Rationalization and optimization of waste management and treatment in modern cruise ships

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ABSTRACT

Here we report over possible optimizations onboard cruise ships in the management of glass, paper and cellulosic waste, ranging from simple rationalization of the materials' use (for glass and paper) to the recovery of some of the energy embedded in paper and other cellulosic waste. This latter option is investigated considering two possibilities: i) the recovery of thermal energy from incinerator's flue gas by means of an absorption plant, ii) the production of syngas to be directly fed to the ship engines. For each option, we calculated the achievable benefits in terms of reduced fuel consumption, avoided CO_2 emissions and cost savings (evaluated on the basis of the avoided fuel consumption). Finally, on the basis of the previously calculated benefits, we defined three different scenarios, each including the rationalization of glass and paper waste management, topped by different combinations of thermal energy recovery/syngas production. We then evaluated these scenarios in terms of environmental and economic benefits. This analysis showed that even trivial approaches, as a simple rationalization of paper consumption, can allow consistent advantages over existing waste management policies; moreover, syngas generators for treating cellulosic waste emerged as very effective tools for lowering the environmental impact of modern cruise ships. Joining these two strategies allows notable savings in terms of fuel, CO_2 emissions and ship operational costs, and could represent a path for sizably reducing the environmental footprint of cruise ships.

1. Introduction

The environmental impact of leisure cruises activity is generating growing concerns, especially with respect to the production of waste, which affects ports and main sea routes (Butt, 2007; Commoy et al., 2005; Klein, 2010). In fact, cruise vessels host and transport large numbers of passengers and crew members, currently on the scale of 1000–5000 people per ship, with the associated production of waste. For example, cruise ships tend to concentrate their activities in specific coastal areas and to repeatedly visit the same ports, creating a significant cumulative impact at the local scale. Moreover, even single, large waste release events (either accidental or intentional ones) can have a sizeable negative effect (Krenshaw, 2009). As cruise ships are like small cities, the wastes they produce are similar in types and amounts to those deriving from standard human activity. For example, Copeland and colleagues (Copeland, 2011) calculated the average waste production for a cruise ship with 3000 people during a week-long cruise as follows: 795 m^3 of sewage, 3785 m^3 of greywater, 95 m^3 of oily water, and 8 tons of solid waste. The problem caused by cruise-generated wastes is expected to become even more relevant in the future, due to the current growth trend of the cruise industry, especially in China (Xu, 2016), even though upon the recent COVID19 pandemic these forecasts will be likely revised.

The implementation of "green policies" for managing these wastes is hence a topic assuming a great importance (Caniëls et al., 2016; Guo et al., 2012; Lu et al., 2009). To this end, the cruise sector has launched initiatives to improve pollution prevention by adopting appropriate guidelines and procedures, and searching for new technologies that can meet existing requirements. The main documents and regulations in the field are related to the Annex V of the MARPOL Convention (MARPOL 73/78), which entered into force on December 31st, 1988, and to its subsequent amendments and guidelines. The latest revised version was adopted in July 2011, while the latest guidelines were adopted in July 2017, marking a significant update to the regulations in the field. The attention to a rational approach for general waste management in these regulations is clear since their introduction, in which it is stated that "Annex V reverses the historical presumption that garbage may

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be discharged into the sea based on the nature of the garbage and defined distances from shore" (Copeland, 2011; Harris, 2011; Iannello et al., 2018; Klein, 2010; MEPC 295 71, 2017).

Many techniques, like anaerobic digestion or biomass-derived syngas production, allow effective energy recovery from wastes (Guo et al., 2015; Puigjaner, 2011; dos Santos and Alencar, 2019), and are today available for agricultural/urban centers uses (Bolzonella et al., 2006; Cao and Pawłowski, 2012; Nghiem et al., 2017), with proven economic advantages (Di Bernardo et al., 2019; Fei et al., 2018; Leme et al., 2014). However, up to now, to the best of the knowledge of the authors, these methods have not been thoroughly analyzed as possible approaches to the problem of waste management in cruise ships, even though they could provide evident benefits in technical, economic and environmental terms. Also novel technologies like thermoelectric generation could help in energy recovery (Champier, 2017; Freer and Powell, 2020), but the harsh conditions of sea operations have prevented until now their reliable adoption. On the other hand, a clever redesign of currently adopted practices, targeting a rational use of resources and an improved recycling of manufacts for further reuse, could contribute to a more effective waste management onboard cruise ships.

Therefore, in this study we present a proposal for a better integrated management approach for some cruise ship-generated waste, allowing to improve the environmental and economic impact of cruise activities. In particular, we propose an analysis of integrated waste management for a model ship with a focus over glass, paper and cellulosic wastes, aiming to material saving and effective waste-to-energy processes. The analysis is carried out using by-purpose developed calculations, except for paper waste, for which existing published works were used with adaptations. The recovery of energy from waste has been considered under the points of view of both incineration with thermal energy recovery from flue gases and biomass-derived syngas production via gasification process, with preliminary quantitative assessments of the involved amounts of matter, energy recovery and economic impact. The anaerobic digestion of food waste has not been considered since current regulations allow to dump this waste at sea and thus its long term storage does not represent nowadays an issue for the cruise industry (even though, in general, dumping at sea any type of waste cannot be seen as an environmentally positive policy). Finally, we describe three different scenarios in which the aforementioned waste management optimizations are used, assessing the contribution of each strategy to the overall improvements in terms of reduction of fuel consumption, operation costs, CO_2 emissions.

2. Methodology

A careful bibliographic research about the currently used methods for the quantification, collection and treatment of waste in modern cruise ships has been carried out. The supply chain related to the management (collection, treatment, storage and discharge) of waste generated by modern cruise ships has been analyzed (Amendments to the Annex of the protocol of 1978 relating to the international convention for the prevention of pollution from ships, 1973 (revised MARPOL Annex V), 2011; Butt, 2007; Caniëls et al., 2016; Commoy et al., 2005; Copeland, 2011; Guo et al., 2012; Harris, 2011; Iannello et al., 2018; Kester, 2003; Klein, 2010; Krenshaw, 2009; Liu et al., 2016; Lu et al., 2009; Singh et al., 2014; Zacho and Mosgaard, 2016). Upon this analysis, we have defined waste management approaches aimed to a reduction of the amount of generated solid waste, and to its storage in safe conditions. We also explored possibilities related to the recovery of energy from flue gases produced by the incineration plant, and to the use of a gasification plant for the production of syngas, as either a complement or an alternative to the standard incineration process.

This methodology was then applied to the case of an existing cruise ship to evaluate the effectiveness of the proposed solutions in a model case. The ship carries 4200 passengers and 1400 crew members, i.e. a total of 5600 people, and is operated 305 days/year. The average duration of a cruise travel is considered to be 7 days, i.e. each seven days the ship returns back to the home port for unloading waste and loading new resources. The dry weight (i.e. with no load, no fuel, no crew) of the vessel is around 141,000 tons.

Currently, on board cruise ships the waste is classified and treated as either dry or wet waste.

Dry waste consists in glass, cans, jars, paper, cardboard, wood (the three latter types grouped under the collective term "cellulosic waste"), textiles (mainly rags), plastics and medical waste, and it is collected manually and transferred to the ship's garbage room, where it is sorted and treated in different ways. Glass is shredded, and cans and jars are compacted, in order to assure a proper storage onboard before being transferred to the mainland. Plastics are also shredded, then compacted and stored until unloaded at ports. Clean paper and cardboard can be either compacted and stored for subsequent unloading at port or incinerated upon a previous shredding step, while polluted paper and cardboard are always shredded to be incinerated. Wood is squashed and then incinerated with polluted rags and medical waste.

Wet garbage consists essentially in food scraps, which are collected using dedicated plants, usually operated under vacuum, with several collection points distributed in the kitchens and in the food preparation areas. The food waste is shredded in pieces, having sizes dictated by the regulations, and then conveyed to dedicated crates. From there it can be dumped outboard, respecting the distances from the coast as per local and general maritime regulations, or treated (mechanical reduction of the liquid content, or drying processes) for subsequent incineration.

In the following we will consider "food waste" all the residues deriving from food preparation and consumption, including spoilage.

The current waste management process can be divided into four phases: collection, treatment, storage and dumping. Fig. 1 summarizes the currently used management approach for solid waste, characterized by a differentiated waste collection, enabled by different containers placed in appropriate positions on board the ship (Butt, 2007; Caniëls et al., 2016; Commoy et al., 2005; Kester, 2003; Klein, 2010). The differentiation is made immediately after the waste disposal, even though the waste is not supposed to be reused.

The here reported main qualitative and quantitative characteristics of the wastes produced in our model cruise ship are based on data provided by Fincantieri S.p.A., the shipbuilding company that built the vessel and that supported the research described in this paper. In more detail, Fincantieri S.p.A. is a large ship-building industry based in Italy, who delivered in 2019 ships for more than 450,000 tons ("Fincantieri," 2020). The collected data have been classified by type and quantity produced per person per day, and are shown in Table 1.

In general, non-reusable waste can or cannot be dumped at sea, in compliance with the requirements of Regulations 4, 5 and 6 of MARPOL Annex V (entered into force on 31 December 1988 and amended last time in 2016 by MEPC. 277(70)). In order to better deal with specific environmental situations, MARPOL also defines certain "special areas" (in terms of well defined geographic zones), for example the Mediterranean Sea, where special methods for the prevention of sea pollution are required. Different aspects of the environmental protection of the sea are under the competencies of United Nations and International Maritime Organization at the

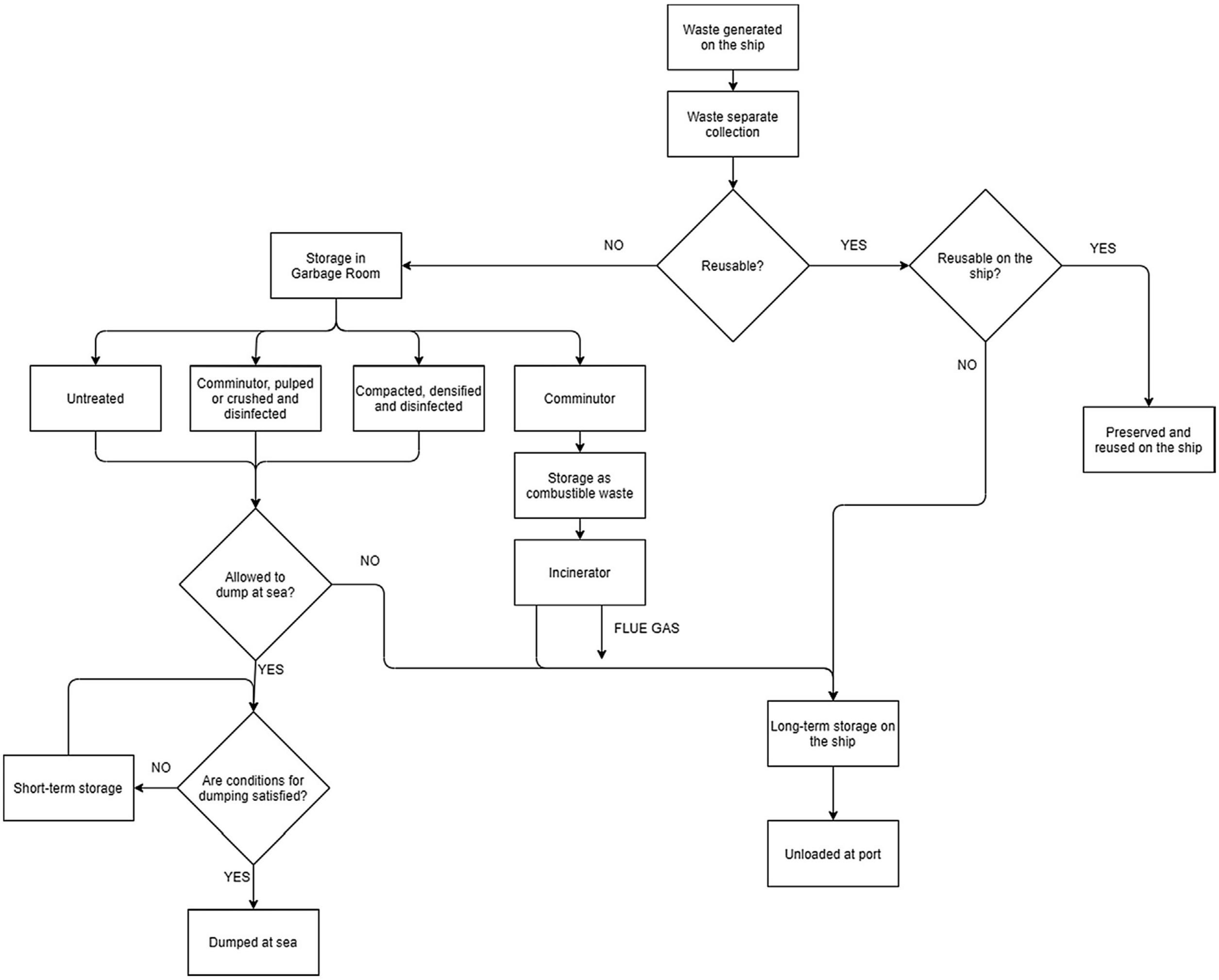

Fig. 1. Solid waste management strategies currently adopted on board of modern cruise ships.

Table 1
Qualitative and quantitative characteristics of the waste produced in our model cruise ship (Data provided by Fincantieri S.p.A.).

Waste type	Daily quantity per person (kg/day*person)	Daily quantity (kg/day)	Notes
Cellulosic waste (paper, cardboard, wood)	About 0.76	about 4256	of which about 7% of paper
Glass and cans	From 0.8 to 1.2	about 5600	80% glass
Wet (food)	From 2 to 2.4	about 12,300	20% solid content
Plastics	about 0.22	about 1230	

international level, while at more local level different actors issue specific regulations (like for example the agencies of the European Union (Carpenter, 2011; De La Fayette, 1999)).

According to the applicable regulations, the waste can be treated with different equipments (comminutors, pulpers, shredders, compactors, densifiers or disinfectors) prior dumping it at sea. In alternative, the waste (either treated or not) is stored in dedicated long–term temporary deposits, in safe conditions (i.e designed to provide the appropriate conditions for avoiding waste dispersion in the environment, hazards, etc.), to be subsequently unloaded in the receiving port.

Different types of waste undergo different mechanical treatments.

Shredding is used for glass, paper, cardboard and plastics (it is possible that different types of waste have dedicated shredding machines).

Compacting is applied to plastics and metals. An additional packing step is usually carried out for paper and cardboard.

The combustible waste can be incinerated according to the rules dictated by Annex VI of MARPOL 73/78 and by national regulations (i.e., only when the vessel is at least 12 nautical miles from the coast). This incineration process produces *ashes*, which are stored in appropriate temporary storage sites in safe conditions and unloaded at the receiving port, and *flue gas*, which, in agreement to said MARPOL rules, are currently emitted into the atmosphere through the chimney without any treatment or purification system (an approach that, though compliant to current rules, could be much improved in terms of environmental compatibility).

Even though other treatments are possible, in the maritime world incineration still occupies an important role, since before considering the potential impacts of carbon emissions the expected ecological impacts for incineration are lower than those deriving from the disposal of waste in deep oceans (Avellaneda et al., 2011).

For non-dumped-at-sea waste, the use of on-board different treatment plants (comminutors, pulpers, etc.) is possible, again depending on the type of considered waste.

During the established ship route, the waste not disposed of at sea and not otherwise treated on board is unloaded at ports equipped with appropriate facilities (like land-based authorized treatment and/or storage plants/sites, ecological islands for hazardous waste, recycling plants, etc.).

3. Results and discussion

The overview of the here proposed integrated waste management system is shown in Fig. 2. The system is based on a series of improvements in terms of waste reduction, collection, treatment and storage, as well as in relation to enhanced energy recovery from the produced waste, as hereafter detailed. All the reported calculations are referred to our model cruise ship, having the main characteristics described in par. 2.

In particular, considering that even the heaviest equipment needed for the here proposed waste management improvements does not exceed 26 tons, when the dry weight of the ship is around 141,000 tons, to the extent of the following analysis the weight of the added equipment and plants will not be considered to be meaningful in terms of impact on the here proposed novel waste management policies.

3.1. Optimization of glass waste management

Currently, the used glass is completely shredded in fragments, stored in appropriate containers and then unloaded at the home port for easy recycling. However, most of the glass waste produced on board consists essentially in bottles of different capacities. If intact, these bottles could be reused without returning to the production cycle, thus avoiding to become waste.

In fact, glass bottles, once emptied, can be returned to the supplier for being re-used and refilled again, for a virtually infinite number of times. To reach this goal, the collection of used bottles onboard can be easily carried out by the crew using simple separate collection procedures.

Even with accurate handling and management of bottles aimed to maximize their return, it is inevitable that some of them will get broken, damaged or worn. In this case the broken glass will be shredded and conferred to land-based recycling companies.

Adoption of reusable glass bottles would allow, in first place, to save the energy required for the shredder activity. In order to quantify this energy we can consider that a glass crusher able to withstand the current ship needs possesses a 5.5 kW$_e$ (electrical kilowatt-hour) power engine and can crush about 1000 kg of glass

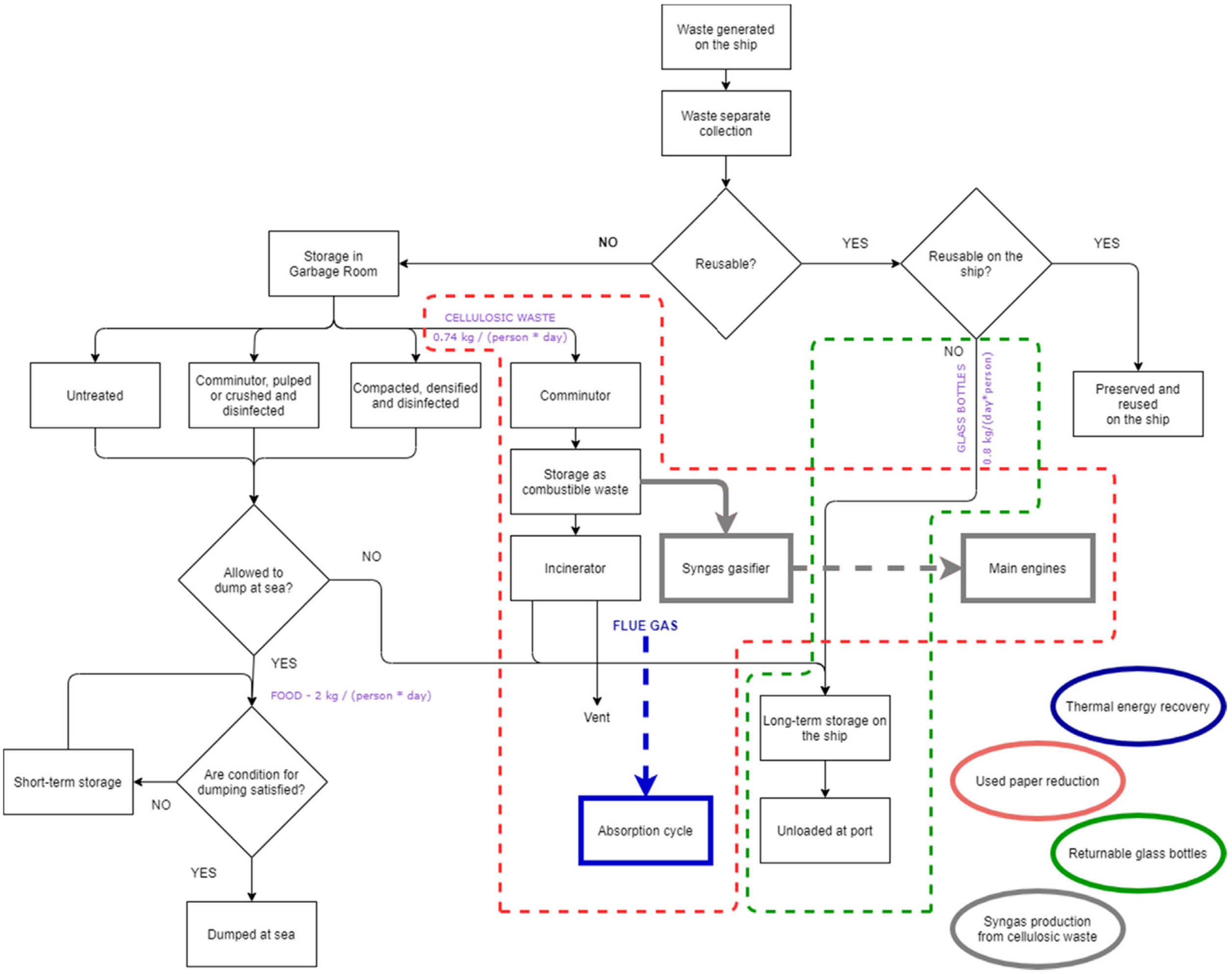

Fig. 2. Scheme of the proposed waste management approach. The new waste management approaches discussed in the paper are highlighted with blue (thermal energy recovery), red (used paper reduction), green (returnable glass bottles), and grey (syngas production) colour. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

per hour. In absence of the returned bottles approach, this crusher works an average of about 4.5 h/day. For calculating the impact of the returned bottles policy, we assume that with the return of the used glass bottles only 20% in weight of the current total glass consumption (related to accidental breakage) will need shredding. In this case the operating time of the crusher will be around 0.9 h/day. This decreased use of the crusher has a positive impact on the ship's electrical energy consumption. In particular, the vessel is equipped with two engines of 16.8 MW each and two engines of 14.4 MW each, for a total nominal power of 62.4 MW; this power is converted into electricity with the help of alternators, which provide electrical energy to all the ship's plants. The specific fuel consumption of the engines in nominal functional conditions is equal to 208.8 g/kWh$_e$. Upon the above mentioned assumption of shredder activity, the returned bottles policy saves about 3.6 h/day of crusher operations, which is translated into about 19.7 kWh$_e$/day, which in turn means a fuel saving of about 4.1 kg/-day. Considering an average operation percentage of a cruise ship of 305 day/year, the current glass consumption is about 1366 t/year and the returned bottles policy would allow a yearly fuel savings of about 1.26 t/year. This corresponds to 423 €/year (based on an IFO 380 fuel price of 0.337 €/kg) and around 4000 kg/year of CO_2 emission savings.).

As is visible, the overall economic advantage of this strategy is marginal with respect to the operational cost of a cruise ship. However, operating in the suggested way would lead to a not immediately recognized energy saving, associated to the need for re-melting the shredded glass in order to manufacture new bottles once the old ones are unloaded at ports. We were not able to identify publicly available cost details for the latter process (i.e., manufacturing of glass bottles from glass cullet, which are the shredded glass fragments from waste bottles), and an estimation of this hidden cost (which is not in charge to the ship owner) would require an LCA approach, that is not in the scope of this paper. Nonetheless, it is possible to make the following considerations: i) the sale cost of glass cullet is around 0.2–0.3 €/kg (depending on the color of the glass; the clear variety is the most expensive one, while mixed colors can get negative prices, i.e., the companies must pay in order to have it collected) ("Recovered glass container prices," 2019), hence we can consider an average cost for glass cullet of about 0.25 €/kg; ii) for manufacturing a new bottle from a melt composed by 100% of glass cullet, the melting costs are about 0.05 €/kg (Assoesco, 2017; "Eurostat," 2020); and iii) around the world the sum recognized to customers is in the range from about 0.03 to about 0.20 €/bottle ("Container-deposit legislation, Wikipedia," 2020). As a bottle of beverage weights on average around 0.5 kg, at a representative return cost of 0.1 €/bottle the value of the returned glass is about 0.2 €/kg.

Upon these numbers it is possible to see that the cost for sanitization and re-labeling of returned bottles must be lower, or at least comparable, to that of melting a bottle from scrap glass.

In addition, it is interesting to notice that this "returned bottles" approach involves a further peculiar advantage, which can be valuable for cruise ship owners: since the bottles are no more shredded after utilization, they can be stored in the same room where they are conserved before being used. In this way it is possible to avoid the use of rooms dedicated to shredded glass, freeing up to 80% of the storage room dedicated to glass, which can be estimated at about 9.5 m^3. This saved space can hence be used for other technical purposes.

3.2. Minimization of paper waste

Paper, cardboard and wood waste (from now on collectively identified as "cellulosic waste") on board cruise ships is produced at a pretty high pace. As shown in Table 1, the daily production of this type of waste for our model cruise ship is about 4260 kg/day, which is a not negligible load to be carried out during the port-to-port navigation. In order to lower this burden, we considered some strategies for the minimization of paper waste generation on board a cruise ship recently proposed by Strazza and colleagues (Strazza et al., 2015).

The first approach is related to the reduction of the printed paper used on board in the form of brochures, flyers, informative leaflets, etc. This type of paper usage was estimated to be about 15 g/day*passenger, which for our model ship corresponds to about 83 kg/day. According to Strazza and colleagues, such a consistent amount can be reduced by 25 to 100% by means of extensive digitalization, informative totems and monitors and dedicated applications on smartphones and tablets. For our purposes we assumed that an overall reduction of 50% of the printed paper is achievable using the aforementioned information digitalization strategies, leading to a saving of about 41.5 kg/day.

The second optimization strategy involves the reduction of the consumption of toilet paper and paper towels by installing single-cut, automatic distributors, which can be placed in transit areas and common areas accessible to passengers, as well as in the cabins. In this way Strazza and colleagues estimated that a 25% reduction of this type of paper usage can be achieved, which is very significant in terms of overall consumption. For our model ship this would mean moving from a consumption of about 179 kg/day to one of about 134 kg/day, i.e. saving about 45 kg/day.

The last optimization approach regards the development of guidelines dedicated to the ship's crew and aimed to reduce their own paper consumption (mainly A3 and A4 sheets of daily notices, internal communications, etc.) during duty activities. In this way the estimated paper savings are around 50% of the current usage. Keeping this percentage for our model ship means that it is possible to move from a consumption of about 102 kg/day to about 51 kg/day.

Summing up these three paper waste optimization strategies (as depicted in Table 2) we estimate for our model ship a paper consumption saving of about 137.5 kg/day. This corresponds to an economic saving of about 1560.00 €/day, according to current (Jan 2020) market prices for these items, which corresponds to a notable yearly saving of about 475.000 €/year.

Again after data reported by Strazza and colleagues (Strazza et al., 2015), this amount of saved paper corresponds to avoided CO_2 emissions for about 251 kg/day of cruise.

Besides of paper, other cellulosic wastes produced onboard (mainly constituted by cardboard and wood) can be recycled once at port, via previous selection (separating contaminated items from clean ones) and storage. However, this approach does not lead to effective optimization of the waste management procedures, since it implies the use of valuable space (needed for storing the separated waste).

A possible solution for reducing or eliminating the generated cellulosic waste left after the above discussed paper consumption optimizations could be that of shredding and burning it in an incinerator. This would result in an instantaneous elimination of the waste. On the other hand, cellulosic materials have a pretty high energetic content, which could be recovered with an appropriate equipment. In the following we will hence analyze how it can be possible to follow this approach.

3.3. Energy recovery from cellulosic waste

Modern cruise ships must treat and process wastes in reduced spaces with respect to ground-fixed installations, due to the necessity of preserving space for maximizing the number of on-board cabins. They also need to reduce as much as possible the space necessary for the waste storage conservation during the cruise. More-

Table 2
Estimations of paper savings achievable on our model ship by simple rationalization of paper use and digitalization of documents (upon Strazza et al, 2015).

Item	Current consumption* (kg/year)	Prospected savings		
		kg/year	€/year	kg CO_2/year
Ship news	25,343	12,671	205,179	29,969
Hygiene paper (towels + toilet paper)	54,694	13,674	18,300	20,143
Crew information paper (A3 + A4)	31,165	15,583	252,321	26,364
Total	**111,203**	**41,928**	**475,803**	**76,476**

over, they need to treat different types of waste (food, plastic, etc.), with the consequent plant complexity, again with an eye to the minimization of the space allowed for such plants and related technical services.

One option for achieving these results is the use of on-board incinerators, which are already present as a standard equipment on cruise ships. Nonetheless, it is in principle possible to explore also other approaches, as hereafter described.

3.3.1. Exploitation of incinerators' exhaust flue gas

Usually, cruise ships designed by Fincantieri S.p.A. take advantage from two small incinerators (less than 2 MW each). The two plants are utilized alternatively one day each, for a daily operating time around 11 h, corresponding to the mean navigation time from port to port away from the coast, and the thermal energy embedded in flue gases is lost through the chimney and released to the atmosphere.

Ideally, this wasted thermal energy could be recovered as electric energy, using appropriate equipment, like a steam turbine. However, from a practical point of view this is not economically convenient, due to the plant costs, the associated logistics (required room for the plant itself and the associated technological services, like pipes, heat exchangers, etc.). In addition, the existing regulations forbid the use of on-board incinerators when the ship is close to the coast, i.e. pretty often during a standard cruise, thus limiting the available time for the practical use of these plants.

On these grounds, a more suitable option could be the direct recovery of at least a part of the residual thermal energy emitted with the incinerator's flue gas. However, up to now such option has not been explored, possibly, again, due to the need to install additional facilities to the ship (as a minimum, a new heat exchanger and the related piping line), with the consequent loss of valuable space. Nonetheless, in the following we will analyze this possibility, with the assumption that the aforementioned minimal plant components (heat exchanger plus piping line) can be fit into existing technical compartments, thus not requiring further free space with respect to that currently used. A further caveat is that this approach can be currently pursued only as a support to, and not as a substitute for, an already existing cooling plant, since, as previously discussed, incinerators can only work during open sea navigation.

The final use of the so-recovered thermal energy must also be carefully considered.

In fact, in a cruise ship the energy for heating the cabins and the other ship rooms and technical compartments must be assured also when the vessel is in port. This energy is currently provided by the main engine, which works at the minimum regime also when the ship is in port (as incinerators can be used only in open sea). The engines generate mechanical work, which is transformed into electrical energy, which is then fed to the services needing it.

A part of this energy is used by air conditioning (Heating, Ventilation and Air Conditioning, HVAC); however, this quota is about one order of magnitude larger than that generated by standard incinerator plants. Therefore, also for air conditioning purposes the use of exhaust thermal energy is not a viable option.

Refrigeration for food conservation (*chilling and freezing systems*), which operates on two different temperature ranges (one above and one below zero Celsius degrees), can instead represent an interesting opportunity for this source of recovered energy. In fact, in our model cruise ship the chilling systems need 414 kW_t, which can be fully provided by one of the two identical incinerators (having an overall power of 3600 kW_t). The extraction of the residual thermal energy from the flue gases of the incinerator can be accomplished by means of an absorption cycle. For this task we considered a water ammonia absorption chiller operating with the generator temperature around 150 °C and the evaporation set to −5 °C, taking into account thermodynamic properties of the ammonia-water system as described by Pátek and Klomfar (1995). With this type of option, a preliminary Coefficient Of Performance (COP), calculated as the ratio between cooling duty and generator heating duty, obtained from the exhaust flue gas, has been estimated to be about 0.5, in line with (Karamangil et al., 2010).

Upon these numbers, for our model ship a preliminary design of such a system foresees to dissipate to seawater the thermal power generated by condenser and absorber, at a maximum temperature of 35 °C. For the heat exchangers functioning, the temperature difference was considered equal to 5 °C. With these values the absorption plant exchanges around 1417 kW_t with the seawater, recovering about 976 kW_t from the incinerator's exhaust flue gas. The so-designed thermal energy recovery system does not need any further electrical energy (except for a small self-consumption, necessary for the pump, which for our purposes can be neglected). The overall cost of this plant can be estimated at about 450,000 € ("Private company communication - Confidential information," 2018).

The use of this system allows to recover thermal energy from the flue gases, with a consequent saving in the overall ship electrical energy utilization, as well as in fuel consumption. To correctly evaluate the amount of these savings it is mandatory to consider the involved system as a whole (from the chemical energy contained in the fuel to the electricity generated by the alternators associated with the main engines). In this view we must consider that the specific fuel consumption in nominal functional conditions is equal to 208.8 g/kWh_e (electrical energy). The electrical power consumption of the currently adopted chilling system, due to the vapor compression system, is about 196 kW_e, which corresponds to a fuel consumption of 41 kg/h of operations. Obviously, such a system won't work on a constant basis, and its factor of utilization will depend on the thermal isolation of the cell and on how frequently the chiller room access door is opened. However, accurate data about the utilization factor of these systems are currently not available, hence we have analyzed three possible scenarios, which correspond to three different utilization factors: 25%, 50%, and 75%, as shown in Table 3. We have also calculated the corresponding cellulosic waste consumption, considering for it a mean LHV (Lower Heating Value) of 17.6 MJ/kg (calculated on the basis of the LHVs reported in ("Phyllis2," 2020)) and an overall effectiveness of the heat exchange system equal to 0.85. This LHV of the considered cellulosic waste, higher than that of simple paper / cardboard, reflects the presence of a sizeable amount of wood in this waste fraction.

Table 3
Calculated savings for different utilization factors of the considered absorption plant.

Utilization factor (%)	Wasteusage (kg/year)	Fuel savings (kg/year)	Economic savings (€/year)	CO_2 emission reduction (kg/year)
25	196,994	34,389	11,589	110,388
50	393,988	68,778	23,178	220,776
75	590,982	103,166	34,767	331,164

The estimated fuel cost is taken as 0.337 €/kg (market price of IFO 380 at Jan 2020). In Table 3 we reported also the estimated savings and the reduction for CO_2 emissions, calculated on the basis of available data (Winnes and Fridell, 2009), and of our estimation for the plant utilization factor.

As is visible from Table 3, even at the lowest utilization factor (25%) the suggested recovery of residual heat from incinerators guarantees a sizeable saving in fuel consumption and in CO_2 emissions. However, considering the additional plant costs (450 k€), for the 25% utilization scenario an approximate estimation (no value actualization, no mortgage, nor any hypothesis of environmental certificates exploitation) provides about 38 years needed for achieving the break-even point, which lowers down to about 13 years for the 75% utilization scenario. The overall convenience of this strategy is hence questionable under the merely economic point of view. Nonetheless, it holds some significance considering the avoided CO_2 emissions, and may assume more importance upon possibly upcoming international regulations further limiting the accepted CO_2 emissions.

3.3.2. An alternative to incinerators for cellulosic waste treatment: Gasification plant with syngas production

Gasification plants can use cellulosic waste for producing syngas. In our case this process can provide a sizeable reduction of weight and volume of the cellulosic material, and a more efficient valorization of its energetic content, at the same time delivering a relevant contribution to the overall energy needs of the ship, since modern dual fuel engines can be fed by either heavy oil or gaseous fuels (as syngas) (Costa et al., 2017; Fernández et al., 2017; Merts and Verhelst, 2019).

As syngas is a hazardous gas, several authors have analyzed its potential safety problems in terms of plant safety and explosion risks, with specific reference to syngas derived from biomass (Di Sarli et al., 2014; Molino et al., 2012; Pierorazio and Baker, 2010), even in presence of advanced equipment like fuel cells (Pastorino et al., 2011). In general, these studies concluded that using appropriate safety measures (mainly extra-careful plant design, and often additional equipment and/or services with respect to standard plants) can be extremely effective to prevent hazards and risks like explosions or fires. On the other hand, in the following, the specific aspects of safety of syngas plants will not be considered, in order to keep the focus of the paper on the more general and policy-relevant aspects of the use of such plants aboard commercial vessels.

In order to evaluate the contribution that a syngas plant can provide to our model ship, food waste has not been considered as a feed, since according to international regulations it can be dumped at sea, which is the standard practice in the cruise industry. Therefore, we considered only cellulosic waste as syngas plant feedstock, under continuous feeding, with the assumption that the produced syngas is used to power the main engine, lowering the overall amount of fuel needed for ship operations.

The daily availability of this type of waste for the considered vessel, accounting for the previously exposed paper minimization strategy (see par. 3.2), is equal to about 4120 kg/day, that is 172 kg/hour (as the syngas plant is expected to operate 24/7).

As reported by Susastriawan and colleagues (Susastriawan et al., 2017), a reactor with cylindrical shape (height of 0.85 m, diameter of 0.3 m) fed by corn straw with a feeding rate of about 9.4 kg/h can produce about 20.12 Nm^3/h of syngas. The chemical composition of corn straws and paper/cardboard/wood are similar, and also their LHVs are very close (Ahmed and Gupta, 2009; Baggio et al., 2008; Hu et al., 2019), so in the following we will refer to these values for a first evaluation of the potential of the discussed syngas plant.

If a syngas reactor replaces one of the two incinerators normally present on a cruise ship, it can occupy the corresponding volume, which can be approximated to a parallelepiped with sides of 6, 2 and 5 m each; using reactors similar to those described by Susastriawan and colleagues (Susastriawan et al., 2017), it is possible to install about 36 reactors. This layout would allow to process a total of about 338 kg/h of material (to be compared to the foreseen 172 kg/h of waste availability), a value that can by far grant the use of all suitable waste daily produced aboard. Indeed, the projected waste amounts can be treated using more compact reactors, leaving residual technical compartment space that could be used for auxiliary plants, syngas storage, additional safety equipment.

The LHV of the syngas produced from cellulosic materials is variable, depending on the used technology, but for our purposes we can estimate it around 14.5 MJ/kg (about 13.0 MJ/Nm^3) (Ahmed and Gupta, 2009; Madadian, 2018). Considering that the hypothesized reactor can produce about 8836 Nm^3/day, the use of this gas will deliver about 114,864 MJ/day of thermal energy. For the IFO 380 fuel the LHV is about 39 MJ/kg. Therefore, using the obtained syngas as a fuel for the main engines will allow a total fuel saving of about 2945 kg/day, corresponding to a total of about 993 €/day of navigation (market price of IFO 380 at Jan 2020). Upon a yearly syngas production of about 2,700,000 Nm^3, the savings will be approximately equal to 900 t/year of fuel, 300,000 €/year and 2900 t/year of avoided CO_2 emissions, which are definitely remarkable.

In order to make a more complete economic assessment, the cost of the so-dimensioned syngas plant (including accessory services like cooling, washing, dehydration, dosing of the syngas to the internal combustion engine, safety-related equipment) needs to be considered. However, to the best of the author's knowledge, such a kind of plant has not yet been installed on cruise ships, basically because of the aforementioned needs of cruise ships for space reserved to cabins.

In this frame, it is not possible to provide here a precise evaluation of the overall costs associated to a ship-compatible syngas plant. Nonetheless, we deem reasonable to use the values associated to syngas plants realized in small cities or for small communities, of a size compatible with the amount of passengers carried out by our model ship. For this estimation, we considered the work of Mondal and colleagues (Mondal et al., 2011), who states that for this kind of plants the 49% (i.e., about the half) of total plant costs is given by feedstock handling, gasifier and gas cleaning (all necessary steps for direct feed of the produced syngas to the ship engine). On this basis, we used our foreseen hourly syngas production (in line with that reported by Trippe et al. (Trippe et al., 2011)) to calculate an approximate plant cost of about 260,000 €. With this reference number, for a simple approach without any further economic consideration (i.e., once again without value actualization, nor mortgage, or environmental certificates exploitation), we make a first estimate of less than one year needed in order to recover the plant costs, when the available cellulosic waste (residual after the optimizations prospected in par. 3.2) is fully exploited. Such a short period would fully justify the installation of this type of plant onboard.

3.4. Scenarios of waste management optimization

In the following we analyze three different scenarios for the practical application of the described waste optimization strategies. For all of them the use of returnable glass bottles and the reduction in paper consumption has been kept as a common background, upon the environmental considerations already exposed in par. 3.1 and 3.2. Taken together, these two options allow to achieve a definitely notable saving in terms of cash (almost half a million euros/year, mostly deriving from the paper optimization).

The following scenarios are based hence on the adoption of the aforementioned glass and paper management policies, topped by the aforementioned thermal energy recovery from waste strategies. The basic assumptions and data underlying these energy recovery strategies are hereafter summerized. The overall ship navigation days in a year has been taken equal to 305; the incineration system was considered operating at 11 h for each navigation day; the chilling plant utilization factor was considered equal to 50%; the syngas plant operating time was assumed to work 24/7 (even with the ship berthed at pier, since a syngas plant has no emissions hindering its operations in port). In addition to these conditions, we assumed a cost of the IFO 380 fuel of 0.337 €/kg (market prices at Jan 2020). We are aware that the use of syngas requires a suitable engine, able to burn the gas, and that hence the consideration of the IFO 380 could appear as not appropriate. However, our model ship currently uses liquid fuels, and dual fuel engines (i.e., engines able to burn liquid or gaseous fuels, or even combinations of the two) are starting to appear more and more often on the market. This choice has thus solid grounds in the ongoing technological developments going on in the naval field.

The three scenarios are defined as follows.

Scenario 1: thermal energy recovery from exhaust flue gas of incinerator, with no further energy recovery; *Scenario 2*: mixed incinerator/syngas use, with the incinerator burning the amount

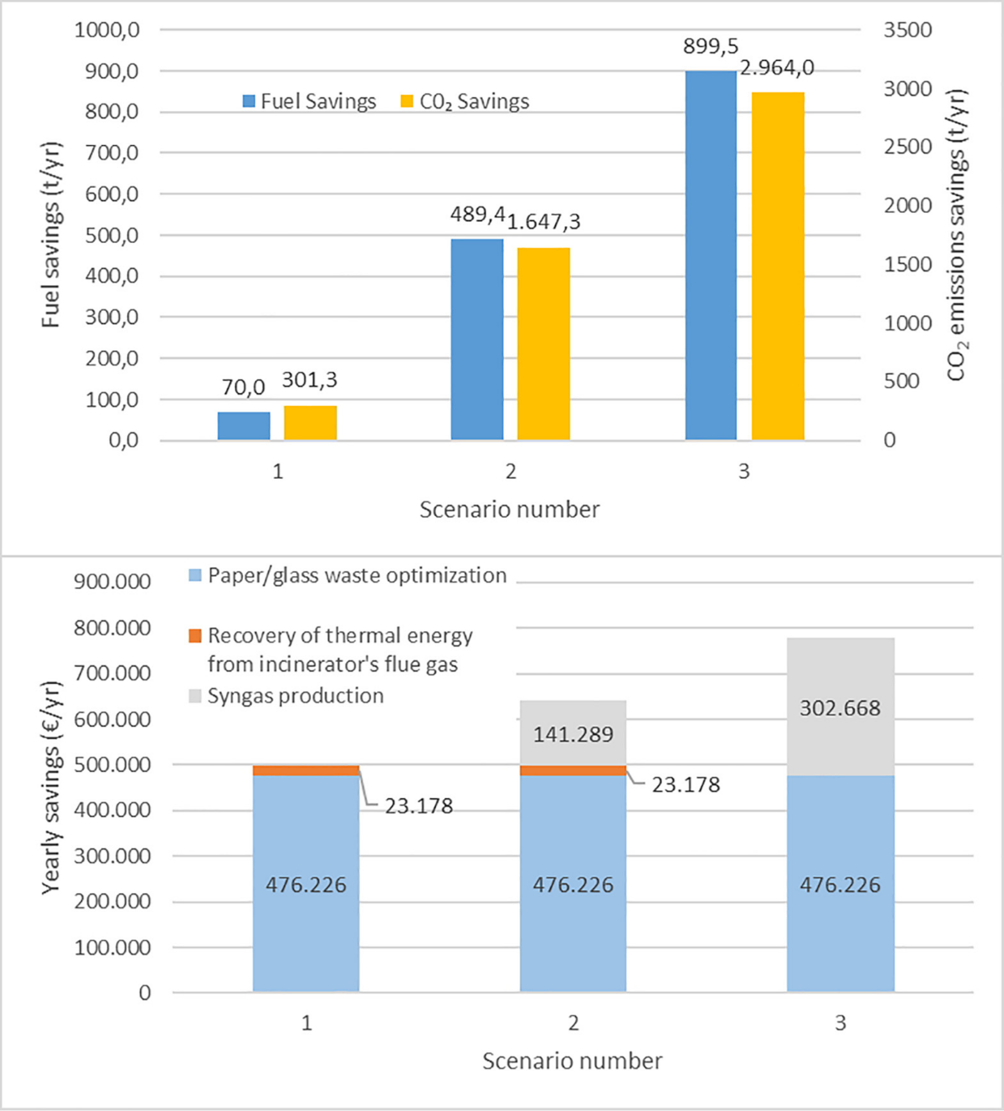

Fig. 3. a): Yearly savings achieved upon the different scenarios for a) fuel consumption (blue rectangles) and CO2 emissions (orange rectangles). b): Yearly cash savings for the considered scenarios, evidencing the contribution provided by each of the proposed strategies, namely paper/glass optimization (cyan rectangles), thermal energy recovery from incinerator's flue gases (orange rectangles), and syngas production (grey rectangles). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of cellulosic wastes necessary to supply (via the absorption plant) the thermal energy for the chilling system, and the syngas plant treating the remaining cellulosic waste; *Scenario 3*: all the cellulosic waste, including the paper waste left over after the use rationalization, destined to syngas production (no incineration).

The benefits of the three proposed scenarios are illustrated in Figure 3 in terms of economic savings (calculated on the basis of avoided costs for saved fuel), amounts of saved fuel and amounts of avoided CO_2 emissions.

As is visible in Fig. 3a, in the first scenario the recovery of the thermal energy deriving from the exhaust flue gas generated by the combustion of the residual cellulosic waste (par. 3.2) provides some modest saving of fuel (about 69 t/year) and CO_2 emissions (about 221 t/year). The economic savings, highlighted in Fig. 3b, are overall meaningful, but only due to the inclusion of the contribution of the glass/paper (mainly paper) use optimization, as the contribution of the thermal energy recovery itself is marginal.

In the second scenario the benefits of the synergy between the syngas plant and the thermal energy recovery are evident from both an economic and an environmental point of view, as this ensures sizeable economic savings (about 165,000 €/year, additional with respect to those already granted by the glass/paper optimization policies, see Fig. 3**b**) and notable savings also in terms of fuel (about 490 t/year) and CO_2 emissions (about 1550 t/year), as can be seen in Fig. 3a.

The benefits of adopting syngas on board are even more evident when considering scenario n° 3, in which all the cellulosic waste (including the paper waste available after the paper consumption optimization step) is fed to the syngas plant to produce gaseous fuel for the ship engine. In this case, more than 2800 t/year of CO_2 emissions are avoided, about 900 t/year of fuel are saved (Fig. 3a), as well as a remarkable amount of money, ranging around 300 k€/year Fig. 3b). This latter result is even more interesting when put on top of the already considered about 500 k€/year savings provided by the glass/paper optimization strategy.

4. Conclusions

In this paper we analyzed the waste management policies currently adopted on board of an existing cruise ship, so to have a real-life case exemplifying the impact that these optimizations could deliver on this type of vessels.

In particular, we focused on several optimization options: minimization of glass waste (via the introduction of "returnable glass"); minimization of paper waste (via rationalization of the production of informative leaflets and minimization of consumption of toilet paper); recovery of some energy from the flue gas produced by the incinerators (already present on cruise ship as standard equipment) via the use of an additional absorption plant; introduction on the ship of a gasification plant able to exploit cellulosic waste for the production of syngas, to be directly fed to the ship engines. For each of these options we calculated the achievable benefits in terms of reduced fuel consumption, avoided CO_2 emissions and cash savings (evaluated on the basis of the avoided fuel consumption). Since many of the proposed solutions were novel to the field, it was not possible to provide precise assessments of the overall costs associated to the different approaches. Nonetheless, for an approximate evaluation of such costs we deemed reasonable to use the values associated to absorption and syngas plants realized on mainland, having a power level/waste consumption rate similar to those of our model ship.

Finally, we analyzed three different scenarios based on different energy recovery options after glass/paper consumption optimization, i.e. thermal energy recovery from exhaust fumes of incinerator (Scenario 1), mixed thermal energy recovery from incinerator/syngas generation from a part of cellulosic waste (Scenario 2) and maximum syngas production from cellulosic waste (Scenario 3). The Scenario 3 is the most effective one, allowing by far the highest savings in terms of money (about 780 k€/year), fuel consumption (about 900 t/year) and CO_2 emissions (about 3000 t/year). The other two scenarios provide lesser advantages, with the number 1 being the less effective.

One of the most interesting outcomes of this study is that for each scenario the most impacting strategy in terms of economic savings is a simple paper use rationalization, which allows to reduce the costs by about 480 k€/year; therefore, it is evident that even a trivial but clever design of the general waste management process, without any expensive investments, can provide very high benefits to the economic results of cruise activities. Moreover, the exploitation of a syngas generator emerged as a key tool for lowering the environmental impact (CO_2 emissions) of modern cruise ships, allowing the direct transformation of waste in exploitable fuel, and a concurrent remarkable economic saving of the operational costs of the vessel.

Future research will involve attempts to integrate the prospected syngas production plants within the already existing on-board waste treatment systems, as well as integrated Life cycle assessment to obtain the best configuration for the waste exploitation.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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