Journal of
Marine Science and Engineering

MDPI

Article

Strategies for Green Shipbuilding Design and Production Practices Focused on Reducing Microplastic Pollution Generated during Installation of Plastic Pipes

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Abstract: In recent years, microplastic pollution has been given increasing attention in marine environments due to the hazard it poses for aquatic organisms. Plastic pipes are now being widely used in shipbuilding, and due to easy processing, they are often installed directly on ships. This includes the cutting and preparation of pipes for welding, which produces plastic debris in the immediate vicinity of the marine environment. Such plastic debris can easily become airborne, and when it is ultimately deposited into the water, it can be a contributor to marine microplastic pollution. This could be reduced if, during the design stage and outfitting stage, engineers would take into consideration ecological aspect of their design, which is currently not the case. Therefore, in this paper, suggestions for green shipbuilding practices, focused on the piping design and production phases, are presented for the possible reduction in operations with plastic pipes, with the main aim of reducing microplastic pollution. Based on these recommendations, additional economic and feasibility investigations are needed to obtain optimal results, which would be beneficial both from a manufacturing and ecological perspective.

Keywords: green shipbuilding practice; shipbuilding; microplastic pollution; plastic pipes

Citation: Lučin, B.; Čarija, Z.; Alvir, M.; Lučin, I. Strategies for Green Shipbuilding Design and Production Practices Focused on Reducing Microplastic Pollution Generated during Installation of Plastic Pipes. *J. Mar. Sci. Eng.* **2023**, *11*, 983. https://doi.org/10.3390/jmse11050983

Received: 31 March 2023
Revised: 27 April 2023
Accepted: 4 May 2023
Published: 6 May 2023

1. Introduction

One of the biggest concerns related to plastic pollution is the increase in the quantity of plastic waste that is not recycled, and that consequently breaks down into smaller pieces, namely, microplastics (MPs) and nanoplastics (NPs). MPs are considered to be plastic particles smaller than 5 mm. These can be divided into primary MPs, which are directly produced in small sizes, or secondary MPs, which are generated from larger parts of plastic debris that deteriorate into smaller pieces due to chemical or physical impact. The lower limit of a microplastic particle is 1 µm [1]. Below this size, particles are considered nanoplastics, which are investigated less frequently because of difficulty in their characterization; therefore, less information about their abundance, risk, and fate is available [2].

Considerable attention has been given to the pollution of waters [3,4] due to the fact that aquatic organisms can ingest MPs, which can then become accumulated through the food chain. Ingestion of MPs can negatively affect the growth and nutrition of animals, and an even greater concern is the possible negative impact on human health [5]. An additional major hazard is that MPs have been identified in environments inhabited by specific bacterial communities, defined as plastispheres [6], which can differ in terms of organisms from the surrounding environment. Therefore, MPs have been investigated as carriers of pathogenic and antibiotic-resistant bacteria and antibiotic-resistant genes [7]. Due to the large surface area-to-volume ratio, MPs can serve as carriers for toxic chemicals, such as heavy metals and persistent organic pollutants, in the environment [8]. Furthermore, the concentration of such chemicals in MPs might even be up to 10^5 to 10^6 times greater than in ambient seawater [9]. Considering that it is still difficult to establish the distribution and the quantity of MPs in water, it is no surprise that new methodologies, as well as the standardization of techniques, are continuously being implemented to provide more insight into the problem [10,11]. Additionally, due to variability among monitoring schedules, a comparison of the various studies is challenging [12]. Therefore, establishing comparable methods and strategies is essential to identify potential sources of pollution, so that mitigation and prevention strategies can be established.

What is concerning is that in addition to direct discharge into water bodies, MPs can undergo atmospheric transport and deposition [13,14]. Considering that MPs exhibit low densities and small sizes, they can easily be distributed and dispersed by the wind and local turbulence [15], and their deposition can ultimately occur at remote locations. This is supported by the fact that the presence of MPs has been observed at the Earth's poles [16], and MPs have also been found in the remote marine atmosphere in the North Atlantic Ocean [17]. However, there are still considerable gaps in our knowledge of this field, and future investigation into the interaction of MPs in the atmosphere, lithosphere, and hydrosphere is needed.

Shipyards and marinas have been identified as locations with high levels of MPs [18,19]. Paint fragments acting as polluting MPs have been recently reviewed in [20], where it is stated that shipping and boating activities, both on water and on dry docks, are sources of pollution. Such activities include the application of protective coating and hull cleaning. However, another important aspect that has not received much attention is the shipbuilding process. During the outfitting stage, which is a broad definition for the installation of all non-structural equipment, systems, and machinery on ship, plastic pipes are being cut and assembled on site. This can be a source of MP pollution; for example, in the work by [2], during the cutting process of PVC pipes, researchers estimated that thousands of MPs might be released from each cutting process. This is a strong indication that operations with plastic materials that are in the vicinity of the sea can be sources of MP pollution. Appropriate measures to prevent MP water pollution are imperative, resulting in the proposal of this work. To the authors' knowledge, there has not been an investigation from the perspective of improving the design process, in which a more ecologically appropriate approach is investigated. Therefore, the purpose of this paper is to propose a framework that will enable shipyards to establish green shipbuilding practices. Possibilities of the improvement of the shipbuilding process are proposed, where fewer interventions at the boat locations are needed. This can allocate operations that produce a greater quantity of debris to the warehouse, where better pollution protection can be established to reduce the possibility of MPs being deposited into the sea.

The paper is organized as follows: in the next section, the shipbuilding production process is presented, with a description of the sources of pollution, legislation implications, and a description of the current production process; in the third section, suggestions for the improvement of modeling and production stages are presented; in the fourth section, a discussion regarding the proposed solutions is given; finally, in the last section, a conclusion of the conducted work is presented.

The estimation of implementing such a strategy is presented. It can be observed that the education of engineers should not require a considerable number of resources in ideal conditions, where people with in-depth understanding and knowledge are engaged in the preparation of educational material. The main problem could be establishing communication between scientists, shipyards, and engineers, and finding appropriate people to prepare the relevant material.

2. Shipbuilding Production

2.1. Shipyards as the Pollution Sources

Depending on the main types of activities, shipyards can be divided into shipbuilding and ship repairing. Shipyards typically have dry docks, workshops, and warehouses where various industrial processes are conducted, such as metal cutting, welding, repair operations, painting, etc. Dry docks are work areas in shipyards that can be flooded to allow vessels to enter or leave. At these locations, a wide range of industrial activities are conducted, which can generate significant levels of pollution. Although there are practices for cleaning dry docks to prevent particles generated during ship construction from being discharged into nearby water [21], these measures do not prevent pollution dispersion during manufacturing operations. For example, when an old antifouling coating is removed during maintenance activities, antifouling paint particles (APPs) are created, which pose an important environmental issue [22]. Antifouling coatings are painted on the hull of a ship or boat to slow down the growth of subaquatic organisms. Considering that such organisms attached to the hull can negatively affect vessel performance and durability, antifouling coating usage is inevitable. MPs can adsorb heavy metals, such as copper (Cu) and zinc (Zn), used in antifouling paints applied to ship hulls and other fixed structures (e.g., buoys, pilings, pontoons), and thus can contain 800 times greater concentrations of metals than the surrounding seawater [23]. All of the manufacturing operations create a high level of contamination, which has been identified in soil samples taken from an abandoned shipyard location in Hong Kong [24], as a result of more than 20 years of industrial activities such as shipyard building, repair, and oil spillages. The abundance of plastic debris has been observed in the case study for the Grand Harbour of Valleta (Maltese Islands), where shipping activities within the harbor include ship repair and shipbuilding [18].

Other than direct discharge into water bodies, a considerable pollution source can be the deposition of airborne MP particles originating from production activities. MP particles deposited into marine environments can be ingested through the food chain, and airborne MP particles can be inhaled, both of which can pose a considerable health risk for humans and animals. The mechanisms of the described processes are depicted in Figure 1. Volatile organic compounds (VOCs) are air pollutants that can have an adverse effect on human health; therefore, their emissions from painting activities have been measured and estimated [25,26]. Workers of shipyard companies are highly exposed to different respiratory hazards [27]; for example, welding activities within enclosed spaces can cause respiratory problems, so adequate ventilation is needed [28]. This ventilation issue cannot always be adequately solved, and inhalation of MP particles can pose a health risk. In addition, such ventilation solutions can cause the transport of particles to coastal surface waters by deposition of airborne microplastics. Therefore, the focus should be on reducing redundant operations and allocating polluting activities to locations that can be more easily regulated. As a result, best practices for the workers' protection can be employed more efficiently.

As mentioned above, it can be observed that shipyards are considered to be pollution sources, and some processes have been identified in research papers; however, the researchers do not provide possible improvements, since they are not familiar with the production and manufacturing procedures, making it hard to identify potential improvements.

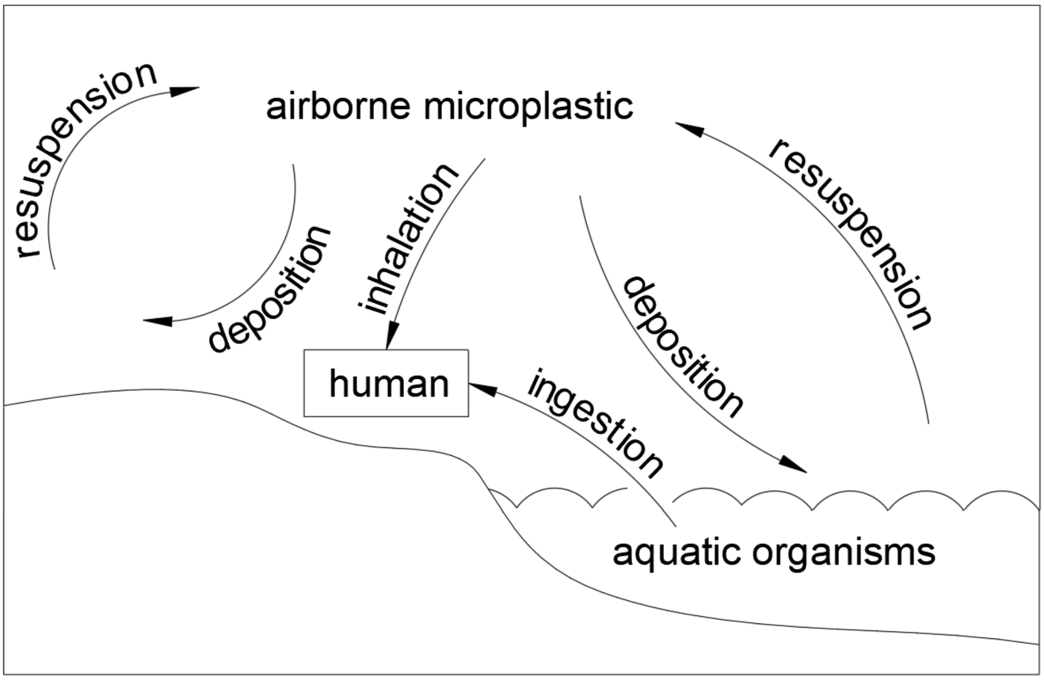

Figure 1. Overview of airborne microplastic transport paths.

2.2. Legislation Implications

Currently, the greatest emphasis in the maritime sector is on decarbonization, where the International Maritime Organization (IMO) requires, by 2050, that total greenhouse gas emissions are reduced by at least half compared to 2008. Recently, the EU's legislative bodies are proposing to include maritime emissions in the EU Emissions Trading System (ETS), which limits greenhouse gas emissions. This will require companies to monitor, report, and verify their greenhouse gas emissions on an annual basis, which can be a significant expense for shipping companies [29]. However, it is a matter of time before policymakers start to more frequently address MP pollution in the maritime sector, considering the increase in plastic and MP legislation worldwide [30,31]. Marine plastic litter has been identified as a major global issue by the United Nations [32]. To reduce discharges of waste by ships, the European Union presented the "European Strategy for Plastics in Circular economy" [33] and Directive (EU) 2019/883, urging that port facilities reduce discharges of waste by ships, indicating that this is becoming a growing concern. The EU Action Plan "Towards Zero pollution for Air, Water and Soil" states that by 2030, the EU should reduce plastic litter in the sea by 50% and MPs by 30% [34]. It is also stated that international cooperation with the IMO will be intensified, and that the Marine Strategy Framework Directive will be reviewed in 2023 to address the need to reduce plastic and other litter and contaminants. Rethink Plastic, an alliance of leading European non-government organizations, suggests that the EU should ban the intentional addition of MPs to hull paints, since antifouling coatings have been identified as prominent and previously overlooked sources of MPs [35].

All of this indicates that the maritime sector will soon need to adjust their practices. Actions that reduce MP pollution will need to be implemented if penalties will be imposed on shipyards that produce pollution greater than the chosen threshold value. Furthermore, from the experience with greenhouse gas emissions, it is only expected that the allowed levels of MP pollution will become more rigorous with time. The adjustment of production activities and implementation of various technologies for pollutant removal could require substantial investment for shipyards; therefore, the improvement of the design process, where activities that cause pollution are avoided if possible, presents a viable solution.

2.3. Current State of Outfitting Procedure

Due to novel requirements in shipbuilding for more energy-efficient, reliable, and environmentally friendly ships, shipbuilding is facing digital transformation [36]. Computer-aided design (CAD) software, such as AVEVA, ShipConstructor, Catia, etc., enable the creation of a ship-based digital prototype, where engineers provide design solutions for the outfitting procedure [37]. This also enables the creation of detailed 2D drawings that are used by the workers for production. Depending on the size and purpose of the ship (yachts, cruisers, cargo ships, etc.), there can be many different auxiliary systems, e.g., heating, ventilation, and air conditioning (HVAC) piping systems, chilled water systems, grey water systems, black water systems, etc. Systems that are mostly made of plastic and are commonly present in vessels are hot, cold, and potable water systems, as well as technical water, grey water, black water, and drain pipe systems. Modeling of ship systems by engineers requires fulfilling the criteria provided by the ship classification, register, flag state requirements, and other international standards. The greater the number and complexity of systems increases the duration of the 3D modeling stage. When shipyards evaluate their design approaches, they mainly focus on the economical aspect, such as defining principles of design solutions with respect to yard standards, reducing pipeline and cable routes, or the design of pipes with the same bending radius [38]. Considering the strong competitiveness in the shipbuilding industry and tight deadlines, it is no wonder that engineers in charge of 3D pipe modeling put their main focus on providing the final product as soon as possible. They do not take into consideration the ecological implications of their designs since there is no legislation or guidelines that require them to do so. It must be taken into consideration that considerable advancements in MP pollution research have only been made in the recent years, and there are still many questions unresolved. Therefore, it is expected that this perspective has still not been implemented in industry standards.

Modelers prepare isometrics, which are 2D drawings depicting isometric views of several pipe spools with additional information about material, dimensions, piping parts, etc. Based on the prepared documentation, workers prepare pipe spools and assemble them. Spools are larger models that consist of pipes, elbows, flanges, reducers, and other parts, which are joined in the workshop before transportation to the ship. Elbows, flanges, and reducers are pre-fabricated parts that facilitate the connection of pipes or other equipment forming a pipe system. They need to be ordered from the manufacturer, therefore, additional cost and delivery time needs to be taken into consideration. The optimization of this pipe preparation phase is important to reduce production time. When the production strategy is being evaluated, the specifics of each shipyard need to be taken into consideration. Some of the factors are vessel type, complexity, and the production of one-offs or a series of several ships. Additional factors can also include organizational structure, and social and cultural factors, such as labor cost and productivity, etc. [39]. The old technique of outfitting implies that the hull of the ship needs to be finished and subsequent outfitting operations are conducted on the ship. The novel practices suggest the implementation of advanced outfitting or pre-outfitting on a single block before they are joined. There are various benefits with this approach, such as reduced operation time and, consequently, shorter production cycle [37,40]. The pre-outfitting approach can be highly beneficial since section units and blocks are equipped in the workshops under better working conditions [41]. This implies that work is not dependent on weather or atmospheric conditions, and includes a well-lit and ventilated environment. There are also some disadvantages to advanced outfitting, such as increased space requirements, the higher risk of rework due to immature engineering detail, a need for more experienced designers who are aware of the capabilities of shipyard outfitting technology, etc. [42]. Considering that it has been reported in the literature that the cost of on-block outfitting is three times higher than the cost of the same outfitting activity conducted in the workshop, and five, or even more, times higher than the cost for on-board outfitting (1:3:5 ratio) [37], there is a strong possibility that the pre-outfitting approach will be increasingly implemented in shipyards.

During the outfitting of piping systems, priority is given to systems that require hot work. This implies that systems that require welding are mounted first because, during the welding process, plastic pipes can be damaged. Therefore, systems that are made of plastic are mounted in later stages, and often during the 3D modeling stage, steel pipes are given priority over plastic pipes. The author participated in projects for more than a dozen European shipyards, which allowed access to various yard documentation, records, site observations, and interviews. It was observed that plastic pipes are often cut, assembled, and mounted directly on the ship, which can create a high level of plastic debris. These activities are conducted on ships because the preparation of isometrics for plastic pipes requires more time for preparing documentation; furthermore, the operation with plastic pipes does not require experienced workers, as is, for example, the case with welders. Considering that these operations of preparing plastic pipes can be conducted at open locations on ships, and in the case of enclosed spaces, ventilation is required, these plastic particles can easily be transported into the maritime environment by workers' clothing, shoes, or through ventilation systems. The reduction in such operations by improving system design and allocating them to a controlled environment can improve the ecological aspect of ship production. Since pre-outfitting of steel pipes has been observed as beneficial, ecological implications could be an additional factor for motivating shipyards to allocate operations with plastic pipes to workshops.

3. Possible Improvements in Outfitting Procedure

3.1. Modeling Stage

During the 3D modeling stage, priority is always given to steel pipes. However, if steel pipe operation was less demanding and produced less debris, the priority could be given to plastic pipes. Examples with the proposed strategies were created using the ShipConstructor AutoCAD-based 3D product specialized for the marine industry. The proposed strategies were prepared in accordance with classification, register, and other relevant standards; therefore, both current and proposed designs are feasible solutions, where the decision as to which one to implement is ultimately down to the modeler. All proposed designs do not affect the structural integrity or safety of the piping systems.

The first example (Figure 2) shows a 3D model consisting of plastic pipes for fresh, hot, and potable water, and steel pipes representing the fire main, chilled water supply, chilled water return, and cable tray. These systems were chosen as examples because they are very common in accommodation areas. Fire main pipes are used for the distribution of seawater used in case of fire. These pipes are usually made of stainless steel or cunife (alloy of cooper, nickel, and iron), materials that are corrosion- and seawater-resistant. Due to material characteristics and the fact that this system is pressurized, they are suitable for pipe bending. Pipe bending is a simple operation where specialized equipment, pipe bending machines, are used to provide curvature to pipes. Chilled water supply and return are systems used for the distribution of cooling medium. Most often, they are made of stainless steel, and are also pressurized systems that enable pipe bending operation. This operation is preferable since it does not require additional parts and no additional operation is needed. From the ecological perspective, the great benefit is that no debris is generated.

A novel 3D modeling strategy is proposed, where the priority is given to plastic pipes (Figure 2). Plastic pipes are modeled in a straight line, and steel pipes undergo a bending operation. It can be observed that in area A of the model in the original design, there are 4 elbows for each plastic pipe, resulting in a total of 12 elbows. Each elbow requires the cutting operation and preparation of the surface, which are operations that generate debris, and could be avoided with the proposed 3D modeling approach. In area B, there can also be observed 4 elbows for each plastic pipe, resulting in a total of 12 elbows. This can also be avoided with adjustments to the cable tray. Cable trays are structures designed to hold wires and cables that have bolted joints (Figure 3). Therefore, a design where plastic pipes are avoided does not considerably increase installation operation complexity.

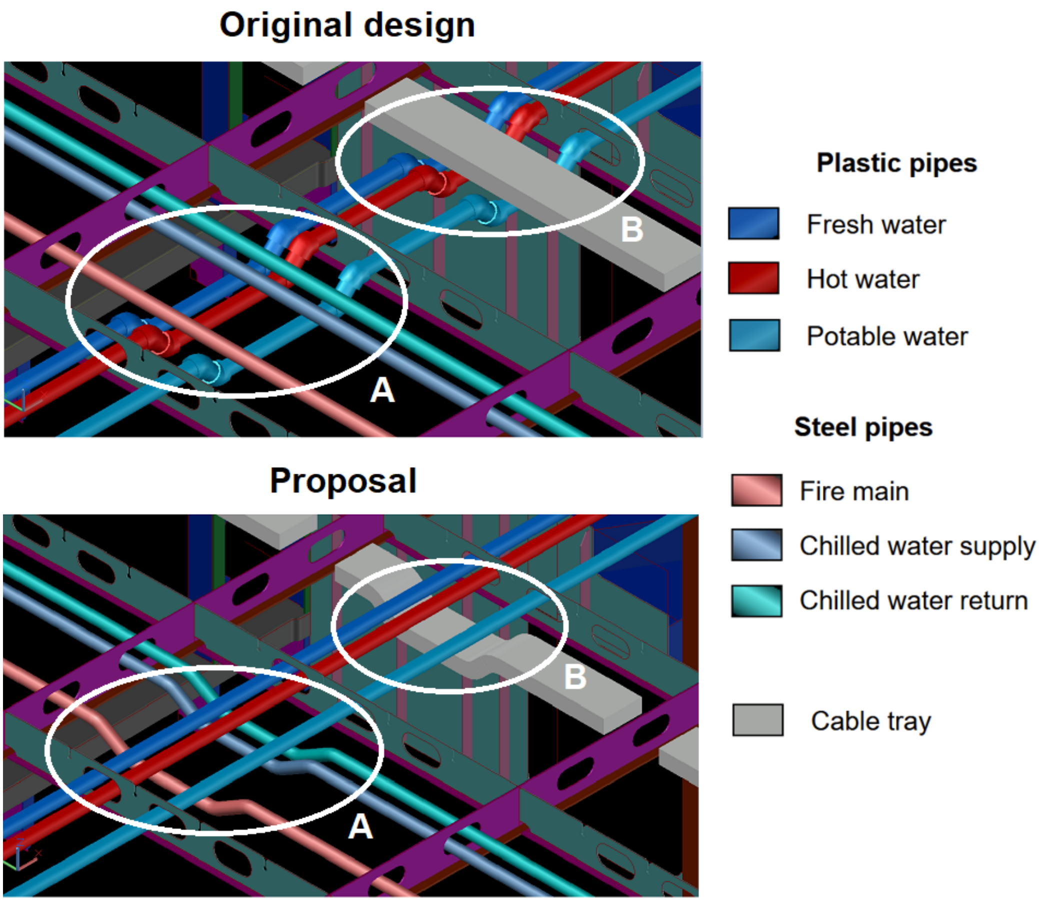

Figure 2. Original 3D model and suggested improvements to 3D modeling of systems. In area A, steel pipes are bent and plastic pipe elbows are avoided. In area B, plastic pipe elbows are avoided with the redirection of the cable tray.

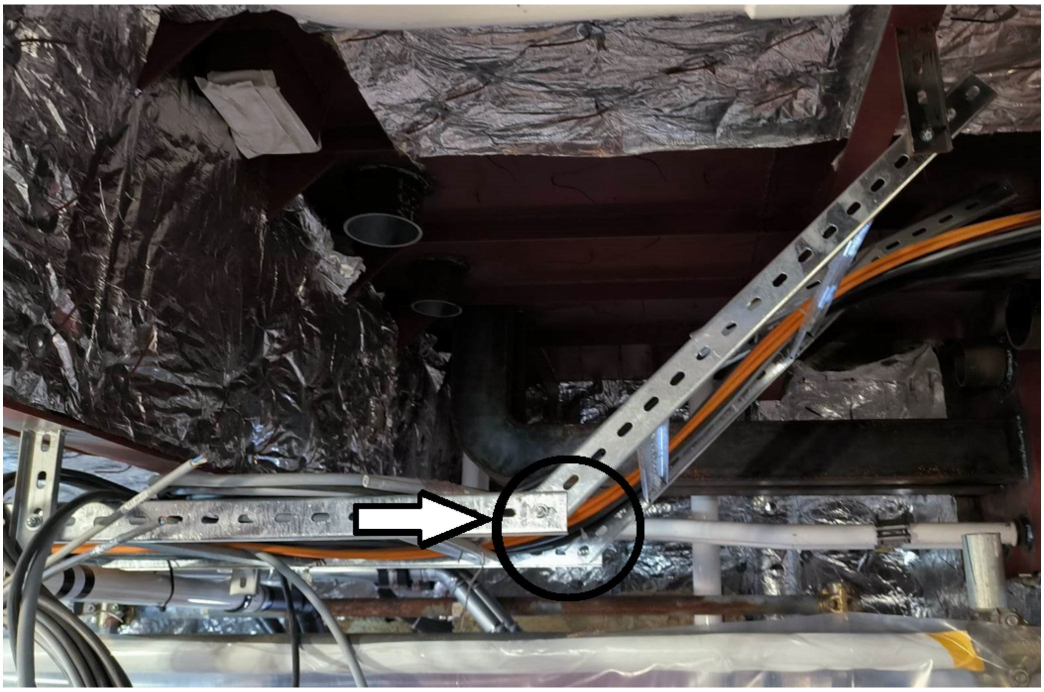

Figure 3. Cable tray with indicated bolted joint.

With the proposed design, plastic pipes only need to be welded on site, and the number of cutting activities is reduced to the minimum. An additional benefit is that this reduces the operation time for the required activities, and also reduces the number of procedures in the enclosed spaces. This approach requires that the modeler is experienced and has an in-depth understanding of shipyard manufacturing procedures and possibilities, and has an ecological motive.

In the second example, the distribution of hot and cold water to consumers is depicted in Figure 4 and in detail in Figure 5. One main is present with distributions to each individual consumer from the main. The first example is one main with distributions to each individual consumer from the main. In this way, 13 elbows are created for each consumer (5 for hot water and 8 for fresh water), resulting in a total of 78 elbows, which all require cutting and surface preparation activities. In this case, steel pipes represent a fuel oil overflow system where pipes are made of steel or stainless steel. It is a gravitational system, therefore, it cannot be bent like the steel pipes in the previous example.

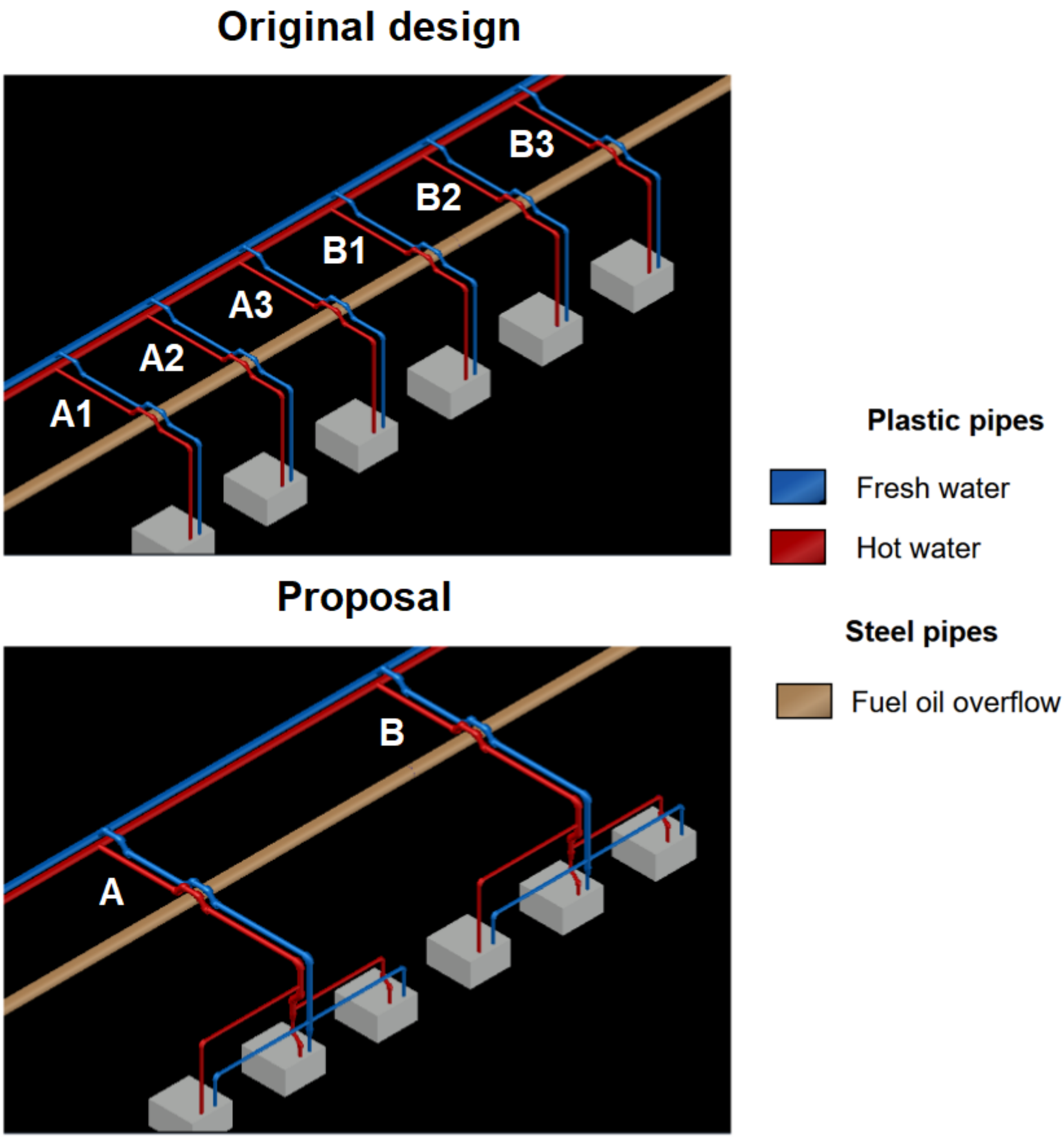

Figure 4. Original model and proposal of distribution of fresh and hot water to consumers. Pipes A1, A2, and A3 are replaced with pipe A of greater diameter, and pipes B1, B2, and B3 are replaced with pipe B of greater diameter.

The proposal is to create secondary mains for the groups of consumers, resulting in a smaller number of elbows. In this way, two pipes are routed to the groups of consumers where, immediately before the consumers, additional branches are created. With this proposal, a smaller number of knees are obtained. For the fresh water, there are now 20 elbows, and for hot water, 22 elbows. This results in 42 elbows, which is a reduction of 46%. It must be noted that, in this case, two additional T-junctions, parts that distribute the flow from the main pipe, are needed that also require cutting operations. It can also be observed that the proposed approach also reduces the number of plastic pipes. In order to preserve requirements of water supply to consumers, three pipes of smaller diameter (DN 25) are substituted with one pipe of greater diameter (DN 40). From the manufacturing perspective, less time is needed, which consequentially reduces the cost of production.

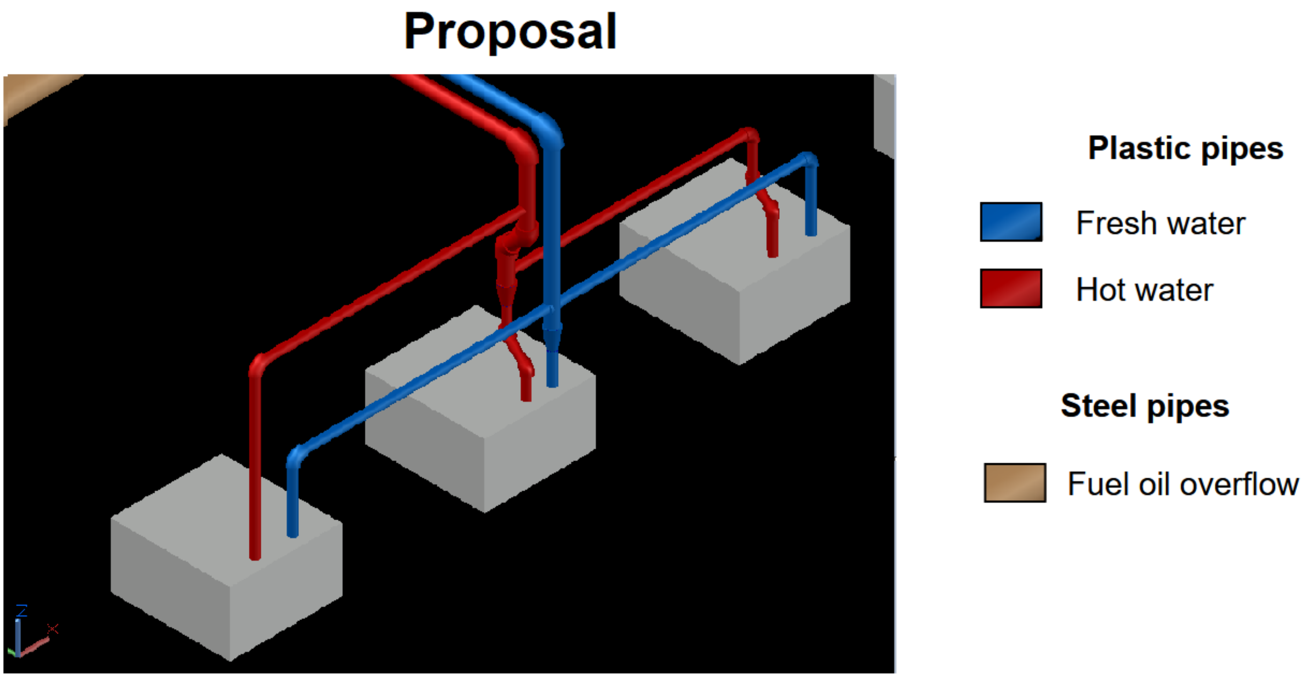

Figure 5. Detail of proposed model of distribution of fresh and hot water to consumers.

The final example is given in Figure 6. It can be observed that redundant elbows were made during the installation of plastic pipes (green circle). This can occur since adjustments to the model are made as new inputs are gathered, the locations of the pipes change frequently, and elbows that were previously modeled are now redundant. Appropriate changes to the surrounding pipes of the initial location, not only to the pipe that needs to be moved, can be beneficial from economical, ecological, and manufacturing perspectives. Experienced engineers will mostly make appropriate changes; however, there are also situations with tight schedules for the delivery, which require that changes are made as soon as possible. Therefore, such tasks require the education of modelers and additional time designated for these final checks, which is often lacking. It must also be taken into consideration that 3D modelers are often not informed as to which pipes have already been mounted; therefore, if pipe routing is changed later in the outfitting phase, changes in the model can be redundant since the pipes are already installed according to the initial model.

Figure 6. Example of installed redundant elbows on the ship.

3.2. Pre-Assembly Stage

For the installation process, plastic pipes need to be cut to appropriate size. Some of the tools used are ratchet cutters for pipes of smaller sizes, hand saws, or circular blades. The following steps include pipe ends being adjusted for welding. This includes preparation of pipe ends and scraping the outside surface of the pipe near the joining location. This is prescribed by the manufacturers, and workers are required to follow these instructions provided in the installer manuals [43,44]. All of these preparation operations produce debris, which is inevitable (Figure 7). These preparation activities, including the cleaning of pipes, are required, since any form of contaminant may ruin the connection. Additionally, the creation of outlets in plastic pipes implies drilling out the holes, which also creates debris.

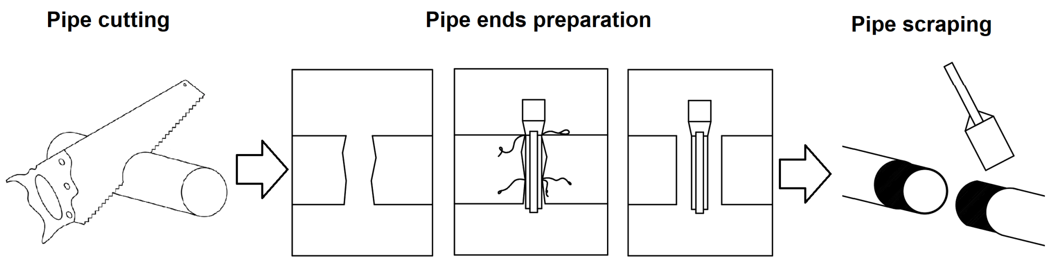

Figure 7. Plastic pipe preparation procedure for welding (after [43,44]).

Therefore, the allocation of plastic pipe preparation to warehouses, rather than in situ preparation, can considerably contribute to the reduction in microplastic pollution. Warehouses are a more controllable environment than ships, and various dust control techniques can be employed. For example, dust control curtains or ventilation systems with extractor fans, which can pull small dust particles towards themselves, can be implemented, and safe disposal of the dust can be conducted. This would require isometric preparation for plastic pipes, where isometrics are usually created only for plastic pipes of a greater diameter, such as DN 150 or DN 200. Isometrics creation would require additional work from the 3D modelers; however, as previously mentioned, it is beneficial to mitigate activities in the pre-outfitting stage. Apart from the economical benefit, this also contributes to improved ecological aspect.

The proposal of novel framework for greener shipbuilding design and production is given in Figure 8. The proposal suggests including ecological aspects in the modeling stage where designs that require operations that produce a lesser quantity of debris are preferred. Furthermore, pipe isometrics for plastic pipes can be made so spools can be prepared in the workshops in a more controllable environment. Finally, during the revision process, it is suggested to conduct additional checks for improvement of the design.

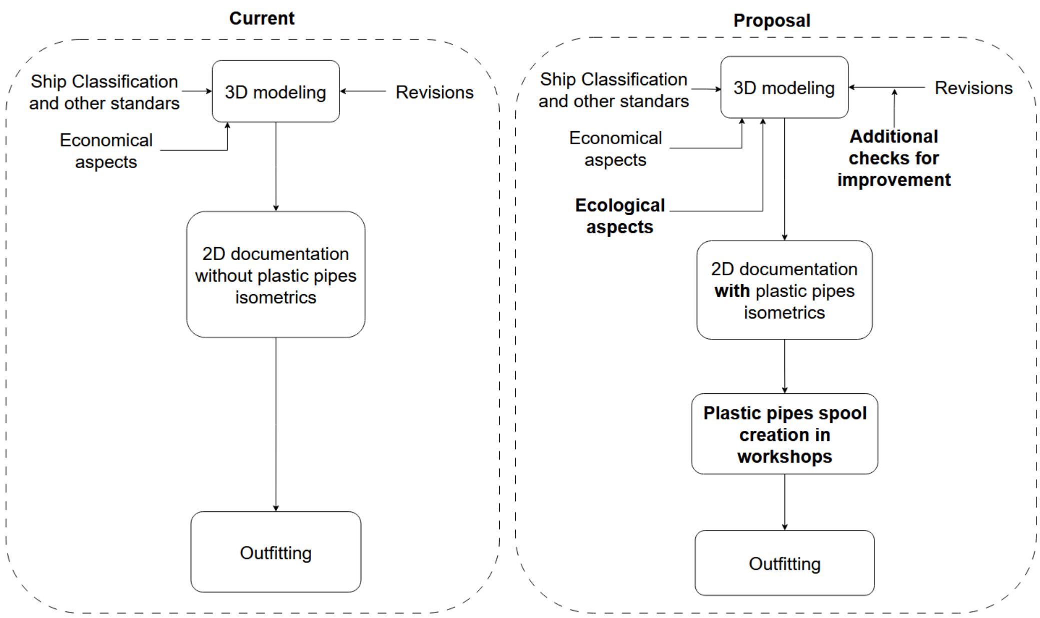

Figure 8. Flowchart of the current and proposed framework with proposed changes in bold.

3.3. Ecological and Economic Aspects of Proposed Strategies

In the example of modeling improvements, it is suggested that, when possible, steel pipes are bent rather than modeling plastic pipes with elbows. From the modeling perspective, the same amount of time is needed for both designs. The influence of design changes is more prominent in the production process. Pipe bending of steel pipes is conducted using specialized equipment, where if preparation activities, such as mounting and pipe positioning, are excluded, one bending process can last several seconds. In general, pipe bending operations in steel pipes are always preferred over welding elbows because pipe bending machines are standard production equipment, and it demands less time, material, and steps. It is also important to note that this activity does not produce any additional debris. Contrarily, activities with plastic pipes require cutting, preparation of ends, and welding, all of which can take considerably more time than steel pipe bending, and produce high levels of debris. Therefore, from the economic and ecological perspectives, the suggested design can reduce operation time, cost, and debris.

Proposed improvements in the modeling stage would require the preparation of educational material and accompanying educational activities. Staff education regarding MP pollution can consist of a presentation on potential hazards to their health and sources of MP pollution in the shipbuilding industry. Preparation of such material can be conducted by scientists already familiar with the subject; as such, the estimation of time needed for preparing such material is 20 working hours. Such material will not need frequent adjustments considering that the main aim will be only to provide a broad perspective. It can be considered that such activity will not present considerable expense. The presentation of material can be provided once to each employee, so the estimation of two working hours is also expected to not present considerable expense. The next step would be to investigate the possibilities of implementing green practices for each shipyard. This can be performed by an external expert who would observe the organization of the shipyard, typical ships being constructed, and the manufacturing process, and conduct interviews with the production team. One of the aims would be to suggest the location and design of warehouses for plastic pipe spooling, with appropriate solutions for ventilation and debris collection techniques. This is estimated at 32 working hours, after which 16 working hours would be required for the preparation of reports and guidelines with proposed strategies for greener production. The proposed time does not include in depth analysis of economic implications, but is rather based on suggestions that shipyards can decide to further explore. Based on the expert report, more specific guidelines for engineers who prepare 3D models can be prepared. These guidelines can consist of a set of solutions and recommendations, such as those presented in this paper. The prepared material can be accompanied by short workshops, where examples will be discussed and explained in more detail to the engineers. A rough estimation of work hours of all proposed activities is given in Table 1. Estimations are based on the authors' experience in the preparation of learning material and engineering experience regarding the education of workers in shipbuilding. Considering that the type and size of the ship that is being constructed can considerably vary, the guidelines for modelers can be prepared for each project. This can be redundant in the case of similar ship or sister ship production.

Table 1. Estimation of working hours required for preparation of material for engineers that prepare ship system models.

	Activity	Duration (Working Hours)
General awareness about MP pollution	Preparation of educational material	20
	Education of each employee	2
Green practices adjusted for specific shipyard or project	Analysis of shipyard manufacturing	32
	Preparation of guidelines for shipyard	16
	Preparation of guidelines for modelers	16
	Education of each employee	2

The suggestion of preparing pipe spools for plastic pipes requires the preparation of documentation, which increases modeling time. For example, for a 60 m superyacht, where documentation time preparation is estimated at 300 h without plastic, it would require 390 h, which is an increase of 30%. Although, this increases modeling time, an overall feasibility analysis should be conducted, where production time is also taken into consideration. It is noted in [37] that the cost of on-board operations can be five times higher than outfitting operations conducted in the workshop, which indicates that this could be a beneficial approach. It also must be noted that on-board activities can increase errors due to limited space. Another suggestion is additional checks for improvement. This would not be a feasible approach for the manufacturing of the first ship in the series, considering that changes are often being made and there is always a tight schedule. However, it would be feasible in the case of sister ship manufacturing. Documentation is always changing for each subsequent ship based on additional requirements and observed improvements; therefore, it would be feasible to observe whether simpler and more ecologically acceptable solutions can be provided. The estimation of proposed activities is given in Table 2. It must be noted that only the time for the identification of potential improvements is provided, considering that the time for making appropriate adjustments can vary according to the number and complexity of alterations that need to be made.

Table 2. Economic aspects of proposed methodology for the example of a 60 m superyacht; h represents working hours.

Activity	Original	Proposed
Pipe spooling	300 h	390 h
Identification of potential improvements	/	40 h
Cost of outfitting activity [37]	5× (on-board)	1× (warehouse)

Regarding the ecological perspective, in the work by [2], an experiment was conducted where pipes of 75 mm and 100 mm diameters were cut with three different saws, and estimated values of plastic particles were reported. Applying these estimations, the results of the proposed improvements for fresh and hot water distribution to consumers are presented in Table 3. It can be observed that a considerable reduction in plastic particles can be obtained, where it must be noted that these estimated values correspond only to cutting operations, without pipe end preparation and pipe scraping operations, which also produce debris. It must also be noted that these values could differ for pipes of different sizes, and are only a rough estimate considering that the strategies and methods for MP particle measurements are continuously improving.

Table 3. Estimation of MP particles generated during pipe cutting operation for original (Figure 4) and suggested design (Figure 4) based on experimental measurements conducted by [2].

	Number of Particles	
	Original Design	**Suggested Design**
MP particles (0.1–5 mm)	$\sim 312 \times 10^3$	$\sim 168 \times 10^3$
MP particles (1–100 µmm)	$\sim 5.9 \times 10^9$	$\sim 3.1 \times 10^9$
MP particles (<1 µmm)	$\sim 121 \times 10^9$	$\sim 65 \times 10^9$

4. Discussion

In this paper, several propositions that could improve the MP pollution status in the shipbuilding industry are presented. Regarding the possible improvement of the modeling stage, where plastic pipes are given an advantage over steel pipes, it must be noted that mitigation of MP pollution can cause pollution from other materials. For example, if plastic pipes are given priority, which now requires cutting the steel pipes and installation of elbows, the pollution in general is not reduced, but the type of pollution is changed. Therefore, it is not suggested that plastic pipes are given an advantage in general. Economic perspective also needs to be taken into consideration since the addition of steel elbows can increase the production cost. This is why an example was chosen where pipe bending is conducted, an operation with no additional material costs. Education of the engineers and workers should be conducted to raise awareness about MP pollution, economic aspects, and the production specifics of shipyards. In this way, it can be determined which improvements and novel strategies could be implemented, and such education is necessary for good practices that satisfy multiple criteria, which are yet to be established. The estimation of implementing such a strategy is presented. It can be observed that the education of engineers should not present a considerable number of resources in ideal conditions, where people with in-depth understanding and knowledge are engaged in the preparation of educational material. The main problem could be establishing communication between scientists, shipyards, and engineers, and finding appropriate people to prepare relevant material.

The second suggestion regarding the spooling of the plastic pipes and the transition of the majority of operations with plastic pipes to workhouses will require substantial economical investments initially. This requires appropriate space in the shipyard and additional costs designated for 3D modeling for the creation of isometrics for plastic pipes. However, in the long term, this could be beneficial to the shipyards, especially if, in the future, novel legislation that penalizes MP pollution is implemented. It is also in line with the future digital transformation of the shipping industry. With the future digital transformation of the shipping industry, e.g., application of a digital twin system for the pipe production line [45], improved process control and efficiency can be obtained with pipe preparation in the pre-assembly stage. This approach could ultimately prevail, which will also improve the ecological aspect of ship production. This has also been investigated in a work by López et al. [46], where particle emissions were measured in shipyards and in workshops during ship maintenance activities, and a greater degree of particle pollution was observed on the ship. It has been stressed that although cleaning is conducted on the ship, deposited dust has the potential to reach surface waters, and that needs to be further studied. Human health and working conditions are also important factors, which would be improved with a such transition. In the work of [46], it has also been noted that protective strategies, such as exhaust ventilation, dust removal, and personal protective equipment, have been implemented, but it was indicated that worker exposure to particle emissions cannot be avoided at all times. Therefore, the allocation of activities that generate pollution particles to workhouses can enable the usage of more advanced protective measures, and workers' protection can be improved. Strategies that prevent, in general, the release of ultrafine, fine, and coarse particles would be even more beneficial, both for human health and for environmental protection. Further investigation into such strategies should be conducted to identify cost-effective solutions, so shipyards would be more willing to implement them.

It is also worth mentioning social responsibility, where environmental awareness and the need for sustainable consumption is increasing [47,48], which can be observed through the consumers' behaviors [49,50]. Based on these observations, it is reasonable to believe that in the future, shipyards that support environmentally friendly business operations would be preferable to the ones which do not implement these strategies.

Considerable research has been conducted aimed at the analysis of pollution emissions and providing obligations to the industry, however, without proposing possible solutions. Thus, tight cooperation and communication between industry and the scientific community is needed, where the exchange of experience and knowledge can help to define solutions that could be beneficial to all parties. This requires synergy between shipyards, workers, 3D modelers, scientists, etc. Methods that reduce the levels of pollution and debris can be beneficial for the reduction in production time, which is a major interest for shipyards. Therefore, collaborations need to be established. All parties should be informed about the usual procedures and their advantages and disadvantages, and novel strategies need to be defined jointly. Due to increasing ecological awareness and the legislation that is being implemented, these changes will need to be implemented soon.

5. Conclusions

MP pollution is an important issue that has been given increasing attention. Considerable efforts are being implemented in various industries to reduce MP pollution, especially ones related to the marine environment, due to the major negative impact of MPs on aquatic animals and, consequently, human health. The maritime environment is especially vulnerable to shipping and boating activities, since they are conducted in or in the immediate vicinity of the sea. Unfortunately, pollution generated during the shipbuilding production processes is inevitable, however, proper strategies can be adopted for their minimization. Previous scientific research is still mostly focused on the identification and quantification of pollution sources with the lack of mitigation and reduction strategies.

This paper puts focus on the part of the production process where considerable improvements can be implemented. It provides several mitigation and minimization of MP pollution strategies during ship production by implementing novel methods during the design phase and outfitting phase of plastic pipes. The first suggestion is that 3D modelers should be educated about the negative ecological impact of MPs, and novel modeling strategies should be adopted with the aim of reducing operations with plastic that produce debris. These strategies must consider that, in an attempt to reduce MP pollution, other types of pollution must not be generated. Considering that the cutting of plastic pipes and preparation for welding is currently mainly conducted on the ship, the second suggestion is that spooling of plastic pipes could be conducted in warehouses under controlled environments, where dust removal practices can be employed more easily.

Previous studies showed that the allocation of on-board activities to warehouses reduces expenses; therefore, the strategies proposed in this paper could be beneficial both from economic and ecological perspectives. However, it must be noted that these previous studies evaluated pipes in general, and there is a need for additional investigation in which only plastic pipes are considered. Therefore, further feasibility research is needed for the suggestions proposed in this paper to be ultimately adopted by the industry. Easier implementation in the industry would be the adjustment of 3D modeling strategies. However, this requires the preparation of educational material and the education of workers, which could appear to the industry as a redundant investment of time and resources. Raising awareness about MP pollution could change that.

Regarding MP pollution characterization, there are several directions for future research. For more appropriate pollution characterization of shipyards, further experiments are needed, such as investigation into MP pollution for cutting different pipe diameters and with the inclusion of pipe preparation activities. Investigation of MP particle transfer by air, clothing, and shoes can also be explored for a more appropriate quantification of MP pollution during shipbuilding activities. Research into different types of plastic materials and possible alternative materials for shipbuilding can be conducted. Results from such investigations could additionally highlight the hazards of MP pollution, both to the marine environment and to workers, and could prompt a faster industry reaction where sustainable practices are more broadly adopted.

The implementation of novel strategies in the shipbuilding industry requires a multidisciplinary perspective, where ecological, economic, and industry perspectives are needed, with tight communication between industry and the scientific community. It is only then that the optimal solutions can be found, and pollution would not simply be transferred from one source to the other, but reduced in general.

Author Contributions: Conceptualization, B.L. and I.L.; methodology, B.L., Z.Č. and I.L.; software, B.L.; investigation, B.L., M.A. and I.L.; writing—original draft preparation, B.L., M.A. and I.L.; writing—review and editing, B.L., M.A., Z.Č. and I.L.; visualization, B.L. and I.L.; supervision, Z.Č. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

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