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Designing a Ship-Generated Waste Management Plan According to the Model-Based Systems Engineering Approach

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Abstract:

Purpose: *The main objective of the paper is to present a new approach in planning waste management on commercial ships, based on the author's model i.e., Planning to Improve Efficiency of Management (PIEWM) created on the basis of GOPRR (Graph-Object-Property-Relationship-Role).*
Design/methodology/approach: *The paper presents issues concerning the planning of waste management on commercial ships. In the research conducted, the Model Based-System Engineering (MBSE) has been applied, which makes it possible to digitise the optimisation of decisions concerning designing and checking the correctness of operation of particular functions of the processes carried out.*
Findings: *Planning to Improve Efficiency of Management (PIEWM) is an information system that can be used to plan shipboard waste management in international shipping in order to reduce the negative environmental impact of sea-going vessels.*
Practical Implications: *The paper presents how systems engineering and domain modelling can be used to develop a concept and at the same time prototype a tool for designing improvement plans for the efficiency of waste management.*
Originality/value: *This paper presents a new approach to shipboard waste management planning using MBSE.*

Keywords: *Sustainable ship waste management, maritime transport, systems optimisation, Model-Based Systems Engineering (MBSE), metamodeling.*

JEL classification: *Q01, Q53, L91, M15, C63.*

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1. Introduction

During the operation of a ship, a huge number of different pollutants are generated, which originate from the propulsion equipment, exhaust emissions, are cargo residues or constitute domestic pollutants (with less environmental impact) (Kaup *et al.*, 2019). Most of the waste generated by the ships is very dangerous for living organisms and aquatic ecosystems, as it destroys the ecological and aesthetic values of the marine environment and poses a threat to human health and life (Deja *et al.*, 2021). Currently, even the most modern ships are producers of many types of environmentally harmful waste. Ocean and sea waters, as transport routes, are becoming more and more exposed to various types of pollution (Balić *et al.*, 2019) generated by vessels, mainly due to the increase in the amount of cargo transported using this branch of transport (Butt, 2007; Deja *et al*., 2018).

In response to the growing environmental problems, carriers and ship owners are forced to look for solutions that would allow them to reduce the negative impact of sea-going vessels on the environment which is generated during their operation. It is important here to support the institutions supervising water transport in terms of creating international legal provisions, which is the first step in protecting the marine environment and, at the same time, taking responsibility for its violation. The next step is for the crews of commercial vessels to follow procedures for the safe, reliable and environmentally friendly operation of vessels (Kaup *et al.*, 2021). Yet another way to reduce the degrading impact of ship operation on the aquatic environment is to propose system solutions relating to individual activities and processes carried out during ship operation both in port and at sea, such as the neutralisation and delivery of waste, the reception of stores and the disposal of cargo residues. These activities result directly from the ship's transport tasks, but their number, scope and nature of work depend on, among other things, the type and size of the ship, its functional-spatial solutions, the number of crew members or the range and region of operation (Pereza *et al.*, 2017; Butt, 2007; Sanches *et al.*, 2020).

Sensible waste management on ships may be directly reflected not only in the improvement of the marine environment, but also in the financial results achieved by the carriers, which will consequently allow for greater dissemination of the proposed solutions in this respect. Therefore, it is advisable to search for system possibilities and, by using selected IT tools, to develop solutions for planning waste management on commercial ships, which will be carried out in a sustainable way and will bring measurable economic benefits.

The paper presents an IT tool that can be used in planning waste management on commercial ships, covering in its scope the processes of collection, recovery and neutralization of waste, including also supervision of such activities and waste disposal sites, etc. The application of such a solution will allow for full and continuous supervision of the activities carried out on commercial ships and will

also make it possible to develop and implement an environmental strategy for a given ship for the following years of its operation.

The aim of this article is to present a new approach to planning waste management on commercial ships, based on an original model, i.e., Planning to Improve Efficiency of Waste Management (PIEWM) created on the basis of GOPRR (Graph-Object-Property-Relationship-Role). The research was conducted on the example of a container ship with a capacity of 4300 TEU.

2. Theoretical Aspects of Designing a Planning Tool to Improve Efficiency of Waste Management

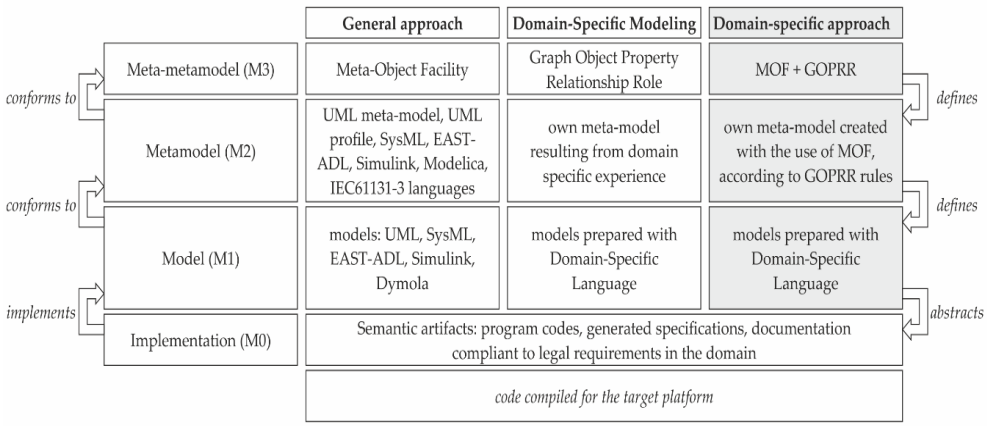
Providing continuity of processes, precise knowledge of their specifications or the ability to track individual works within their scope are just some of the functions that are implemented by solutions whose concept is based on Systems Engineering (Pietrusewicz, 2019). The more complex a technical system is, the greater the complexity of its processes increases. Additionally, taking into account the changing legal conditions, it is difficult to ensure comprehensive implementation of the required processes while achieving low costs, high quality and a high level of safety and a high level of safety. Systems based on numerous documents with many specifications of design and production requirements can be significantly improved with MBSE (Model-Based System Engineering). This method describes all requirements and specifications of the final products and coordinates all related activities.

As product complexity increases, the need to improve the design process of model-based systems becomes increasingly important. Model-Based Systems Engineering (MBSE) enables distributed teams to collaboratively analyse requirements, optimise design decisions and verify the correct operation of specific features, or to automate the delivery of solutions. Model-Based System Engineering is a set of methods and tools thanks to which complex, multidimensional design problems, usually resulting in the source code of devices or another version of documentation satisfying needs of various stakeholders, may be solved in an easy way thanks to decomposition into simple, usually one-dimensional issues. These models are powerful tools for describing the structure, behaviour and properties of designed systems. The issue discussed in this paper (i.e., Planning to Improve Efficiency of Waste Management) requires the development of an architecture model, including:

- structures of Planning to Improve Efficiency of Waste Management (PIEWM),
- the activities that comprise it, together with the parameters that describe them,
- a documentation generator that eliminates the need for the planner to spend time on the final version of PIEWM.

As part of the design work, a framework structure is developed (a modelling tool consisting of a metamodel, a diagram structure design and a documentation generator). The paper proposes the GOPRR approach (Kelly *et al*., 2008). Metamodels are used to describe the organisation and structure of the created models. Meta-metamodels (M3) are a formal description of metamodels (M2), they define the rules applied in the metamodelling process (M2). Metamodel (M2) describes the syntax of models (M1), additionally due to a variety of extensions and additional rules metamodels (M2), define the semantics of models (M1). This layered approach to the metamodelling is shown in Figure 1.

Figure 1. *Layers of modelling*

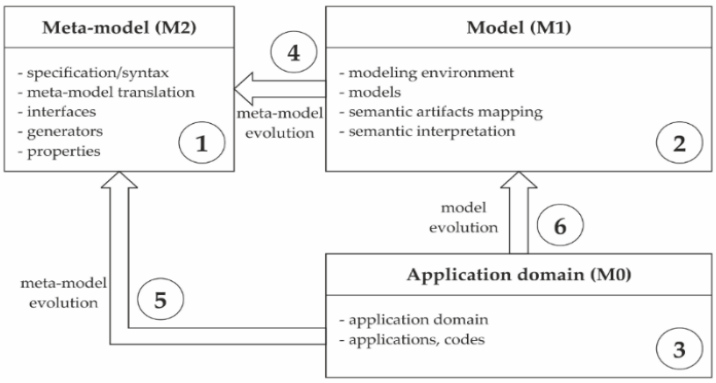


Source: *Pietrusewicz, 2019. Metamodelling for Design of Mechatronic and Cyber-Physical Systems.*

At the metamodel level (Pietrusewicz, 2019), the GOPRR approach (M3) was used. A summary of the developed metamodel (M2) is presented in section no 7 (EWM design framework of) this paper. The selected figures show the elements of the model (M1) for Planning to Improve Efficiency of Management (PIEWM). Thanks to the documentation generator prepared as part of the design work (both as part of the modelling objects for the improvement of the design work and as part of the complete plan), the editing phase of the semantic artefact (M0) was completely eliminated, which in this work represents a plan for improving efficiency of waste management.

The work on metamodelling projects is contained in a cycle, the course of which is shown in Figure 2. The design processes which use the metamodelling approach (e.g. domain-specific languages for modelling of effective waste management planning) start with determining the domain and its metatypes (stereotypes). They are defined with the use of metamodel (M3) in software solutions dedicated to metamodel (M2) creation (Pietrusewicz, 2019).

Figure 2. *The design process of metamodelling (creation of domain-specific modelling languages). Metamodelling design process. (1) metamodelling tools; (2) modeling tools; (3) solution, i.e., generated documentation; (4,5) evolution of metamodel; (6) evolution of model*



Source: *Pietrusewicz, 2019. Metamodelling for Design of Mechatronic and Cyber-Physical Systems.*

3. Methodology

The main objective of the article is to present the possibility of using the MBSE approach for waste management planning on commercial ships, based on the author's model, i.e., Planning to Improve Efficiency of Management (PIEWM). The research in the article was conducted on the example of a container ship. In order to achieve the objective, the research activities were divided into 3 stages, including: a review of the most important research questions, an analysis of the possibilities of improving the organisation of waste management and an analysis of the results, which is presented in Figure 3.

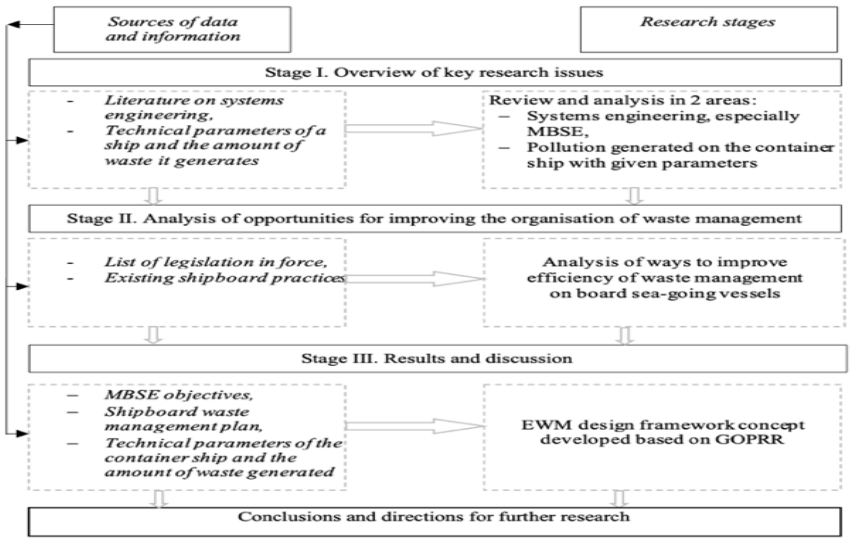
Stage one introduced the theoretical aspects of designing a planning tool to improve the efficiency of waste management, with particular reference to the Model Based Systems Engineering (MBSE) approach. This stage also analyses the pollutants generated on the container ship under study, broken down into domestic, oil, cargo, atmospheric and other pollutants. The second stage consists in the analysis of ways to improve the efficiency of waste management on a sea-going ship. Both the applicable legal acts, in terms of waste reception organisation, and the current practices on commercial ships were taken into account.

The third stage is the presentation of the EWM design framework concept, developed on the basis of GOPRR. The method used is Model Based System Engineering (MBSD), which makes it possible to optimise decision-making processes concerning the design and verification of specific functions of implemented processes. The Graph-Object-Property-Relationship-Role (GOPRR) approach was used to develop a model of the waste management planning structure. Enterprise Architect software with its MDG metamodeling technology was used to

carry out the research. The research was carried out on the example of waste management on a container ship, which is equipped with an incinerator and has no other waste treatment equipment. As a result, the author's model Planning to Improve Efficiency of Management (PIEWM) was obtained, which can be used to plan waste management on a ship in international shipping, to increase its efficiency and increase protection of the aquatic environment.

The last part of the paper presents the conclusions from the analyses carried out and indicates the directions for further research focusing on the possibilities of efficient adaptation and application of the concept developed.

Figure 3. *Research framework*



Source: *Own elaboration.*

4. Shipboard Waste Management in International Shipping

Sustainable waste management is a requirement for the ship owner and crew to operate a ship in accordance with the international legal provisions of MARPOL 73/78 and the ship owner's ISM management system. The domestic waste generated during the operation of a ship can be as harmful as oil or chemicals to the marine environment. The biggest threat is plastic, which can float for years. In any form, plastic poses a threat to the environment. Small particles are eaten by marine organisms and larger fractions pose a direct threat to marine creatures.

Every ship in international shipping is subject to specific provisions that clearly define how waste must be managed on board and how and when it must be disposed of. Sea-going ships are required to comply with applicable international legal requirements, with the MARPOL 73/78 Convention being particularly important in

this respect. The provisions set out in the document apply to all types of vessel and states party to the convention are obliged to implement the rules contained therein (Slišković *et al*. 2018). Currently the document consists of 6 annexes, each of which refers to a different source of pollution of sea waters from ships: oils, noxious liquid substances, harmful substances carried by sea in packages, sewage, rubbish, air pollutants. The provisions contained in Annexes V and VI translate both directly and indirectly into what impact the ship's crew has on waste management (Vaneeckhauteab and Fazlia, 2020).

However, it is important to note that the legal guidelines for pollution management, depending on the sailing region, may contain more strict requirements. This includes "special areas" (IMO, 1973). In addition, ships operating from ports belonging to European Union countries are required to comply with a number of requirements set out in EU directives (Kaup *et al.,* 2019). From the point of view of waste management at the interface between land and sea, there are also very often special requirements of the individual countries where the ship is operated. The huge number of regulations in force and constantly changing in this respect causes an increased interest of shipowners and carriers in system solutions in this scope.

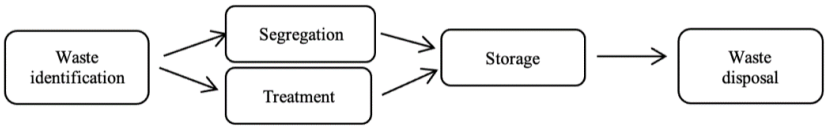
Therefore, it is advisable to apply systems engineering methods that will support the organisation of sustainable waste management on sea-going ships. The use of solutions based on models and metamodelling will make it possible, among other things, to supervise and verify the implemented processes, especially in the documentation (Kelly *et al*., 2008).

Under current international provisions, every ship of 100 gross tonnage (GT) and above and every vessel authorised to carry a minimum of 15 persons and fixed or floating platforms are required to have a *Waste Management Plan*. In addition, every ship of 400 gross tonnage (GT) and above and vessels authorised to carry 15 or more persons which are engaged in voyages to ports or are operated at marine terminals, in accordance with the standards of MARPOL 73/78, and any fixed or floating platform, must have a waste record book. Under the current guidelines, every ship of 12 metres overall length or more, and floating platforms, must be fitted with plates notifying crew and passengers of waste management requirements.

The Waste Management Plan is a document which the shipowner is responsible for preparing, in accordance with the guidelines contained in MARPOL 73/78 Annex V. The latest amendments in this regard were introduced by MEPC.277(70) which entered into force on 1 March 2018. It outlines the legal basis and model for the management of all shipboard waste. The document contains instructions on waste treatment and management, storage location and segregation. It also contains the responsibilities of the crew and the persons designated to manage waste. The Shipboard Waste Management Plan is part of the International Management System - ISM Code. Figure 4 shows the different phases of waste management on seagoing

ships in accordance with the guidelines of Resolution MEPC.295(71) and MEPC. 220(63).

Figure 4. *IMO Guidelines for Development of Waste Management Plans*



Source: *IMO, 2012 and IMO, 2017*.

Description of the individual phases:

a) *Waste identification* – is a process defined by the provisions of MARPOL73/78 (Annex V). On board the ship, a person, appointed by the company's Management System, is responsible for the application of the provisions and guidelines of the Shipboard Waste Management Plan and for the proper instruction of the crew, the identification of storage locations and the subsequent management of the waste once it has been identified.
b) *Segregation* – is carried out by crew members appointed for that purpose by the master. In respect of the ship's departments, it is carried out respectively: on deck in the places designated for that purpose by the deck department. In the superstructure by the accommodation department and by the seamen of the deck department. In the engine department by engine department seamen. All segregation is to be conducted in a location that will provide safety and protection from contamination of the ship or discharge of waste into the sea.
c) *Storage* – storage of waste takes place in a dedicated location as set out in the Shipboard Waste Management Plan. Each category is assigned a container, which is located in a designated place.
d) *Waste disposal* – waste disposal must be carried out in accordance with the detailed guidelines contained in Annex V of MARPOL 73/78 MEPC 277(70) (IMO, 2018).

5. Waste Generated on the Container Ship: A Case Study

Characteristics of the main groups of pollutants necessary for the development of the preliminary model for the container ship under study are presented in Table 1. The vessel under study is a Container Ship (Panamax) with a capacity of 4300 TEU. The vessel is 262 m long, 32 m wide, built in 2009 in Korea, DWT 51807 mt. The ship is manned by 20 crew members, divided into three departments - machinery - 8 people, deck - 11 people, catering - 3 people. The ship operates in international shipping.

Table 1. *Types of pollution on the container ship under study*

	Types of pollution	Characteristics
1.	Domestic pollution	associated with the accommodation and living conditions of persons on board ships; the amount of this pollution is closely related to the number of crew and passengers; includes all types of pollution originating in the accommodation of the ship;
2.	Oil pollution	includes oil sludge from fuel and oil separators, lubricating oil residues, water contaminated with engine oil;
3.	Cargo pollution	non-hazardous cargo residues, which mainly consist of rubbish, cargo residues remaining in bilge sumps (spills from containers);
4.	Air pollution	occur in the form of exhaust gases, wastes, oils and oil, gaseous pollutants from fire extinguishing equipment on ships, exhaust gases from main propulsion engines and auxiliary propulsion engines, leaks from container cooling systems;
5.	Other	includes paints used for hull maintenance which consist of components which pose a serious threat to the marine environment (i.e., pigment, binder, solvent), residues from the use of main engine scrubbers and auxiliary equipment.

Source: *Own elaboration based on (IMO, 1973).*

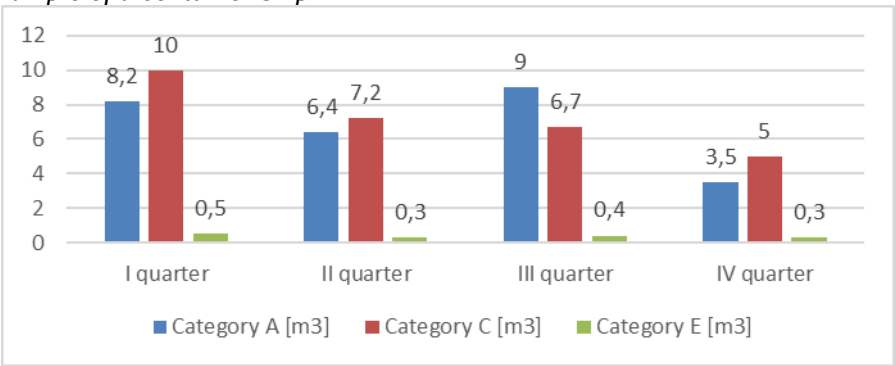
Each type of pollution presented in Table 1, occurring on the container ship under study, generates waste, which should be managed in a sustainable way. Neutralization or elimination of these pollutants often requires involvement of additional installations, devices or materials, which influences the creation of next groups of wastes. Therefore, introduction of complex solutions, both organisational and technical, for sustainable waste management on ships is so important.

On the basis of the conducted research, the figure no 5, presents a yearly summary for three waste subgroups: A (plastics), C (municipal waste e.g., paper products, rags, glass, metal, bottles, china crockery, wood, etc.), E (incinerator ashes), classified according to MARPOL 73/78 Annex V. Adopting sustainable waste management allows to reduce the amount of waste generated. The article presents the results obtained on a container ship with the above parameters in 2020, after introducing, i.a., new organisational solutions for waste management. Figure 5 shows a significant decrease in the volume of waste generated in Q4 compared to Q1 for each category mentioned. A drop of 57.32% was observed for plastics (A), 50% for municipal waste (C), and 40% for ashes (E).

Importantly, during the period under study, organisational solutions were introduced on board, such as additional training and creation of environmental awareness, to improve the efficiency of waste management on board. A significant decrease was achieved for all categories analysed by involving the crew. Particular attention should be paid to the reduction of plastics generated on board (57.32%), which was achieved, inter alia, through the proper involvement of the crew in following the developed procedures, proper collection and further treatment. It is therefore

important to develop a systematic approach so that the results in this area can be continuously improved, as well as to introduce system changes on other vessels. The following section therefore presents a modelling approach using MBSE.

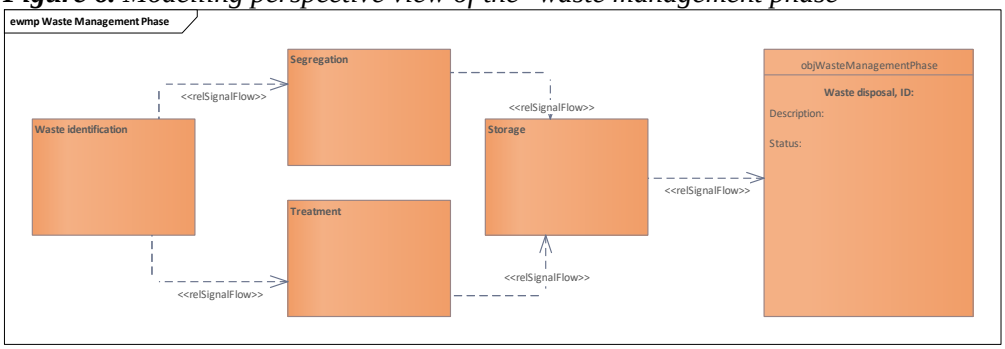
Figure 5. *Annual distribution (2020) of waste generation in m3 of categories A, C, E by example of a container ship*



Source: *Own elaboration.*

Particularly important for the transparency of the issues discussed and for the structuring of the documentation generated during the Planning to Improve Efficiency of Waste Management is the appropriate classification of the pollution generated on board, which will form the basis for the development of modelling solutions, for the concept and prototype of a graphical modelling environment. Figure 6 presents the model elements (M1) related to the definition of the waste management phases. Object obj The pollutant contains information defining the type, indicating what the pollutant results from, what it consists of and defining which waste management phase the pollutant is currently in. Obiect The Waste Management Phase indicate the source of the definition of the phase, the ship management area it covers, and recall any additional requirements to the phase definition.

Figure 6. *Modelling perspective view of the "waste management phase"*



Source: *Own elaboration.*

6. Ways to Improve the Efficiency of Waste Management on Board Seagoing Ships

The development of optimal solutions for waste management on sea-going ships is very complicated, i.a., due to a huge complexity of legal provisions depending, i.a., on the area in which shipping is carried out. The increase in importance of maritime transport in the world is inextricably linked to the increase in pollution from ships, which threatens the marine environment (Wilewska-Bien *et al.,* 2016). The relatively high costs associated with the collection and further management of waste and cargo residues from ships force the maritime industry to develop and implement new solutions which will allow to organise the negative environmental impact of waste. Moreover, they will influence the optimisation of costs connected with the waste management process. Therefore, it is important to look for solutions facilitating these processes. On the basis of conducted researches, areas of activities which should improve waste management on the ship under study could be indicated in organizational and technical terms.

a) training and environmental awareness

Crew training and environmental awareness is a key element in effective shipboard waste management.

- Crew training – provision of well-trained staff to operate complex ship systems is a key element in a smoothly functioning system. Properly trained staff is a guarantee that the provisions of the International Ship Management Code and MARPOL 73/78 will be complied with. Benefits of organising crew training with regard to Annex V and VI of the Convention:

- Annex VI - Operation of scrubbers, proper operation of the main engine and auxiliaries is closely linked to emissions reduction and accident reduction during normal vessel operation.
- Annex V – Adequate preparation provides a guarantee for the correct passage through the management phases and safe storage during operation.

- Environmental awareness - developing environmental awareness is an important and often overlooked factor in optimising waste management on board. By increasing crew awareness and directly involving every crew member in sustainable waste management, we are able to motivate the crew to be more disciplined and show concern for environmental issues.

b) Introduction of an external "operator" by the ship owner

The introduction of an external operator is intended to establish an assisted "ship" to control and improve waste management. By introducing an additional reporting system (usually weekly), which includes, i.a., data on the amount of waste

generated, its volume and the space occupied for storage on the ship. With this information, the external operator decides where and how the waste of each category will be delivered. Nowadays, when waste disposal is very costly, using an external operator who is able to arrange waste collection without the need for a direct ship, is economically viable. If we consider oily waste, the involvement of an external company outside the port infrastructure represents a significant cost reduction for the ship owner.

c) Introduction of modern technological solutions to reduce the volume of waste generated (compactors, crushers, incinerators)

The use of modern technical solutions for waste management, such as compactors, crushers, incinerators, allows to reduce the volume of generated waste, which is very important especially during long voyages. These are specialist devices that require professional handling. Processing of various types of waste using the above mentioned equipment is specifically sanctioned by the provisions of MARPOL 73/78.

d) Optimisation of supply and the appropriate choice of packaging for the products used (application of the reverse logistics concept)

Activity entirely dependent on the ship owner. The purchasing department is responsible for the correct organisation of deliveries and the use of appropriate packaging. Through proper planning, ergonomics and optimisation, the amount of packaging used can be reduced, resulting in less waste, which then has to be processed and stored on board. Another element is the use of packaging that can be recycled more easily.

7. EWM Design Framework

According to the GOPRR approach, the design of the modelling framework is divided into phases:

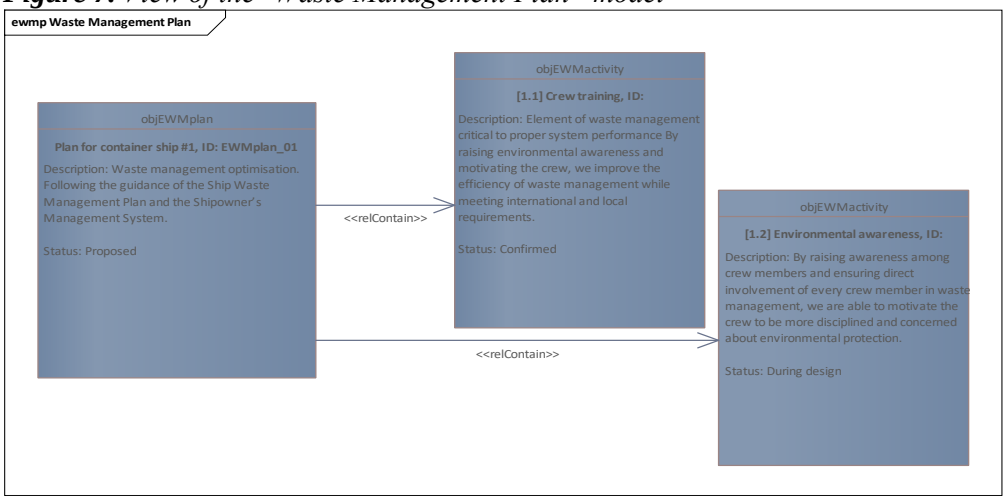
1. development of the definition of graphs (diagrams), reflecting the modelling perspectives;
2. development of object definitions and their parameters;
3. development of definitions of properties of individual objects;
4. definition of relations that occur between objects, but also graphs (possibility of nesting graphs in modelling objects);
5. port definitions, if it is necessary to model the information flow in the designed system.

The presented GOPRR approach allowed us to rapidly build a prototype of a tool for modelling and generating documentation of waste management plans for a container ship, into markdown or HTML documents. The GOPRR method is usually applied at a very early stage of metamodelling, due to the possibility of immediate

modelling, without the need to compile a modelling framework, as is the case with MDG technology known from Enterprise Architect software. In the present work, first the MetaEdit+ software was used. After initial work on metamodel and stabilization of stereotypes definitions for objects and relations ships, second metamodel has been developed with the use of Enterprise Architect, as a unique combination of GOPRR approach and utilization of modelling strengths of the Meta-Object Facility approach (Figure 1). It is innovative approach proposed in (Pietrusewicz, 2019). Figures 7 presents a sample model of a waste management plan prepared for a container ship using Enterprise Architect software.

Figure 7 presents a view of the model fragment related to the Effective Waste Management plan (*objEWMplan* data object). It consists of predefined or currently defined activities (EWM activities). Each of the activities included in the plan (*objEWMactivity*) contains a number of essential information for the whole plan: premises, persons responsible for a given activity, concrete actions, expected results and possible output indicators.

Figure 7. *View of the "Waste Management Plan" model*



Source: *Own elaboration.*

7.1 Summary EWM Design Framework

Modelling objects are grouped within the diagrams (modelling viewpoints):

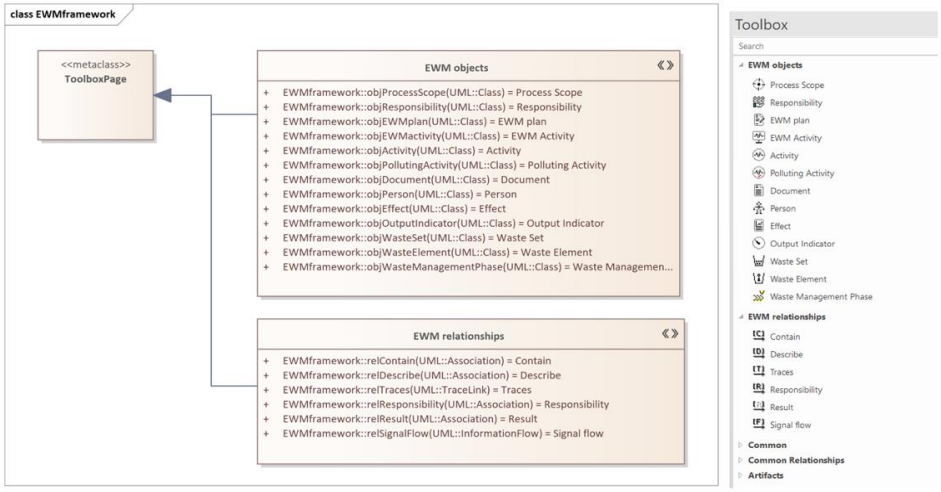
- Graph "Effective Waste Management Planning (ewmp)": *objEWMplan*, *objEWMactivity*, *objEffect*, *objActivity*, *objOutputIndicator*, *objPerson*, *objDocument*;
- Graph "Waste Types (wt)": *objWasteSet*, *objWasteElement*, *objPollutingActivity*, *objDocument*;

- Graph "Waste Management Phases (wmp)": *objWasteManagementPhase*, *objProcessScope*, *objResponsibility*, *objPerson*, *objDocument*.

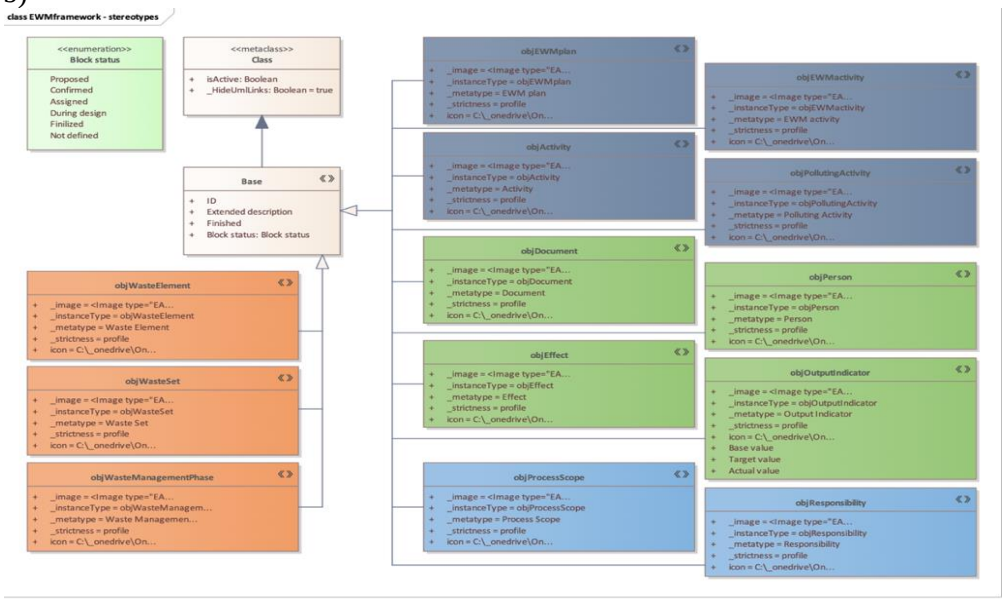
Figure 8 shows the modelling toolbox design view (icons assigned to modelling objects) along with the toolbox view of the prototype version of the tool. Figure 9 presents the definition of relationships within the modelling framework.

Figure 8. *Metamodel for modelling items (toolbox profile) (a) and domain-specific modeling language (b)*

a)

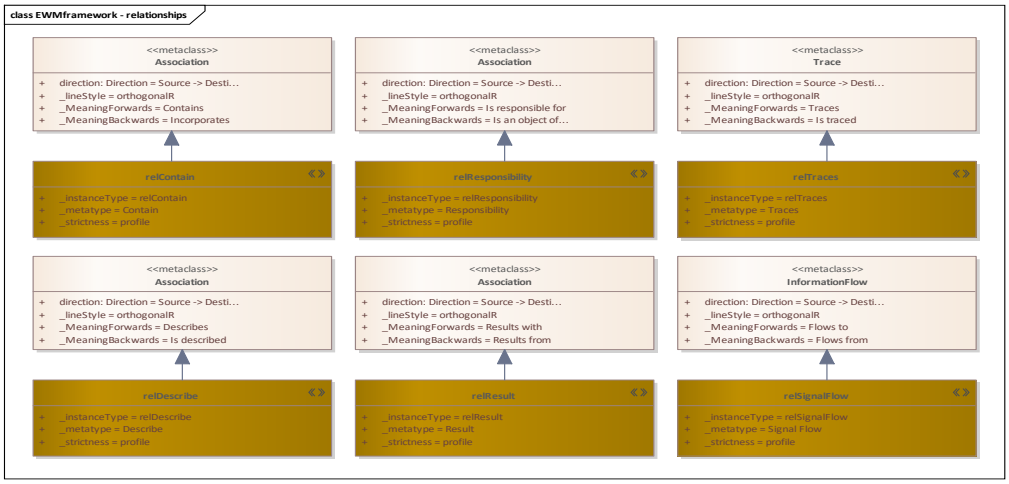


b)



Source: *Own elaboration.*

Figure 9. *Metamodel for stereotyped relationships*



Source: *Own elaboration.*

8. Conclusion

Improving waste management on sea-going ships requires extra activity and commitment from the crew, but also an up-to-date knowledge of the relevant legislation. Therefore, it is necessary to introduce solutions optimising particular processes. Significant reduction in the volume of generated waste can be achieved by improving waste management.

This paper presents how a prototype of a design tool for improvement plans of waste management efficiency can be developed through systems engineering and domain modelling a concept and at the same time. At a time when in many ports the fees for waste handover are very high or there is simply no possibility of handover, volume reduction is an important element of management. All this translates into costs that are generated by the ship. An important aspect is to relieve the crew of the extra work and functions associated with waste treatment and storage.

However, this requires additional crew training and the introduction of new procedures in the management system. This requires a system support to control the whole process. This can significantly improve efficiency and reduce the time crews have to spend treating waste. The use of any technical equipment for waste treatment can reduce the volume of waste generated. All of these elements introduced into the Management System can bring measurable benefits to the ship owner. Introducing external operators, optimising deliveries and reducing or replacing packaging with reusable (or more easily recyclable) packaging are all actions that fit into sustainable waste management on sea-going ships.

This paper presents how, through systems engineering and domain modelling, a concept and at the same time a prototype of a design tool for improvement plans regarding the efficiency of waste management can be developed. The presented concept allows robust, highly formal way for creation of waste management plan in a structured graphic way. Additionally, proposed here solution introduces functionality of automatic generation of necessary documentation, that results in much more efficient work on waste managaement plans as compared to classical document-based apporach.

The paper does not present a full analysis of the PIEWM concept, but only its outline and initial version of modeling framework. The authors are conducting further research, which will be presented in subsequent publications

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