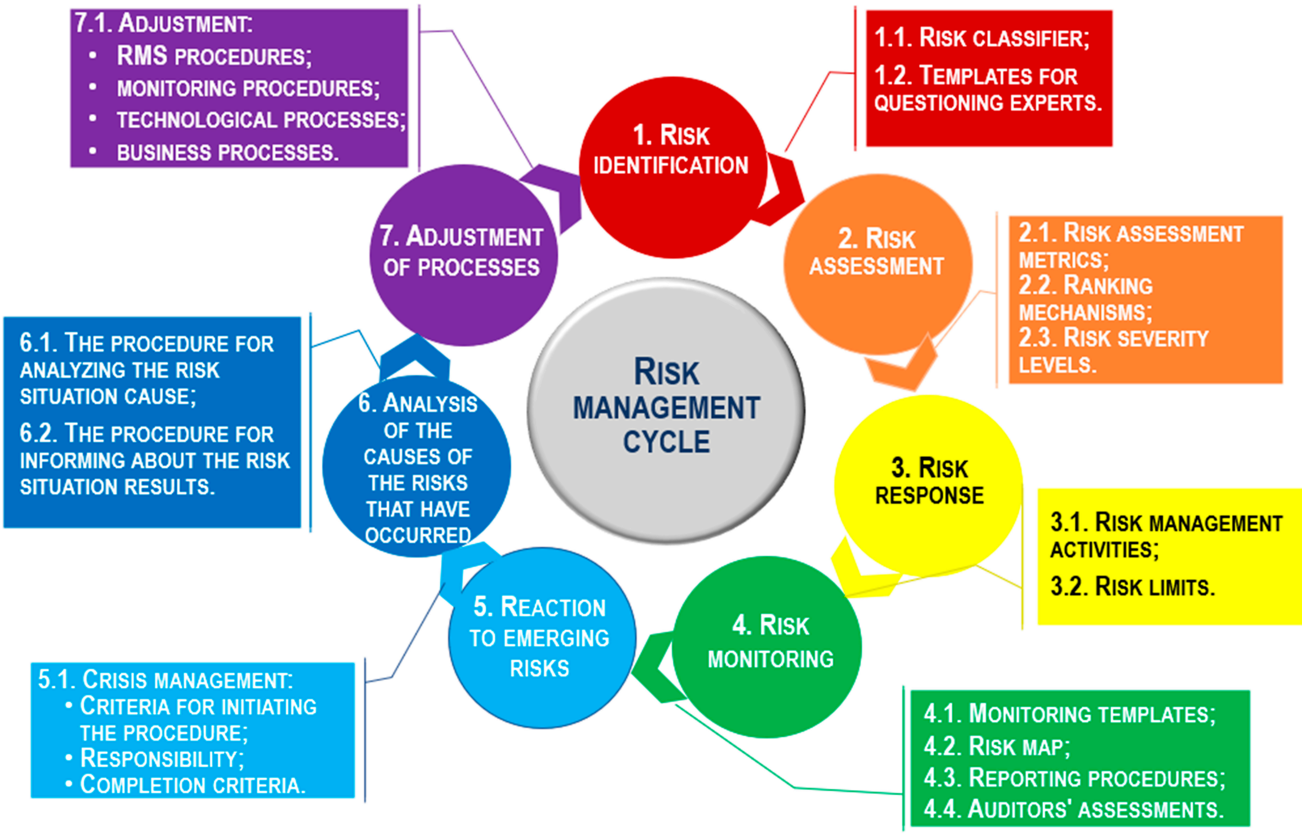

Figure 2. Diagram of the risk management system.

The concluding phase of the evaluation, known as the risk profile, encompasses a numeric and descriptive representation of the risk. The assessor distinctly depicts the trustworthiness (or lack thereof) of the acquired risk estimations. As a rule, when there is a lack of information, appraisers use assumptions that protect health, especially at the early stages of risk assessment. Risk overseers might determine that further details are required to diminish ambiguity surrounding crucial risk elements and might ask for supplementary data gathering and a revised evaluation, which will help make more realistic assumptions.

The most effective direction in building risk management systems is ontological engineering. Researchers in the field of ontological engineering propose several useful steps and combinations [53–60]. From the point of view of developing the ontology of the subject area of the RMS, the following tasks will be required:

(1) Conceptualization, implying the identification of concepts and relationships between them in the interrelated areas of risk management, the subject area and the field of data mining, as well as the generation of accurate and clear textual definitions of concepts and relationships;
(2) Formalization, in which a formal model of the concepts and relationships identified at the previous stage is created;
(3) Implementation in the language of ontology representation.

The objectives of ontological engineering include the following: enhancing the integration of information vital for making administrative choices, improving the effectiveness of information extraction and offering the capability for collaborative processing of knowledge through a unified semantic representation of the knowledge domain.

In the research being carried out, the development of ontologies is essential for the following:

(4) Clarification and harmonization of terminology of different fields and port activities;
(5) Definitions of basic concepts in the study of the anthropogenic effects of port on the natural environment;

(6) Systematization of interrelations between concepts and identification of classes and subclasses of ontologies;
(7) Structuring of knowledge and information, taking into account the research being carried out.

Ontological engineering was carried out on the basis of risk classification within the framework of the meta-ontology of risks of the subject area under consideration (Figures 3 and 4).

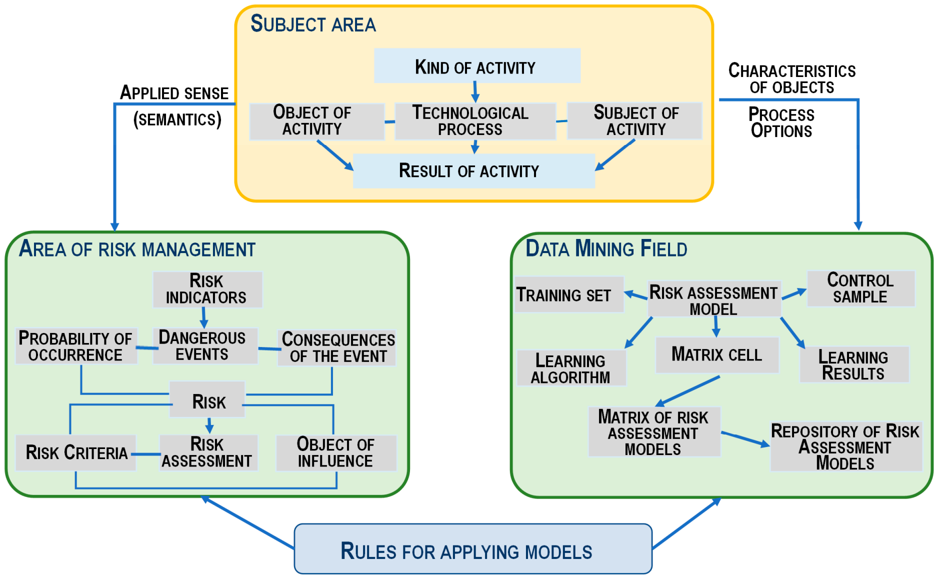

Figure 3. Simplified scheme of the subject area of the RMS.

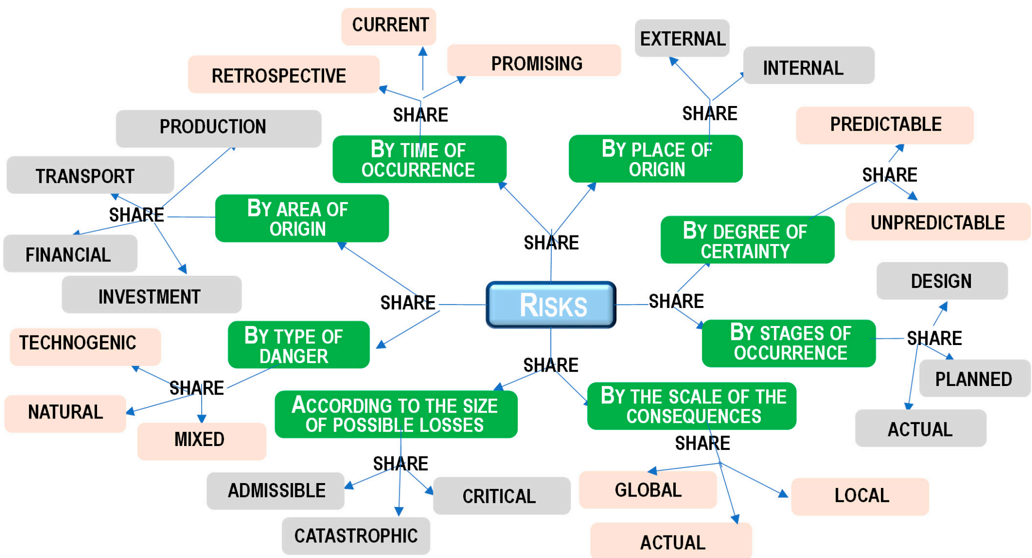

Figure 4. Ontological model of the subject area "Risk management of port activities".

5. Results and Discussion

The Arctic holds significant importance within the realm of Russia's national interests. Concurrently, a crucial objective is the advancement of the Northern Sea Route that enables logistics and the populace's mobility. Thus, Arctic seaports receive special focus alongside development of the Arctic zone territory. As demonstrated earlier, ports contribute to the growth of the maritime transport system but can also pose a variety of challenges relating to port operations and shipping. Consequently, when devising development strategies, it is essential to consider all potential risks that may result in adverse environmental impacts.

5.1. Classification of Ports as Sources of Risk

Considering all coastal devices with the adjacent water area, united by the common name "ports", it is necessary first of all to pay attention to their wide variety. First of all, it is necessary to classify ports according to a number of features, which is convenient not only for analyzing their production goals, but also for studying them from a risk and management optimization perspective.

Ports are classified according to the following main characteristics:

(a) geographical location;
(b) Attitude to international trade;
(c) Volume of annual cargo turnover;
(d) Appointment;
(e) Annual duration of operation;
(f) Relation to water level.

Based on the unique characteristics of the transportation, geographical positioning, morphology of the shores and connections with inland waterways, ports can be divided into three groups:

- Those located in deep natural bays protected from the open sea by capes acting as natural breakwaters (for example, Yokohama, New York, Rio de Janeiro, Istanbul);
- Those located in shallow bays or on coastal plains, where protection from the open sea is provided by artificial breakwaters (for example, Casablanca);
- Those located in estuaries of navigable rivers away from the mouth (for example, Hamburg, Le Havre, London, Montevideo, Montreal).

Ports are distinguished by geographical location: river, reservoir, estuarine, coastal, lagoon and island.

River ports on free rivers, depending on their location on the river, are divided into channel ports, the entire water area and mooring front of which are located directly in the riverbed and inland, or backwater ports, in which the water area and the mooring front are in a natural backwater or in an artificial bucket; in the latter case, the port is called a bucket. Inland ports are usually used for winter settling of ships, and therefore have ship repair plants in their composition. Large ports are often mixed if they have both sections located in the riverbed and bucket sections.

Reservoir ports are located in the upper reaches of reservoirs. They, like the sea ones, have protective structures that protect the raids and berths from waves, since waves during a storm can reach a considerable height in these areas.

Estuary ports are distinguished by the merging of both marine and river waterways within them. The majority of the world's major ports, such as St. Petersburg, London, New York, Hamburg, Rotterdam, and Antwerp, are situated at river estuaries. Port devices are placed, as a rule, along the banks of the river or in pools dug in the shore. At the same time, ports tend to be located at some distance from the sea in order to avoid the construction of protective structures. In some cases, on large rivers, seaports are situated a significant distance from the estuary, and they should be classified as a special category of inland seaports (for example, Arkhangelsk).

Coastal seaports are created on the open seashore and, in order to protect their waters and berths from waves, protective structures have to be built. If the port is located in a natural, partially protected bay, then the length of the protective structures is small.

Lagoon ports are located in the depths of lagoons formed on sandy shores due to the deposition of natural braids separating the lagoons from the sea. Such ports do not need protection from waves, but have approach channels on which it is necessary to maintain depths by removing sediments by dredging.

Island ports are located on islands and have no land connection with the coast. They are created for the transshipment of cargo between different types of vessels or for receiving vessels that, due to heavy draft, cannot approach the berths of the main port.

In relation to international trade, seaports are divided into ports of global, international and domestic importance. Ports of global importance are the centers of world trade and accept ships sailing on all seas and oceans. Ports of international importance accept vessels sailing within the basin on which the port itself is located. Ports of internal importance, or coastal ports, serve domestic transportation between ports of a single country.

According to the size of annual freight turnover in maritime transport, major ports with a cargo turnover of 10–20 million tons or more are distinguished, among which the largest ports with a cargo turnover of 50–100 million tons or more form a group of world-leader ports, the total number of which is about 30.

According to the national economic significance, the main classification feature of the port is the volume of work performed by the port, that is, cargo turnover and passenger turnover, depending on which the following is determined: the administrative structure of the port and its operational staff, the amount of funds for its operation and repair work, the amount of work on its development, the class of the main structures, the marks of the territory and calculated water levels. Due to the different complexity of processing various cargoes, the port category is determined by the cargo turnover in conditional tons.

If passenger berths are located in a common berthing front with cargo berths, the port category is determined by the average daily cargo turnover of the cargo area (in conditional tons). When designing a separately located passenger area, its category is determined depending on the average daily passenger turnover (in conditional passengers).

According to the nature of the processed cargo, seaports are divided into universal and specialized.

Universal ports accept and process all types of cargo—general, bulk, pillowcase, etc. For their processing, certain sections of the port have a certain specialization and are equipped for loading and unloading containers, oil, coal, ore, grain, timber, chemicals and other cargo. Ports of a universal type prevail in economically developed countries with a diversified economy, and in general they are the overwhelming majority.

According to their purpose, ports can be divided into transport, military, commercial and safe haven ports.

Transport ports intended for the transfer of goods and passengers between modes of transport can be divided into general-purpose ports, where a variety of cargoes are processed and passengers are transferred, and special ports designed for the processing of any one cargo (coal, ore, oil, timber, etc.). As a rule, special ports have powerful high-performance reloading devices that serve to process only one type of cargo. Devices for transshipment of other types of cargo and passenger berths in special ports are of secondary importance. It is not uncommon to encounter special passenger ports in which cargo operations are limited to baggage transshipment. In general-purpose ports, various cargoes are overloaded, and reloading devices are more versatile. The largest domestic and foreign ports are general-purpose ports.

Military ports or fleet bases are designed to serve the navy. They are characterized by the presence of large raids, pools for ship repairs, special warehouses of military equipment and food. Extensive barracks are often located on the territory of the military port. Fortifications and other engineering structures are available for the defense of the port.

Commercial ports, of which fishing ports have received the greatest development, are equipped with refrigerator warehouses and have processing enterprises in their composition. Such ports, being the bases of the fishing fleet, have, as a rule, their own ship repair devices.

Ports of refuge are designed to shelter ships that are not designed for the action of large waves during a storm. As a rule, natural bays and lagoons are used for ports of refuge, producing a minimum amount of dredging in them to create raids.

According to the annual duration of operation, ports on inland waterways are divided into permanent and temporary. Permanent ports are operated throughout navigation. Temporary seasonal ports function only for part of navigation, which is due to hydrological conditions (the duration of the high water period when ships can approach the berths) or seasonality of cargo (for example, agricultural products). Usually, temporary ports of small size are, rather, marinas. Temporary ports, built to serve large construction projects and operating for only a few years, sometimes receive millions of tons of cargo during their operation.

In relation to the water level, seaports are open and closed. Closed seaports are located in basins separated from the sea by locks or semi-locks. Due to this, the amplitude of tidal fluctuations decreases in a closed water area by maintaining an elevated water level, which significantly reduces the cost of berthing facilities and facilitates the handling of ships.

5.2. Ports of the Russian Arctic Zone: Current Status and Development Prospects

By the year 2035, the Northern Sea Route (NSR) is expected to be operational throughout the entire year, and a safe transport corridor. The single operator of the NSR, Rosatom State Corporation, is formulating a development strategy for the Arctic route and adjacent territories. The Northern Sea Route's progress will be jointly managed by three entities—Rosatom, the Ministry of Transport, and the Ministry of Development for the Far East and the Arctic. This strategy consists of three implementation phases. Between 2019 and 2024, the primary objective is to attain 80 million tons of cargo throughput on the Northern Sea Route and initiate eastward transportation. By 2030, with the aid of new nuclear icebreakers and upgraded port infrastructure, year-round navigation across the entire NSR area will be established. In the final phase, by 2035, the cargo throughput increase could reach 130–170 million tons.

The Arctic's advancement is a continuous, multi-phased endeavor encompassing various infrastructural and technological objectives, and the region's future relies on their realization. The cultivation of potential zones should occur simultaneously with the upkeep and modernization of present infrastructure, all while fostering conditions for the population to live comfortably beyond the industrial areas, which is closely related to risk management. A significant part of infrastructure projects in the Arctic is associated with the realization of its industrial potential, which is accompanied by the development of the transport industry, including the port infrastructure of the NSR.

The warming of the Arctic in many areas is likely to facilitate access to offshore deposits and lead to an increase in maritime traffic. Climate change can significantly affect ice conditions, especially in the shallow seas of the Arctic shelf, where the routes of the Northern Sea Route pass. However, the ice-free period may become more stormy, and the displacement of ice masses and appearance of icebergs will create additional risk factors for sea transportation and hydrocarbon production. A decrease in the Arctic seas and an increase in the frequency and strength of storm surges, combined with an increase in sea level, can lead to increased coastal erosion, resulting in possible complications for coastal infrastructure (ports, storage facilities, terminals). It should be noted that, along with the increasing availability of shipping routes, overland transportation routes and pipelines may be destroyed due to thawing of the soil in the permafrost zone. As the frozen ground melts, roads, pipelines, airports and engineering infrastructure structures will deform, requiring repairs, additional maintenance, and new design approaches, which will increase construction and operating costs.

Russia has a long history of presence in the Arctic, conducting economic activities not only on land, but also on the shelf. The largest projects are being implemented on land in the mining (Kola Peninsula, Taimyr, Northeast Yakutia, Chukotka) and the oil and gas sectors (the Yamal Peninsula is undergoing active development, and the Gydan Peninsula is being cultivated); the nation has gained hands-on experience executing oil and gas initiatives on the Arctic shelf. The exploitation of resources from the shelf and the Arctic seas coastline requires the establishment of efficient transport and engineering infrastructure capable of operating under harsh environmental conditions. The transport scheme created for the development of the Western Arctic Shelf covers the shelf and the coast of the Barents, White, Pechora and Kara Seas. Currently, three transport projects are functioning steadily: the Lukoil terminal in Varandei, the shipment of oil from Kolguev

Island and the supply of oil from the Gulf of Ob. It is obvious that the development of hydrocarbon deposits will take place using the Northern Sea Route, and the volume of transportation will steadily grow.

The existing ports (Figure 5, Table 1) of the Arctic Basin (Amderma, Anadyr, Beringovsky, Dixon, Dudinka, Igarka, Mezen, Naryan-Mar, Onega, Pevek, Providenia, Tiksi, Khatanga, Egvekinot) are an integral part of the AMTS and intermediate points to ensure safe navigation and bunkering of transport vessels following according to the NSR. With the increase in the extraction of natural resources of the north and the intensity of shipping, we should expect an increase in the interest of local authorities in the development of port facilities not only for the export of natural resources, but also for the import of necessary products to ensure the livelihoods of people in the Far North and the introduction of new technology.

Figure 5. Map of the ports of the land territories of the Arctic zone of the Russian Federation.

Six major investment projects will be implemented in the Arctic zone of the Russian Federation with state support. These include the creation of a mining and metallurgical combine in the Murmansk region, the expansion of the Siradasai coal deposit in Taimyr and the launch of an enterprise for the extraction and processing of lead–zinc ore on the Southern island of the Novaya Zemlya archipelago. Other projects include a specialized deep-water terminal for transshipment of mineral fertilizers in the port of Murmansk, a salmon and trout breeding plant in the Murmansk region, as well as technological modernization of the Vitino port and the Belomorskaya oil storage facility. It is expected that the total volume of investments in these projects will exceed RUB 200 billion (USD 2.07 billion on 21st September 2023). This decision will increase the investment attractiveness of the Arctic, positively affect the socio-economic conditions of the region and improve the quality of life of local residents in the region as a whole.

Table 1. Characteristics of Arctic ports.

Region	Port	The Area of the Seaport Territory (ha)	The Area of the Seaport Water Area (km^2)	Number of Berths/Piers	Length of the Berthing Front of the Seaport (p.m)	Maximum Dimensions of Vessels Entering the Port (m)			The Period of Navigation in the Seaport
						Precipitation	Length	Width	
Ports of the Western Arctic	Murmansk	645.9	53.7	111/2	13246.48	Not limited			year-round
	Arkhangelsk	215.26	1120	75/0	8884.14	9.2	190	30	year-round
	Kandalaksha	25.44	5.09	5/0	584.45	9.8	200	33	year-round
	Vitino	18.66	11.59	4/0	512	11.1	230	32.2	year-round
	Onega	2.68	845.59	7/0	880	13.6	242	32.4	year-round
	Mezen	191	191	3/0	215	4.2	120	20	01.05–01.10
	Varandei	1.47	24.98	2/0	199.86	3.5	120	15	01.06–30.12
	Naryan-Mar	22.5697	5.6256	6/0	730.66	Mixed-navigation vessels (river–sea)/sea vessels			June–November
						3.6/3.6	114/90	14/16	
	Sabetta	179.5	1177	11/0	2 365.8	12	315	50	year-round
	Dudinka	24.92	30.22	9/0	1 723.6	11.8	260.3	32.2	01.01–20.05, 15.06–31.12
	Dixon	4.77	0.182	2/0	243	8.0	100	20	June–October
	Khatanga	10.62	3.70	5/0	400	4.17	136	16.5	June–October
Ports of the Eastern Arctic	Tiksi	7.29	96.78	2/0	315.0	3.9	129.5	15.8	15.07–30.09
	Pevek	19	8.9	3/0	500	9	172.2	24.55	03.07–25.10
	Anadyr	11.89	45.33	6/0	686	7	177	25	01.07–01.10
	Provideniya	12.7	13.02	4/0	350.82	10	200	24	01.06–01.12
	Egvekinot	7.17	5.75	2/0	570.62	7.5	150	21	July–November
	Beringovsky	22.12	47.07	4/0	269	13	190	33	01.07–01.10

The Yamal Peninsula, located in the Yamalo-Nenets Autonomous Okrug (Figure 6), is among Russia's most crucial strategic regions for oil and gas, the industrial development of the fields of which, as well as the adjacent waters, will ensure an increase in gas production, as well the volume of cargo transshipment through Sabetta Port, which is projected to amount to 30 million tons in 2030. To fill the NSR with cargo flows, the resource base and port infrastructure will need to be developed. Today, the ports of Dudinka and Sabetta are operating, including the "Gates of the Arctic" terminal of Gazprom Neft in the Gulf of Ob.

Figure 6. The Yamalo-Nenets Autonomous Okrug.

The transshipment of oil and petroleum products in the Arctic is associated with the development of ports such as Varandey (oil, general cargo), Kharasaway (oil and gas condensate), Vitino (oil, petroleum products, condensate), etc. The Arctic seaport of Varandey is located on the coast of the Barents Sea in the area of the Varandey Bay and is intended for the export by sea of oil produced in the north of the Nenets Autonomous Okrug. Lukoil has created and successfully operates the Varandey oil shipping terminal in the Barents Sea, with an estimated throughput capacity of 12 million tons per year. Varandey receives a year-round ice-class bulk fleet with a length of up to 258 m, a width of up to 34 m and a draft of up to 14 m. On the eastern shore of the Varandeysky Shar Strait, there is a cargo terminal with a 200 m long mooring wall, which is used for transshipment of general cargo in summer, capable of receiving vessels with a draft of up to 2.6 m and a length of up to 120 m.

An LNG transshipment terminal is planned to be built in the Urals, 50 km from Murmansk, which will increase the efficiency of LNG delivery from the existing Yamal LNG and Arctic LNG-2 plants. Among the key seaports in the Arctic, including those related to the implementation of promising projects, we can name the Arkhangelsk commercial sea port of year-round navigation, which has a capacity of up to 100 thousand tons and transshipment of all types of cargo: containers, timber, cardboard, paper, pulp, coal, oil, and export–import cargo.

In the Nenets Autonomous Okrug, a project is being developed for the deep-sea ice-free port of Indiga, focused on the export of up to 50 million tons of coal, as well as the Sosnogorsk–Indiga railway, associated with the Indiga–Ukhta–Perm Barentskomur project. A total of 70 million tons of cargo can be exported through the port of Indiga along the Northern Sea Route, of which 50 million tons are coal from Kuzbass, whose production is growing, and it is impossible to export everything to the east due to infrastructure restrictions.

The construction and reconstruction of infrastructure facilities is planned in the Dixon seaport: the Chaika coal terminal and the Tanalau oil terminal (Payakhskoye and Severo-Payakhskoye fields). The construction of a new port is necessary for the transshipment of coal mined at the Lemberova River site on Taimyr. Chaika will be the first deep-water coal terminal in the Arctic zone of Russia. The planned capacity of the terminal is over 10 million tons of coal per year. The Tiksi seaport handles food, general construction cargo, containers, coal, roundwood, forest products, petroleum products and cargo delivery to the Asia–Pacific countries.

Provideniya is a seaport of federal significance, which has a geostrategic advantage; represents a point of formation of a caravan of ships following the icebreakers along the NSR; has a cargo mainly of diesel fuel, coal, food and building materials; and accepts cruise ships.

The seaport of Pevek has the deepest berths and is the most mechanized port. The main types of cargo are general, container, coal, sand, crushed stone and light oil products. An infrastructure modernization project is being implemented.

A promising project of the deep-sea port "Severny" has been developed. The terminal in Sever Bay is planned by Neftegazholding to ship oil from the Payakh group of fields located on the Taimyr Peninsula. The design capacity of the terminal is 7.5 million tons per year.

The economic growth in the Arctic zone, underpinned by its isolation from the primary industrial areas of the country, requires the construction of an extensive system of railways and highways for two main purposes: to sustain considerable mining activities and to provide essential supplies to the Arctic regions. A number of major initiatives are focused on developing transportation infrastructure within the mainland portion of the Arctic zone.

Murmansk Transport Hub involves the establishment of transportation facilities along the western coast of Kola Bay, encompassing coal and oil terminals as well as the Sevodny–Lavna rail connection.

As shipping activity in the Arctic Ocean increases (anticipating an 80 million ton growth in cargo traffic along the Northern Sea Route by 2025), the modernization and expansion of both the railway network and icebreaker fleet become necessary. The Yuzhno-Tambeyskoye gas condensate field (Yamal LNG) development and the construction of Sabetta port on Yamal have served as catalysts for the growth of cargo transport along the NSR.

The Northern Latitudinal Passage, a railway within the Yamalo-Nenets Autonomous Okrug (Ob–Salekhard–Nadym–Novy Urengoy–Korotchaevo), is aimed at connecting the Northern Railway with the Sverdlovsk Railway in the future, providing a direct route to the Ural's industrial enterprises. As such, it functions as a supplementary transportation corridor, ensuring essential logistics for the advancement of shipping in the northern seas.

The "Bovanenkovo-Sabetta" railway, spanning 170 km, aims to link the Northern and Sverdlovsk Railways to the port of Sabetta on Yamal, serving as a natural extension of the "Northern Latitudinal Course."

The "Belkomur" railway ("White Sea-Komi-Ural") is intended to link the Perm Region and the Komi Republic, extending through Arkhangelsk to the White Sea. Its projected length is approximately 1200 km.

The "Barentskomur" railway ("Barents Sea-Komi-Ural") is designed to establish a connection between the port of Indiga (Nenets Autonomous Okrug), Sosnogorsk (Komi Republic), Midnight (Sverdlovsk region) and Surgut. The estimated total length of the railway is around 1200 km.

The "Karskomur" refers to the railway line extension from Vorkuta, reaching the Arcturus port on the Kara Sea (roughly 200 km in length).

The proposal outlines the execution of initiatives under the Federal Project "Northern Sea Route," which is part of an extensive plan for modernizing and extending core infrastructure until 2024. Additionally, the plan encompasses measures targeting the enhancement of the region's resource foundation and the development of the Northern Sea Route itself: the development of parameters for the development of the raw material base; the development of a program for the development and state support of domestic shipbuilding for the construction of modern cargo ships; the development of navigation, hydrographic, hydrometeorological, rescue, communication and information infrastructure of the NSR; and the development of a system of centralized operational and tactical management of year-round navigation throughout the NSR water area on the basis of the creation of a single dispatch center for navigation management on the NSR and the organization of transportation on a regular basis.

5.3. Risks in the Expansion of Shipping in the Arctic: Negative Consequences of Port Activities

Currently, a collection of ontologies categorized as informal ontologies is being created. These ontologies emerge from discussions and refinements of terms and definitions, pinpointing fundamental ideas, and outlining connections between concepts. Given their purpose, these ontologies have a practical nature, as they illustrate a conceptual model to analyze human-induced influence on the natural environment stemming from port operations. To enhance comprehensibility, these ontologies are visually represented, facilitating collaboration among professionals from various fields.

Every human endeavor has a connection to the human-induced influence on the environment. This anthropogenic effect results in alterations to the natural environment, introducing new elements such as pollution. Pollution affects the atmosphere, soil, water, plants, animals and microorganisms. The origin of this pollution can be traced back to industrial enterprises, encompassing energy and municipal infrastructures.

In the literature [61], anthropogenic factors are classified based on their characteristics:

(1) By their nature—mechanical, physical or chemical;
(2) By their physical properties—substance, process, phenomenon and object;
(3) According to the stability of changes they cause in nature—temporary reversible changes, relatively irreversible changes, absolutely irreversible changes and anthropogenic stress on ecosystems;
(4) Based on the ability to accumulate—either at the time of production or over an extended period;
(5) Determined by the frequency—as either a continuous, periodic or sporadic factor;
(6) According to the ability to migrate—non-migrating, migrating with the flow of air or water, migrating with means of production or migrating independently.

The human-induced element is responsible for the anthropogenic influence on the natural environment, stemming from the processes and conditions of an entity's operation and its specific attributes. When considering port operations, such factors include emissions, waste, radiation, noise, vibrations and more. The scope of the anthropogenic element relies on the variety and nature of the resources, as well as the techniques employed by the entity in question.

The anthropogenic influence stems from human-induced factors, resulting from economic or other human actions on components of the natural environment. Human-induced factors of port installations exert physical, chemical, biological, electromagnetic and noise influences on diverse aspects of the natural world. The degree of anthropogenic effect is ascertained by the human-generated strain, which relies on the intensity of the factor, environmental conditions and the duration of exposure.

Human-caused contamination arises from alterations to the natural environment's components due to anthropogenic influences. The extent of pollution relies on the human-related burden and establishes the amount of harmful substances present in the environmental elements. The level of pollution is identified by the makeup of detrimental substances, the capacity for adapting to human-induced effects, and the impact's duration.

Anthropogenic pollution results in various consequences, including the seizure of territory, depletion of land, landscape disturbance, destruction of vegetation cover, pollution and drying of water bodies, acidification of soil in adjacent territories, animal and human diseases, etc. Figure 7 demonstrates the main interrelationships of the basic concepts.

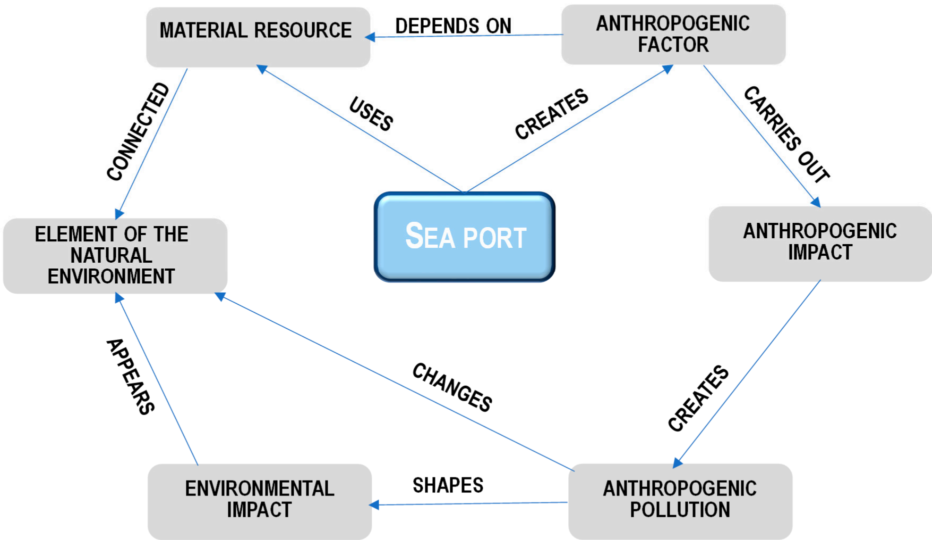

Figure 7. Meta-ontology of the impact of the port's facilities on the natural environment.

In this study, these concepts are considered as the basic classes of meta-ontology, which is the basis for a more detailed consideration of the concepts of the next levels of the ontology system being developed.

Therefore, a comprehensive examination of each concept enables one to consider all the details within the subject area, categorize them and establish connections to acquire pertinent information.

The most important concept is the anthropogenic factor, which is one of the classes in the ontology presented in Figure 8 which itself demonstrates other concepts related to the research being carried out and related to the anthropogenic factor. Firstly, the anthropogenic factor arises as a result of the activity of an energy facility and depends on the energy resource used (its type and qualitative characteristics).

Anthropogenic factors include emission, discharge, waste, noise, radiation, etc. The anthropogenic factor exhibits specific properties, including exposure frequency and migratory ability, which should be considered when evaluating its impact on the environment. As mentioned above, the influence of the anthropogenic factor is carried out by anthropogenic impact and has a quantitative measure, which is characterized by quantitative emission indicators.

Analogous specifics are being created for each utilized concept. As mentioned previously, the notion of human-induced contamination is an outcome of anthropogenic influence, which subsequently shapes the ramifications of such pollution. The effect on a component of the natural environment is gauged by the pollution level, relying on human-related strain. Simultaneously, it is crucial to consider the characteristics of cyclical occurrence and accumulation potential, as depicted in Figure 9.

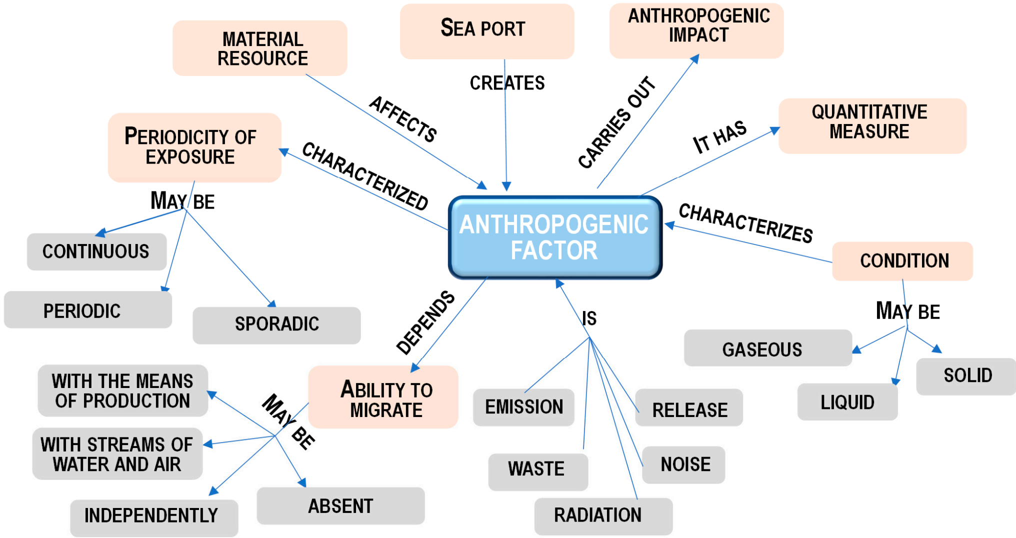

Figure 8. Ontology of the anthropogenic factor.

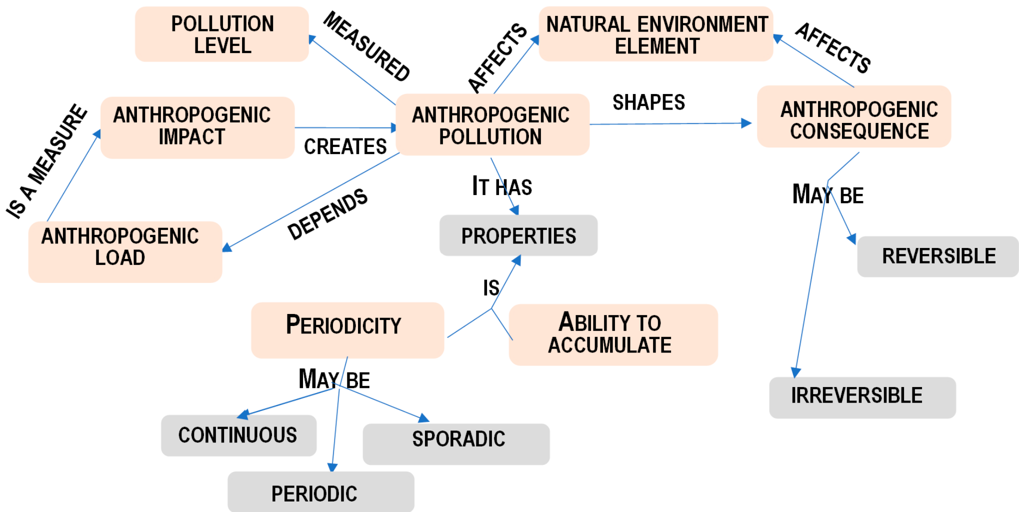

Figure 9. Ontology of anthropogenic pollution.

Therefore, a meticulous examination of all concepts permits one to consider all the details within the subject area, categorize them and establish connections for selecting pertinent information.

In subsequent layers of the ontology framework, the object types, along with their technical and operational attributes required for executing assessment methods of their effects on the natural environment, are examined. The established ontology network serves as the foundation for an intelligent decision support system as well as the construction of databases and knowledge repositories that facilitate the creation and operation of a risk management system.

The risk does not exist by itself, but is considered in the context of a valuable resource (asset). Often the concept of "risk" is confused with the concept of "threat". A threat is a potential occurrence of an adverse event that damages the protection mechanisms with some degree of destructiveness or directly affects a valuable resource, which leads to negative consequences. The consequences can be expressed in the form of financial, material, moral, reputational or other damage.

As noted earlier, the value of the risk level is used by the decision maker (risk manager) to select a protection strategy. The following threat protection strategies were identified:

1. Risk reduction by lowering the level of threat implementation conditions (vulnerabilities) through the use of protection mechanisms;
2. Risk prevention by avoiding the threat or eliminating the source of the threat;
3. Acceptance of negative consequences and absence of any actions to reduce the level of risk or to transfer risk, i.e., full or partial transfer of responsibility for the consequences of the realization of an adverse event to third parties (insurance).

The ontological model in Figure 10 reflects the relationship between the main concepts and the risk management component of the integrated port safety system. It is, on the one hand, quite universal, since the concepts included in it are invariant with respect to various definitions of risk; on the other hand, the semantic meaning of concepts can be easily adapted to a specific subject area.

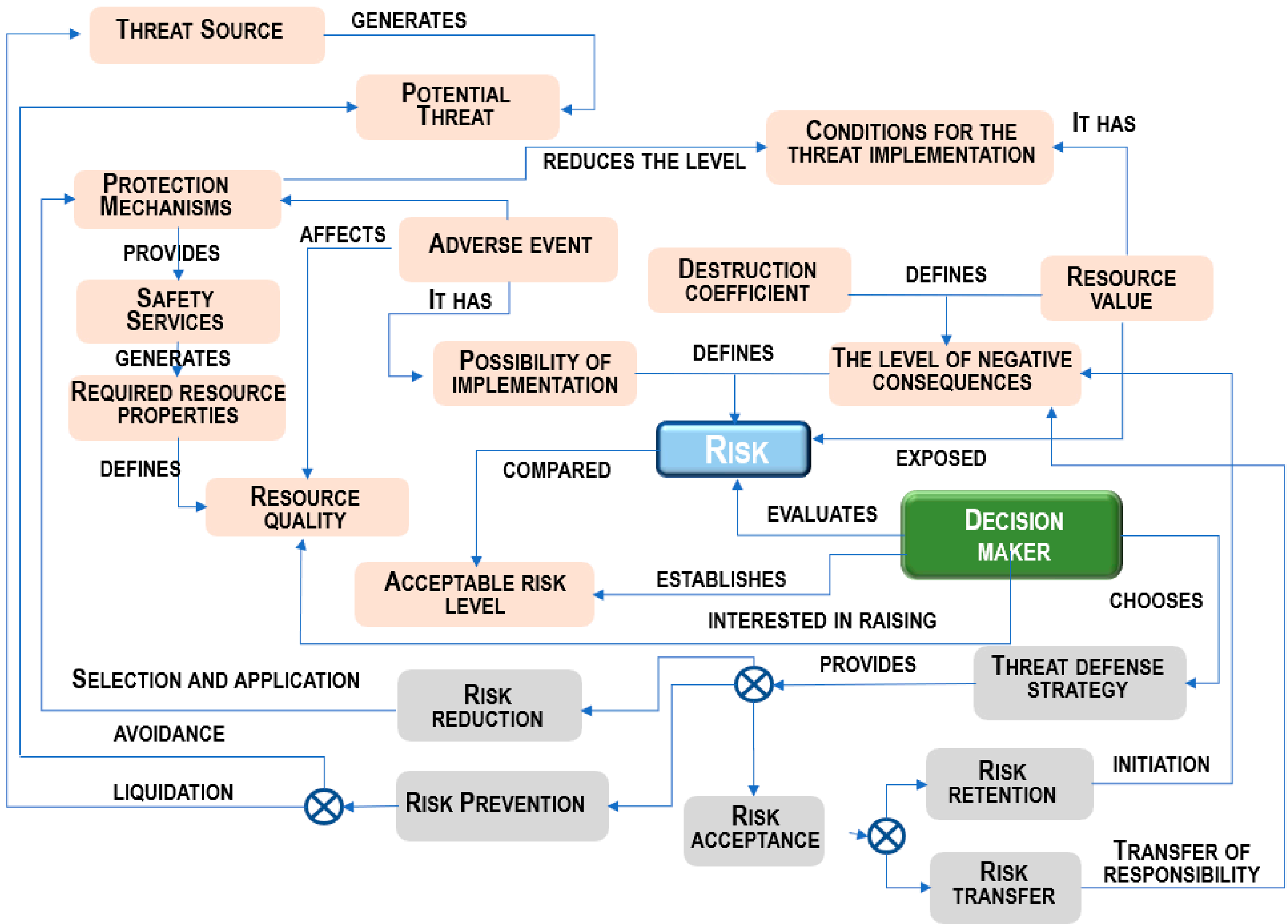

Figure 10. Ontological model of the risk assessment process.

So, for example, Table 2 shows the interpretation of the concepts of the ontological model in the assessment of environmental and information safety.

The proposed ontologies can be used as an intellectual basis for the "smart port" model, which helps support decision making within the framework of managing basic business processes as well as allowing for condition monitoring and predictive repair of port infrastructure using forecasting methods. The concept of a "smart port" will help not only improve the infrastructure of the Arctic ports by automating basic operations, but also reduce the risks of delays in the provision of services and the costs of repairing infrastructure based on a risk management system. As practical proposals, managers and politicians are offered the development of incentive and supporting measures related to the digitalization of infrastructure project management systems, which will allow the implementation of the proposed concept of a risk management system based on ontological engineering. Further research will be related to the assessment of the anthropogenic load of infrastructure facilities based on simulation modeling.

Table 2. Semantic interpretation of the concepts of the ontological model.

Risk	Environmental Risk	Information Safety Risk
Potential threat	Natural (man-made, anthropogenic) danger	Threat
Conditions for the implementation of the threat	Vulnerability of the environment	Vulnerability
Adverse event	Negative impact on the environment	Attack
Consequences of the occurrence of the event	Adverse changes in the natural environment	Damage
Valuable resources	Natural environment	Information assets
Resource quality	Environmental quality	Quality of information
Required resource properties	Necessary environmental properties	Information safety properties
Protection mechanisms	Environmental protection measures	Information protection mechanisms

6. Conclusions

Being a strategic direction of development, the Russian Arctic territories require a competent and sustainable approach to their development, including sea port infrastructure, based on the postulates and principles of the "blue economy". In this paper, we analyzed ways to safely use the Arctic water potential for the Russian Arctic's sustainable development. The ontological models created within the framework of engineering are universal for any type of port and can be used to build a risk management system. The main task in the development of port infrastructure in the Arctic zone is to maintain the ecological balance and control the anthropological impact. Therefore, the first vector of control in the risk management system is environmental, which allows one, within the framework of an environmentally friendly strategy, to monitor and minimize the negative impact on the environment, preventing adverse changes in the ecosystem. The implementation of these initiatives is necessary through a new system of technical and technological solutions, known as the "smart port" concept. This new type of port is a combination of the latest advances in information technology with modern management practices through the digitalization of processes and systems. On the other hand, the developed ontology system is the basis for an intelligent decision support system and the creation of databases and knowledge bases that serve to create and work with a risk management system. Therefore, the second vector of control in the risk management system is information security. These principles were considered when building an ontological model of the risk assessment process. Based on the information accumulated in the databases during the operation of each specific port, the content of management activities will be developed in the implementation of the risk management policy; however, the risk management mechanism itself, in accordance with the developed system of interconnected ontologies, remains unchanged.

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