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Multi-objective decision support to enhance environmental sustainability in maritime shipping: A review and future directions

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ABSTRACT

This paper aims to examine the potential of multi-objective optimization (MOO) as a decision support to improving sustainability in maritime shipping. We focus on environmental sustainability and the trade-offs involved with economic and operational objectives. Through a systematic approach, we review the literature on environmental sustainability, decision support and multi-objective optimization in maritime shipping. We identify the gaps and directions for future research. It is expected that the next generation of decision support systems for maritime transport will exploit the theoretical development in MOO to facilitate informed decision making in maritime supply chains considering environmental sustainability and the competing objectives.

1. Introduction

Sea transport is a vital component of the world's economy, as the largest carrier of freight around the globe. Environmentally sustainable operations in maritime shipping have emerged as important topics for firms involved in maritime supply chains and policy makers (Cheng et al., 2013). In this line, the emission of greenhouse gases (GHG) from maritime transport has attracted increasing attention as a global issue over the past decade (Qi and Song, 2012). The International Maritime Organization estimated the level of GHG emitted by ships in 2007 at 1046 million tons of CO_2, about 3.3% of the global emissions (Buhaug et al., 2009), and in 2009 has set a target of a 15% reduction in maritime emissions by 2018 (Buhaug et al., 2009). Minimizing the carbon footprint and fuel consumption is a strategic direction for shipping companies. Research indicates that the financial and business performance of companies can be directly influenced by socially and environmentally responsible business practices (Sarkis, 2006). A reduced environmental impact and enhanced fuel efficiency will directly contribute to the environmental sustainability and economic prosperity of maritime supply chains, and furthermore will indirectly contribute to social sustainability as the third pillar, via improved quality of life: more economic operations can create more jobs in the shipping industry.

In the past few years, there has been a growing interest among researchers and practitioners to reduce the carbon footprint of maritime shipping by adopting sustainable operations management practices. These include operational decisions such as speed reduction, berth scheduling and route re-engineering to rationalize fuel consumptions and to reduce CO_2 emissions. The earlier work in this area has regarded minimizing GHG emissions as an implicit objective, surrogated by minimizing fuel consumption and cost, which could be combined with other items (such as penalty charges). We argue that such an

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assumption could negatively affect the post-optimization analysis by overlooking the true cost of GHG emissions and its impact on the environment. It would be illuminating for members of maritime supply chains to assess the trade-offs involved with their operational decisions, including energy consumption (and not just its cost) and GHG emissions, as explicit decision criteria. Such an approach will support informed decision making through the analysis of the impact of operational decisions (such as scheduling, routing and speed decisions) on the environment.

This paper aims to address this gap by providing a systematic overview of the extant literature on sustainability in maritime shipping as a challenge involving multiple objectives. We examine the potential of MOO to facilitate informed decision making by shipping companies. We have selected three distinctive areas for our literature search. First, we consider sustainability in maritime supply chains as a focused area of our exploration. Given that enhancing sustainability in maritime shipping involves trade-offs between environmental, economic and social dimensions, we are interested to examine the potential of MOO to analyze such trade-offs among competing objectives such as fuel emissions and service level. Therefore, we explore the extant body of literature on multi-objective optimization in maritime shipping as the second area of investigation. The outcome of the literature review in those areas is expected to contribute to theoretical implication of the study. The implementation of MOO based methodologies for practitioners requires the development of decision tools that can be used by members of maritime supply chains as they are usually not experts in mathematical modeling and analysis therefore require systematic support by information systems that are equipped with user friendly and easy-to-use user interfaces. Also, any trade-off relationships among multiple objectives in an optimization problem can best be analyzed and visualized through what-if analysis which is one of the core functionalities of a DSS. Hence we examine the literature on decision support systems for maritime shipping as the third area of examination to identify practical implication of the study. We explore these three areas (i.e. environmental sustainability, decision support systems (DSS)[1] and MOO in maritime supply chains) in a systematic way, outlined in Section 3, and place particular emphasis on the overlaps across the three areas.

Earlier survey papers have examined various focused areas in maritime operations. Christiansen et al. (2013) surveyed the recent developments in ship routing and scheduling as the fourth review by the authors in over three decades. Earlier reviews on this topic include Christiansen et al. (2004) and Ronen (1983, 1993). The literature on bunker optimization methods in maritime shipping has been reviewed by Wang et al. (2013a). Tran and Haasis (2013) review the literature on network optimization in container liner shipping in three categories: container routing, fleet management and network design. Our survey is distinctive from earlier work in terms of its aim, focus and scope. We are particularly interested in the role of MOO as a DSS to enhance the sustainability of maritime supply chains, an area which has not been explored previously. The main contributions of the paper can be summarized as follows:

- Our work has identified the gaps in the theoretical development of MOO as part of a decision support system to enhance environmental sustainability in maritime shipping.
- Through a systematic approach, our research identified the extant body of literature in three areas, namely environmental sustainability, DSS and MOO in maritime transportation.
- By analyzing the literature in the aforementioned areas and their overlap, we provide a detailed discussion of their aim and objectives, methodological approach, the type of data and key findings.
- We assess the trend of publications in the aforementioned areas to identify those areas that need future attention to facilitate informed decision making in maritime transportation, considering environmental sustainability as an explicit objective.

The remainder of the paper is organized as follows. Section 2 provides an overview of decision making in maritime shipping. The methodological approach undertaken is introduced in Section 3. The three research areas are reviewed in Sections 4–6. Finally, Section 7 concludes the paper by discussing the main finding including gaps, trends and future research directions.

2. Decision making and sustainable maritime transportation

Sustainable maritime transportation involves complex decisions and multiple actors. Moreover, it is influenced by economic, social and environmental responsibilities (IMO, 2013). The realization of a sustainable maritime transportation system faces multifaceted challenges regarding technical and organizational barriers, market and policy framework support, and socioeconomic acceptance (Tsamboulas and Moraiti, 2013). Informed decision making in such environment requires adequate support to underpin the so-called three pillars of sustainability for members of maritime supply chains. The majority of the existing decision tools for maritime transportation focus on cost and/or operational performance indicators. Examples of such systems are introduced by Fagerholt et al. (2009) and Lam (2010). Sustainability measures are now being considered in commercial decision support systems (DSS) for maritime transportation. Kontovas and Psaraftis (2011) surveyed the literature on speed decisions and its impact on the environment. They discussed lessons learned by slow steaming providing the link between economy and the environment for the sustainability of liner shipping. More recently, Psaraftis

[1] We use DSS as an acronym in both the singular and the plural case.

and Kontovas (2013) summarized speed models in maritime transportation, i.e. models in which speed is one of the decision variables.

Sustainability considerations in maritime shipping involve several and usually conflicting objectives. As an example, minimizing fuel emissions, an indicator of environmental sustainability, and maximizing service level, a performance metric for economic prosperity, cannot be achieved at the same time. As a result, the associated decision problem has the potential to be modeled and tackled as a multi-objective optimization problem (MOP). MOP aims to find a vector of decision variable $\tilde{x}$, for an optimization problem including multiple objectives that can be stated as: Minimize (or Maximize) [Set of objectives]; subject to [Set of constraints]. Without loss of generality, such decision problem minimize a vector of M objective functions $f_i(\tilde{x})$ where $i = 1, 2, \ldots, M$; subject to inequality constraints $g_i(\tilde{x}) \geqslant 0$ and equality constraints $h_k(\tilde{x}) = 0$ where $j = 1, 2, \ldots, J$ and $k = 1, 2, \ldots, K$. A decision vector $\tilde{x}$ dominates decision vector $\tilde{y}$ (also written as $\tilde{x} \succ \tilde{y}$) if and only if: $f_i(\tilde{x}) \leqslant f_i(\tilde{y}) \forall i \in \{1, 2, \ldots, M\}$; and $\exists i \in \{1, 2, \ldots, M\} | f_i(\tilde{x}) < f_i(\tilde{y})$. All decision vectors that are not dominated by any other decision vector are called non-dominated or Pareto-optimal. The reflection of Pareto-optimal set in the objective space is called *Pareto frontier* and usually takes the form of a trade-off curve. There are various solution approaches for solving the MOP, including: sequential optimization, ε-constraint method, weighting method, goal programming, goal attainment, distance based method and direction based method (Collette and Siarry, 2003). Given the complexity of MOPs in most practical instances, metaheuristics such as evolutionary algorithms have extensively been applied to solve large scale and complex MOPs (Deb, 2001; Coello et al., 2007).

The implementation of trade-off analysis for shipping companies and port operators requires the development of decision tools. A decision support system (DSS) is aimed at supporting decision making of top managers or executives who are usually not experts in mathematical modeling and analysis. Handling multi-objective problems by such decision makers require systematic support by an information system that visualize optimization results of different scenarios in which the weights of conflicting (or complementing) objectives are adjusted to find the best strategies for maritime transportation meeting the legal regulations and at the same time maximizing company performance indicators. A DSS comprises a set of procedures to assist managers in making informed decisions (Little, 2004). Generally speaking, a DSS contains five main components: data base (DB), model base (MB), knowledge base (KB), decision procedures (DP) and a graphical user interface (GUI) (see Fig. 1). The DB stores the data whilst the MB and KB store the collections of models and knowledge, respectively. The procedures contained in the DP are used to choose appropriate model(s) from the MB and extract relevant data and knowledge from the DB and KB respectively to facilitate informed decision making. The GUI allows the user to interact with the system. The trade-off relationships among multiple objectives are visualized through easy-to-use GUI.

Despite its importance, studies on DSS for the maritime industry are considerably fewer in number than those for other sectors in the transportation industry, including land and airline applications (Fagerholt, 2004). The maritime industry's conservative thinking (Fagerholt, 2004) and traditional reticence to invest resources in organizational problems (Grabowski and Hendrick, 1993) are criticized as the reasons for such a lack of studies on DSS for maritime shipping. Therefore, the majority of studies in the literature have been theoretical and experimental in solving maritime routing and scheduling problems (Fagerholt et al., 2009). DSS create in general more benefits when they are used to support semi-structured and unstructured decision problems, as decision makers need to consider not only quantitative but also qualitative variables. Decision makers for planning and implementing green maritime shipping without exception have to address such decision problems considering the complexity and large number of variables (Barnhart and Laporte, 2006). This triggers an alarm for the scholars in the field and it is timely to review the existing studies on DSS for sustainable maritime shipping and identify future research directions.

Multi-objective optimization (MOO) can be embedded in a DSS framework for trade-off analysis. In this scenario, a multi-objective optimizer will act as an integral component of the MB. It uses the data stored in the DB and/or those captured through the GUI. The final Pareto frontier is then represented to the users via the GUI.

MOO has been considered as a decision support in a number of applications, for instance by Blecic et al. (2007), Kollat and Reed (2007) and Finkelstein et al. (2009). In order to demonstrate the idea of using MOO in a DSS framework, consider the Pareto frontier shown in Fig. 2, which visualizes the trade-off between service level and CO_2 emissions in a hypothetical ship scheduling problem. The conflict between the two objectives in maritime shipping has been discussed by a number of scholars, including Corbett et al. (2009) and Qi and Song (2012). Slow steaming, which is a common practice to save fuel, tends to prolong the vessel's journey time. In case of delays, vessels usually sail at faster speeds (hence more fuel consumption) to make up for the delays and to meet the service levels, as agreed by ports and customers. Depending on the vessel's specification, load and environmental conditions, fuel consumption is usually a cubic function of speed (Fagerholt et al., 2010; Meyer et al., 2012). If service levels were the only decision criteria, any (feasible) move toward the right hand side of the x-axis, for instance from schedule **a** to **b** could be justified. Such a move could be made by fast steaming in multiple legs along a shipping route. In a multi-objective analysis however, and as the Pareto frontier indicates, such transition in some areas will only result in a marginal benefit (i.e. increased service level) at the expense of a significant sacrifice of the other criteria (i.e. CO_2 emissions). The actual shape of Pareto frontier for any vessel depends on a number of parameters, such as load and environmental conditions. A fast trade-off analysis between schedules **a** and **b** could support ignoring a 10% increase in service level (at schedule **b**) and going for schedule **a** in order to save 30% extra emissions.

There are cases in which it is important to consider the total cost of shipping explicitly (Palacio et al., 2013; Psaraftis and Kontovas, 2010). This is the case, for instance, when delays are subject to penalties, or reward mechanisms are in place for

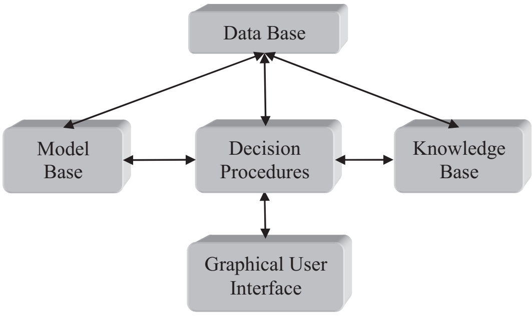

Fig. 1. The main components of a typical decision support system.

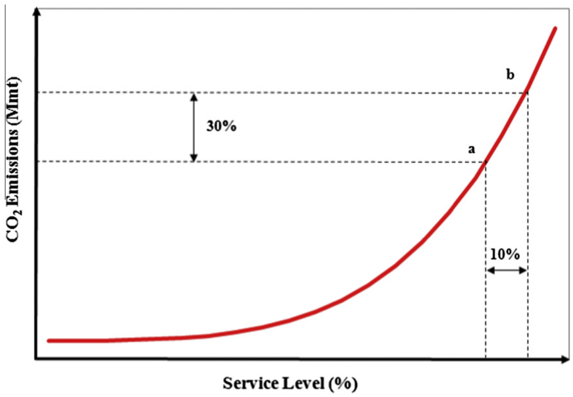

Fig. 2. The Pareto frontier of a typical bicriteria ship scheduling problem.

delivery within tight and expedited time windows at some ports. Such decision problems would entail the analysis of trade-offs in a three-objective problem in order to minimize emissions whilst maximizing service level and minimizing cost. The Pareto frontier in this case will be a surface as depicted in a hypothetical vessel scheduling problem in Fig. 3.

3. Research methodology

We adopt a systematic approach to review the extant literature in order to identify the gaps in the application of MOO to support decision making in maritime shipping, focusing on environmental sustainability and the trade-offs involved, including those with economic sustainability. Fig. 4 illustrates the three focused areas that we cover in this review. Environmental sustainability in maritime shipping is a key attribute of our survey so it is selected (circle A) as a focus area of our search. Given that enhancing sustainability in maritime shipping involves likely trade-offs between environmental, economic and social dimensions, we are interested to examine the potential of MOO (circle C) to analyze trade-offs among competing objectives such as fuel consumption and service level. Furthermore, the application of MOO based methodologies for practitioners requires the development of decision support systems that can be applied in shipping operations. Hence we are interested to examine the status quo of DSS for maritime shipping (circle B) and areas for further development to characterize trade-offs involving sustainability metrics.

We searched databases that index relevant publications to the research area. These include: ABI Inform, Business Source Premier, ACM Digital Library, IEEE Xplore, Science Direct, and Scopus. We restricted the search to peer reviewed journals and conference proceedings whose full texts were accessible through the above databases. In category 'A' we excluded papers that addressed the cost minimization of maritime operation without explicit consideration of the associated cost on environment or society as the two pillars of sustainability. For an up-to-date review of previous research on cost minimization in maritime operations, the reader may refer to Christiansen et al. (2013) and Wang et al. (2013a). In category C, we considered those papers addressing multi-objective optimization problems in the maritime area. As such, we exclude papers using multi-attribute decision making (MADM) from this category as they deal with 'selection' rather than 'design' problems.

We searched the databases (title, keywords and abstract) using combinations of the keywords to find the core of the literature as detailed in Table 1. For instance, to find articles in category 'A', we combined (using AND) the key words under maritime shipping (using OR) with any of the keywords under category 'A' (using OR). We then examined the found articles

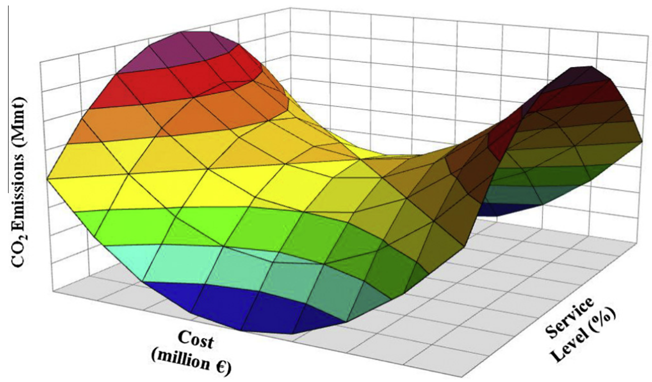

Fig. 3. The Pareto frontier of a typical three-objective vessel scheduling problem.

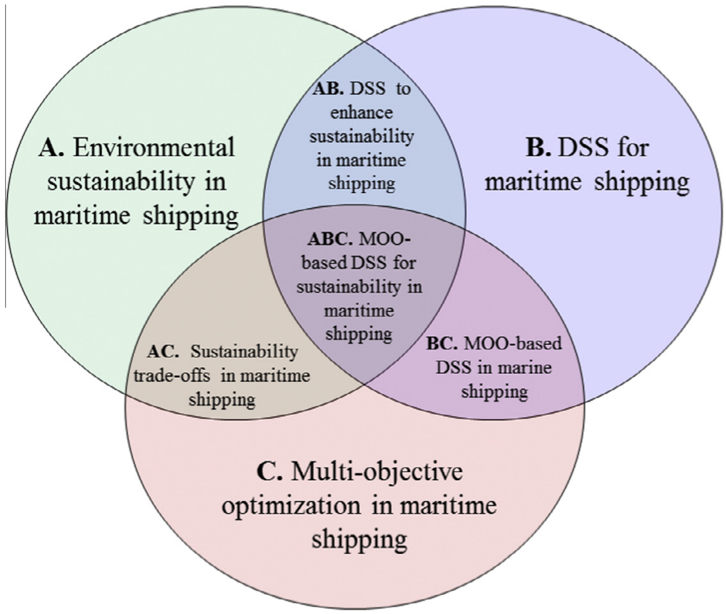

Fig. 4. The scope of the literature review.

to ensure their relevance to the focused areas of this survey. After close examination of the articles, we removed those articles that did not address at least one of the three areas A, B or C. To ensure the coverage of the search, we further examined the list of references of the remaining articles and included new items not found through the database search. As a coverage test, we tracked forward a number of key references identified in the previous stage using Google Scholar's citations reporting utility. We examined the articles that cited these references and added new items to the list. We refined the search keywords as new items were identified and reran the search iteratively using new keywords. The final set of keywords is listed in Table 2. At the end of this process, 52 articles were found that address at least one of the three focused areas of this survey. Table 2 provides a summary of these papers, including their aims and objectives and the areas that they address (A, B, C).

4. Environmental sustainability in maritime shipping

Sustainability has imminently become of great influence in the design of organizational business models (Sarkis et al., 2013). This has invariably resulted in increased interest in sustainability related research and the maritime sector is not left out. The observed trend in maritime sustainability literature as will be seen in subsequent sections is the extensive use of certain modeling approaches which have proven to be very helpful theoretically but without much practical implementation. The emphasis on fuel consumption minimization (mostly single objective optimization) hence emission reduction coupled with the previously mentioned trend further constrains the practicality of the solutions obtained. Many of the researches also affiliate their motivation to the environmental regulations imposed by various world organizations such

Table 1
The key words used for searching the data bases.

	AND			
	Maritime shipping	OR		
		A. Environmental sustainability	B. Decision support	C. Multi-objective optimization
OR	Sea transport; Maritime logistics; Liner shipping; Sea port; Marine shipping	Sustainability; CO_2 emission; GHG emission; Carbon dioxide; Fuel consumption; Fuel emission; Greenhouse gas emission; Slow steaming; Speed optimi?ation	Decision support system; DSS; Decision support; Decision aid; Decision tool; Decision making	Multi-objective optimi?ation; Multiobjective optimi?ation Multi-criteria; Multicriteria; Multiple criteria; Bicriteria; Pareto front*; Trade-off analysis; Tradeoff analysis; Efficient frontier

* Any string of characters; ?: Any single character.

as the International Maritime Organization (IMO). All of these factors although very helpful for theoretical understanding, still leave an implementation gap hence the proposition of multi-objective DSS in maritime sustainability research. This approach offers not only a methodical advantage (which has been duly discussed in Section 2) but also a possibility of practical implementation of solutions obtained. The following paragraphs present discussions based on trend observed in the reviewed set of literature.

We begin with the trend observed with the increasing awareness about sustainability in maritime shipping. This trend is indicated by the increasing number of publication in this area in recent years. Fig. 5 shows this trend based on the number papers reviewed in this section.

Between the years 2000–2005 only one paper published on sustainable maritime. The number has increased to four between the years 2006–2010. The bulk of literature reviewed (a total of 21) were published between 2011 and 2014. The trend shows that there is a great awakening to maritime sustainability research particularly in the current decade. This may be due to reinforced emphasized being placed on maritime research and as well as increasing demand for sustainable shipping practices.

Another observed trend is the solution approach employed by the researchers. It was observed that majority of the papers reviewed employed some form of technical approach as solution to their proposed problem. These technical approaches include: slow steaming (Cariou, 2011; Yin et al., 2014; Woo and Moon, 2014), speed optimization (Kim et al., 2014; Ballou et al., 2008; Sheng et al., 2014), scheduling optimization (Brouer et al., 2013; Lam, 2010) berthing optimization (Wang et al., 2013b; Du et al., 2011), weather routing (Windeck and Stadtler, 2011; Balmat et al., 2011), fleet deployment (Fagerholt et al., 2009) and other technical operation improvements (Krozer et al., 2003; Liao et al., 2009; Song and Xu, 2012a; Yang and Chang, 2013; Balland et al., 2014). The other solution approach prominently employed is the effect/implementation of policy (Lai et al., 2011, 2013; Cariou and Cheaitou, 2012; Doudnikoff and Lacoste, 2014; Yang et al., 2013). Fig. 6 shows the number of papers in either category.

Building on the solution approach employed by the reviewed set of literature, we also identified a trend in the modeling approach employed in solving the identified problems. Out of the a total number of 26 papers reviewed in this section, 18 of them made use of mathematical modeling, 5 made use of computerized simulation and 3 employed theoretical analysis in solving their proposed problem. Fig. 7 illustrates this classification.

The reviewed set of literature above centers around environmental sustainability in maritime shipping, certain trends were identified in the course of this review. The extensive use of mathematical modeling/programming is observed in the reviewed literature. This method is advantageous in that it allows for modeling a great many of the complexities that the maritime sector presents; however, the downside side is the practicability of the solutions obtained. It is presumed that the use of other experimental techniques (qualitative/quantitative, etc.) to corroborate modeling effort might be beneficial for practical implementation. In addition to this, the implicit consideration of fuel consumption as a decision variable in a reasonable number of the papers that modeled the problem as a cost minimization problem (Sheng et al., 2014; Woo and Moon, 2014; Fagerholt et al., 2009) may not be very appropriate because the solution obtained might not necessarily have a positive impact on the environment. Furthermore, despite extensive research in this area much of it is not implemented, with the exception of Brouer et al. (2013), which expressly states real life application. This is due to what can be considered as a knowledge gap between academia and practice, which the development and implementation of DSS can help bridge. Table 3 presents a classification of the papers reviewed in this section.

5. Decision support systems for maritime shipping

While most of the studies aim at proposing algorithms and models for optimizing maritime operations, only limited number of studies propose DSS to support the decision making of maritime operation managers. As shown above in Table 2, DSS for maritime shipping was discussed in 12 papers. Further details of these papers are provided in Table 4.

DSS identified in maritime industry are mostly designed to support vessel scheduling problems. MoDiSS (Kim and Lee, 1997) is the first generation of DSSs that solves ship scheduling problem based on a generalized set-packing model to maximize revenue meeting cargo delivery requirements. In similar time, CMSS (Computerized Marine Scheduling System)

Table 2
The list of papers addressing the focused areas of this survey (A, B, C).[a]

ID	Reference	Aim and objectives	Area A	Area B	Area C
1	Balland et al. (2014)	To discuss ‘energy paradox’ in maritime transportation and criteria for selecting cost-efficient air emission controls	✓		
2	Cariou (2011)	To measure CO_2 reduction rate due to slow-steaming strategy for various container trades and calculate break-even-fuel price in which the strategy shows to be effective	✓		
3	Cariou and Cheaitou (2012)	Assessing the impact of regional speed limit policy imposed by EU on the overall CO_2 reduction and private and public cost	✓		
4	Chang et al. (2013)	To measure the greenhouse gas emissions from port vessel operations in Korea (Incheon port)	✓		
5	Doudnikoff and Lacoste (2014)	Exploring the possible consequences of the future low sulfur fuel requirements in SECA on vessel speed	✓		
6	Gibbs et al. (2014)	To calculate GHG emissions from end-to-end maritime transportation chain including emissions from ports	✓		
7	Psaraftis and Kontovas (2013)	Understanding the inter-play effects of different approaches to reducing maritime GHG emissions	✓		
8	Wang et al. (2013b)	To extend Du et al.’s (2011) work on berth allocation optimization considering fuel consumption and vessel emissions. They propose quadratic outer approximation approaches instead of a tractable mixed integer second-order cone programming model	✓		
9	Woo and Moon (2013)	To analyze the relationship between voyage speed, CO_2 emissions, and operating cost to find the optimal voyage speed to minimize operating cost and to satisfy the emission reduction target of IMO	✓		
10	Yang and Chang (2013)	To compare the energy and CO_2 reduction of rubber-tired gantries (RTGs) and electronic RTGs for handling cargo in ports	✓		
11	Yin et al. (2014)	Analyzing how can slow steaming save bunker consumption and benefit the environment and its negative impact on revenue through longer container transit time	✓		
12	Fagerholt et al. (2010)	Developing a fuel consumption minimization problem as a shortest path problem	✓		
13	Kontovas and Psaraftis (2011a)	To investigate an operational scenario, focusing on speed reduction for container vessels and its impact on fuel emissions	✓		
14	Schinas and Stefanakos (2012)	Investigating the financial impact of the sulfur limits imposed by MARPOL Annex VI	✓		
15	Zhu et al. (2013)	To develop a framework for allocation of emissions at cargo-level in the maritime supply chain	✓		
16	Franc and Sutto (2014)	Exploring the impact of a cap-and-trade system on the organization of container shipping lines and European ports	✓		
17	Kim et al. (2013)	To determine the ship speed, fleet size, and chartered ship number subject to environmental regulations consisting of a carbon tax and an emission trading scheme	✓		
18	Lindstad et al. (2011)	Investigating the effects of speed reductions on the direct gas emissions and costs of maritime transport	✓		
19	Schrooten et al. (2008)	To develop and test the usability of an activity based emission model named MOPSEA to determine emissions from vessels	✓		
20	Du et al. (2011)	To propose a berth allocation model considering fuel consumption by casting the nonlinear problem as a mixed integer second order cone programming model, also analyzing the vessel emissions in mooring periods through a post-optimization phase on waiting time	✓		
21	Lättilä et al. (2013)	Analyzing impacts of dry ports in Finland in comparison with direct driving to a sea port	✓		
22	Yang et al. (2013)	To empirically examine the relationship between internal green practices, external green integration, green performance, and firm competitiveness in the context of container shipping	✓		
23	Lai et al. (2013)	Investigating the impact of the green practices on shipping design for compliance (SDC) on financial and service performance of shipping firms	✓		
24	Kim et al. (2014)	Minimizing fuel consumption by optimal determination of sailing speed for a ship operating on a route with a specific route with time windows for calling time	✓		
25	Krozer et al. (2003)	Review of improvement options for environmentally sound and cost-effective short sea shipping	✓		
26	Lai et al. (2011)	Investigation of the motivation for the adoption of green shipping practices amongst shipping companies	✓		
27	Liao et al. (2009)	Comparison of emission from truck based transport with sea (intermodal) transport.	✓		
28	Fagerholt et al. (2009)	Addressing fleet deployment in liner shipping to minimize total cost of the company’s own vessels, the ballast sailing costs between voyages and the costs for hiring spot vessels or to maximize profit		✓	
29	Fagerholt and Lindstad (2007)	To introduce a DSS for ship routing and scheduling called TurboRouter		✓	

(*continued on next page*)

Table 2 (*continued*)

ID	Reference	Aim and objectives	Area		
			A	B	C
30	Bausch et al. (1998)	Presenting an Excel based simulation and optimization based DSS for vessel employment scheduling, loading and delivery planning with minimal cost while satisfying operational requirements		✓	
31	Lam (2010)	To provide decision support to ship liners in port selection, ship scheduling and financial analysis decisions		✓	
32	Fagerholt (2004)	Developing a DSS for vessel fleet scheduling, named TurboRouter and to share the experience obtained from the development of commercial software for shipping companies		✓	
33	Kim and Lee (1997)	To develop prototype of an optimization-based DSS for ship scheduling, called MoDiSS		✓	
34	Wong et al. (2010)	Empty container repositioning to minimize total repositioning cost and dissatisfied demand			✓
35	Sheng et al. (2014)	To optimize speed and refueling points to minimize total cost in the presence of bunker prices (in different ports) and bunker fuel consumption rate uncertainties			✓
36	Wong et al. (2009)	Empty container repositioning to minimize total repositioning cost and dissatisfied demand.			✓
37	Imai et al. (2006)	The stowage and load planning of container ships to maximize ship stability and to minimize number of container re-handling			✓
38	Homayouni and Tang (2013)	Coordinated scheduling of cranes and vehicles in container terminals to minimize total traveling time of the vehicles and delays in the operation of cranes			✓
39	Ballou et al. (2008)	To develop a DSS named VVOS to support optimized ship operation including the ship's hull design, propulsion system, sea keeping models and safe operating limit in order to reduce fuel consumption and GHG emissions	✓	✓	
40	Balmat et al. (2011)	Risk assessment in maritime shipping regarding safety at sea and in particular, pollution prevention on the open sea based on speed and relative position of ships with respect to maritime shipping lanes	✓	✓	
41	Windeck and Stadtler (2011)	To develop a DSS for liner shipping network design that considers environmental factors and minimizes cost and CO_2 emissions	✓	✓	
42	Bruzzone et al. (2010)	Proposing a simulator for assessing environmental impact of port operations	✓	✓	
43	Balmat et al. (2009)	Presenting a fuzzy approach for the maritime risk assessment, named MARISA for safety and oil pollution prevention at sea	✓	✓	
44	Palacio et al. (2013)	Determining container depots to minimize total cost of the network and the environmental impact of the depots and their associated transport operations	✓		✓
45	Chen et al. (2013)	Optimizing truck arrival patterns at marine container terminals to reduce emissions from idling truck engines by minimizing both truck waiting times and truck arrival pattern change	✓		✓
46	Qi and Song (2012)	Optimal vessel scheduling considering uncertainty in port time and frequency requirements on the liner schedule considering fuel consumption and service level	✓		✓
47	Brouer et al. (2013)	Present the vessel schedule recovery problem (VSRP) to evaluate a given disruption scenario and to select a recovery action that balances the trade-off between increased bunker consumption and the impact on cargo and the customer service level	✓		✓
48	Hu et al. (2014)	To allocate the berth and quay-crane to vessels by minimizing fuel consumption and emissions of the vessels	✓		✓
49	Song and Xu (2012a)	Comparing CO_2 emissions from direct and feeder liner services in the case of Asia–Europe Services	✓		✓
50	Song and Xu (2012b)	To develop an operational activity-based method to estimate CO_2 emissions from container shipping	✓		✓
41	Corbett et al. (2009)	Exploring policy impacts of a fuel tax and a speed reduction mandate on CO_2 emissions by applying a profit-maximizing equation to estimate route-specific speeds which are economically efficient	✓		✓
52	Grabowski and Hendrick (1993)	Assessing the trade-offs between crew size and shipboard safety		✓	✓
Total counts including overlaps			40	12	14

[a] A: Environmental sustainability in maritime shipping; B: DSS for maritime shipping; C: MOO for maritime shipping.

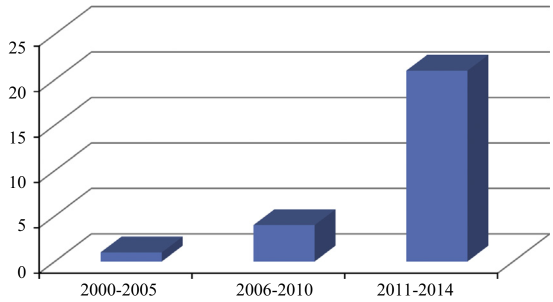

Fig. 5. Number of papers published on maritime sustainability.

is proposed by Bausch et al. (1998) based on Elastic Set partitioning (ESP) model. Both DSSs are based on PC and use data on vessels, cargoes, and ports for generating optimized vessel schedules. A commercialized DSS, TurboRouter (Fagerholt, 2004), extends functionalities of the DSSs by integrating port-to-port distance calculation module and more sophisticated GUIs. Also, more variables including cargo time windows, compatibility between vessels and loading/discharging ports, split cargoes, compatibility between vessel equipment/certificates and products to be shipped, etc. are taken into account by a heuristic solver. Apart from vessel scheduling problems, DSSs in maritime industry are supporting decision makers for trade-off analysis of crew size and ship safety (Grabowski and Hendrick, 1993), liner shipping network design (Lam, 2010), maritime risk assessment (Balmat et al., 2009, 2011), and analyzing the impact of maritime operations on the economy and the environment (Bruzzone et al., 2010; Windeck and Stadtler, 2011).

From Table 4, it can be inferred that studies on DSS in sustainable maritime transportation is still in early stage as only few number of studies can be found from the search. Only three studies were identified with regard to environmental impacts of maritime operations in relation to the increased regulations on GHG emissions by EU and IMO. Ballou et al. (2008) propose a VVOS (voyage and vessel optimization system) that provides decision makers with tools to analyze fuel consumption and GHG emission considering ambient ocean conditions, the ship's hull design, propulsion system and sea keeping models as well as user-defined safe operating limits. Bruzzone et al. (2010) develop a simulation based DSS to support port managers' decision making with regard to the environmental impact of port operation activities. They use Greenlog Simulator for the analysis and compare the environmental impacts of two scenarios in port operation: ship with internal power supply during stopover in port and power grid supplied ship. The latter is reported to have less environmental impact according to a case study. Finally, Windeck and Stadtler (2011) propose an idea of applying a mixed integer programming model to develop a DSS for solving a liner shipping network design problem to minimize the cost and emissions by considering environmental influences (waves, currents and wind).

What-if analysis is cited as key functionalities of proposed DSS and its use can be classified into three categories. Firstly, a group of studies uses what-if analysis to measure the impact of market and/or environmental uncertainties on performance indicators (Kim and Lee, 1997; Bausch et al., 1998; Balmat et al., 2009; Lam, 2010). MoDiSS and CMSS allow decision makers to analyze the impact of uncertainties in cargo demand and charter price of vessels on the overall revenue of a shipping company. On the other hand, users of MARISA (Balmat et al., 2009) can analyze the change on ship risk factors by changing weather conditions including wind speed, visibility and period o the day. Finally, a DSS developed by Lam (2010) can be used to analyze the impact of changes on oil price, cargo demand, charter hire fee, and load factors on the overall profit and loss of liner services in the design of liner service network. Secondly, what-if analysis is also used for comparing alternative solutions. TurboRouter users can analyze the impact of manual cargo-vessel assignment (Fagerholt and Lindstad, 2007) by overriding a generated assignment by the system. This is useful when a user wishes to calculate opportunity cost of assigning a vessel for a particular cargo. The Greenlog simulator (Bruzzone et al., 2010) is used to analyze how different configuration of

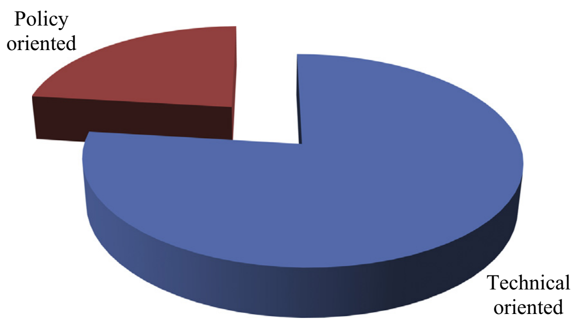

Fig. 6. Classification of literature on sustainable maritime based on solution approach.

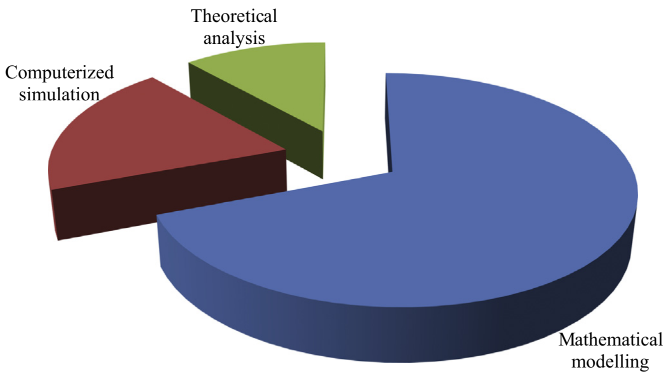

Fig. 7. The trend in modeling approach.

Table 3
Summary of papers on environmental sustainability in maritime shipping.

Reference	Solution approach	Modeling approach
Cariou (2011)	Technical (Slow steaming)	Mathematical modeling
Yin et al. (2014)	Technical (Slow steaming)	Mathematical modeling
Kim et al. (2014)	Technical (Speed optimization)	Computerized simulation
Brouer et al. (2013)	Technical (Schedule optimization)	Mathematical modeling
Sheng et al. (2014)	Technical (Speed and fuelling decision optimization)	Mathematical modeling
Lam (2010)	Technical (Schedule optimization)	Computerized simulation
Ballou et al. (2008)	Technical (Speed optimization)	Computerized simulation
Woo and Moon (2014)	Technical (Slow steaming)	Mathematical modeling
Fagerholt et al. (2009)	Technical (Fleet deployment scheduling)	Mathematical modeling
Krozer et al. (2003)	Technical (Operational improvement)	Theoretical analysis
Balland et al. (2014)	Technical (Operational improvement)	Theoretical analysis
Liao et al. (2009)	Technical (Operational improvement)	Mathematical modeling
Yang and Chang (2013)	Technical (Operational improvement)	Mathematical modeling
Wang et al. (2013b)	Technical (Berth allocation optimization)	Mathematical modeling
Du et al. (2011)	Technical (Berth allocation optimization)	Mathematical modeling
Song and Xu (2012a)	Technical (Operational improvement)	Mathematical modeling
Chen et al. (2013)	Technical (Operational improvement)	Mathematical modeling
Chang et al. (2013)	Technical (Operational improvement)	Mathematical modeling
Lättilä et al. (2013)	Technical (Operational improvement)	Mathematical modeling
Lai et al. (2011)	Policy	Theoretical analysis
Cariou and Cheaitou (2012)	Policy	Mathematical modeling
Doudnikoff and Lacoste (2014)	Policy	Mathematical modeling
Balmat et al. (2011)	Technical (Routing)	Computerized simulation
Windeck and Stadtler (2011)	Technical (Routing)	Computerized simulation
Yang et al. (2013)	Policy	Mathematical modeling
Lai et al. (2013)	Policy	Mathematical modeling

a port nodes (ship, trucks, rail, transtainer, portainer, reach stacker, dock-yard or dock transshipment) makes difference on the total emission of GHG in the port. Finally, what-if analysis is used to analyze trade-off relationships of conflicting performance indicators like ship operation cost (crew size) and safety (Grabowski and Hendrick, 1993); fuel consumption and service level agreement (Ballou et al., 2008).

The studies reviewed above focus on limited features of DSS including the visualization of the solutions of optimization algorithms and allowing decision makers conduct what-if analysis. On the other hand, how to adopt DSS by maritime practitioners has attracted less effort. This is notable as there are scholars that highlight a unique culture of the maritime industry that has stronger resistance in the adoption of new ICT tools in their business processes (Fagerholt, 2004; Grabowski and Hendrick, 1993) than other transportation sectors. Also, most of the DSS reviewed are based on quantitative decision models (MILP for example) and a very limited number of qualitative decision models (fuzzy logic adopted by Balmat et al., 2011, 2009) have been adopted for developing DSS for maritime decision makers. This is an important research gap as decision makers in maritime shipping are dealing with diverse semi- or un-structured decision problems and solving such problems requires systematic support from DSS.

6. Multi-objective optimization in maritime shipping

Our systematic review of the literature shows a growing interest in analyzing trade-offs in decision problems in maritime shipping involving multiple objectives. To the best of our knowledge, the first paper published on MOO for maritime shipping

Table 4
The summary of studies on DSS for maritime shipping.

Reference	Decision problem	Model
Grabowski and Hendrick (1993)	Shipboard manning to analyze trade-off between crew size and ship safety	Heuristic method and what-if analysis
Kim and Lee (1997)	Ship scheduling problem	Set-packing model
Bausch et al. (1998)	Scheduling of short-term marine transport of bulk products	Set-partitioning model
Fagerholt (2004), Fagerholt and Lindstad (2007)	Vessel fleet scheduling for cargo delivery	The insertion heuristic algorithm, a hybrid local search algorithm
Fagerholt et al. (2009)	Fleet deployment in liner shipping	Multi-start local search heuristic algorithm
Lam (2010)	Port selection, vessel fleet scheduling, financial analysis	Analytic hierarchy process (AHP), traveling salesman problem model
Balmat et al. (2009, 2011)	Maritime risk assessment	Fuzzy logic based simulation
Ballou et al. (2008)	Fuel consumption & GHG emission analysis	Voyage optimization algorithm (no detail provided)
Bruzzone et al. (2010)	Analyzing environmental impact of port operations	GreenLog Simulator
Windeck and Stadtler (2011)	Liner shipping network design to minimize fuel consumption and GHG emissions	Mixed integer linear programming (MILP)

was by Grabowski and Hendrick (1993) on the trade-offs between crew size and shipboard safety. Since then, there was a period of silence for over a decade until 2006, when Imai et al. (2006) published their paper on load planning of container ships. In the past decade, we have observed an increasing trend in applying MOO to different problems in maritime shipping. The literature in this domain can be classified into two broad categories based on either the exclusion or inclusion of sustainability as an explicit decision criterion. Initial attempts in applying MOO to problems in maritime shipping mainly fall in the first category, whereas the recent trend demonstrates the increased popularity of sustainability metrics in the MOO-based decision models. Table 5 summarizes the articles on MOO for maritime shipping in the two categories based on their objectives and solution techniques. We discuss the literature in these two categories in the following two subsections.

6.1. MOO in maritime shipping without sustainability measures

Majority of the earlier research in this area has handled multiple decision criteria by converting the multi-objective problem into a single objective counterpart (Imai et al., 2006; Homayouni and Tang, 2013; Sheng et al., 2014). To the best of our knowledge, Wong et al. (2009) and Wong et al. (2010) were the only papers that attempted to search the whole Pareto frontier using population based approaches. This approach has the advantage of less dependence on problem specific knowledge and user preference *a priori*. In terms of decision criteria, we did not observe a pattern or preferred set of objectives in the reviewed literature. Some scholars address the trade-offs between total operational cost and aspects of service level (Wong et al., 2009, 2010; Sheng et al., 2014), whereas others address trade-offs between operational and/or safety related indicators (Grabowski and Hendrick, 1993; Imai et al., 2006; Homayouni and Tang, 2013).

In terms of solution approach, researchers have used a mixture of heuristics (Grabowski and Hendrick, 1993; Sheng et al., 2014) and metaheuristics (Imai et al., 2006; Wong et al., 2009, 2010; Homayouni and Tang, 2013) to solve the MOO models. Our literature review shows particular attention to the use of real data for the validation of the developed models. Majority of the scholars in this category have validated their models using real or pseudo-real data. These include Grabowski and Hendrick (1993) who demonstrate the applicability of their DSS using real case studies of two different ships and voyage profiles, operated by different companies; Wong et al. (2009) and Wong et al. (2010) who validated their approach based on simulation data of trade between the Asia–Pacific and Europe involving multiple ports in the two regions as supply and demand points; and Sheng et al. (2014) who tested their model using two real world service routes, Malaysia Service (MAS) and Asia–Europe Express (AEX).

The majority of the MOO-based models incorporating non-sustainability measures have assumed deterministic variables and parameters in their modeling. However, uncertainty of maritime operation has started to capture the attention of researchers in recent years (Homayouni and Tang, 2013; Sheng et al., 2014). This trend is expected to continue in light of the inherent uncertainties in operational as well as environmental conditions that affect maritime supply chains.

Overall, it can be concluded that the MOO-based approaches in maritime without sustainability metric have addressed real-world problems. These problems are complex for which, exact optimization methods have limited applications. As a result, a range of customized heuristic or metaheuristic methods are used to find approximation of Pareto optimal frontier. Complexity of the problems is increasing as a result of incorporation of uncertainties, which necessitates the application of stochastic optimization methodologies. Finally, the reliance on real data for the validation of the proposed models is a promising direction, which has the potential to make positive impact on improving a balanced portfolio of performance metrics in maritime operation and the ultimate use of the developed models by practitioners.

6.2. MOO in maritime shipping incorporating sustainability measures

Considering sustainability measures in maritime shipping has received increasing attention from researchers and practitioners. Given the inherent trade-offs involved in enhancing sustainability in maritime transportation, MOO is becoming a popular approach to help ship liners and port operators in making informed decisions when aiming to achieve their business objectives.

In light of the impact of speeding decision on fuel consumption, several authors have addressed the influence of speeding on not only fuel emissions, but also other performance criteria. Although slow steaming has been the main operational policy by ship liners, it is ignored at some points along the shipping routes to make up for the delays and to benefit from the available slots at ports. As a result, fast steaming which has negative environmental impact, is followed for improving service level and to meet the agreed schedule with customers. Corbett et al. (2009) initiated one of the first attempts in addressing the trade-off between fuel emission as a function of speed and service level to incorporate sustainability as an explicit objective in a MOO approach in maritime shipping. They explore the impacts of fuel tax and the speed reduction mandate on CO_2 emissions by applying a profit-maximizing equation to estimate route-specific, economically-efficient speeds.

Subsequently, minimizing fuel emission has become a prominent decision criterion in developing multi-objective models in conjunction with performance and/or service oriented measures. These include the work of Song and Xu (2012a,b) in analyzing the trade-off between CO_2 emissions and port handling rates; Qi and Song (2012) and Brouer et al. (2013) addressing the trade-off between fuel emission and service level in liner shipping; and Hu et al. (2014) who address the berth and quay-crane allocation problem to vessels by minimizing the fuel consumption and emissions of the vessels. It should be noted that ships are not the only source of emission in maritime logistics. To the best of our knowledge, Chen et al. (2013) addressed for the first time emissions by trucks at ports in a multi-objective model. They analyze the trade-off between truck idling emissions and truck arrival patterns in a container terminal.

Besides emission-related research, the only paper that considered trade-off between sustainability and performance oriented metrics was presented by Palacio et al. (2013) in which, they have addressed environmental issues related to the location decisions. The authors aim to locate container depots to minimize the total cost of the network, the environmental impact of the depots and the transport operations associated with them.

The literature on MOO-based research including sustainability can be classified into stochastic and deterministic models. In the stochastic category, Song and Xu (2012a,b) and Qi and Song (2012) consider variable port times as the source of uncertainty. In the same category, Chen et al. (2013) consider stochastic arrival times for trucks in their model. Stochastic models have the flexibility to capture more realistic situations but at the same time are more complex to solve compared to deterministic problems. The work of Corbett et al. (2009), Brouer et al. (2013), Palacio et al. (2013), and Hu et al. (2014) have considered deterministic parameters in their modeling in order to be able to solve the associated problems more easily.

The source of data for the validation of the proposed models and solution techniques is another dimension that differentiates the literature. Corbett et al. (2009) and Hu et al. (2014) used artificial or simulated data in their research. Meanwhile, Song and Xu (2012a,b), Qi and Song (2012), Brouer et al. (2013), Chen et al. (2013) and Palacio et al. (2013) used real (or pseudo real) data. The academic contributions of the latter category of papers are presumably more readily available for the adoption by practitioners.

The majority of the papers that have adopted MOO in addressing maritime shipping have dealt with sustainability measures. This trend has been more visible in the recent past. Weighting and ε-constraint methods were extensively used to convert the multi-objective problems into single objective problems. This approach has limited adequate exploration of the Pareto frontiers. A few attempts have been made to explore the whole Pareto frontier using evolutionary algorithms (e.g. Wong et al., 2009; Chen et al., 2013). Uncertainty in data and decision criteria has received limited attention in the literature. Given the significant uncertainties in maritime supply chains, it is expected that more research will be carried out in this domain. The subjectivity of some of the decision criteria (such as service level) could add further complexity in the development of realistic mathematical models. Fuzzy models have the potential to address some of this challenge. As such, it is expected that the literature will grow in this direction by developing multi-objective fuzzy and/or fuzzy stochastic models (Lootsma, 1997; Mohan and Nguyen, 2001).

7. Discussion and future directions

Our literature review reveals that the three areas of this survey have received varied attention and grown at different levels. Fig. 8 illustrates the trend of publications on maritime shipping in the three areas covered in this survey.[2] As can be seen in the figure, environmental sustainability has received the highest attention in the past years followed by MOO. The number of publications on DSS appears to have seen its peak between 2006 and 2010 and while it has continued to grow since then this has been at a relatively lower rate compared to the other two areas.

A scaled representation of the growth of the body of literature in these areas is provided in Fig. 9. As can be seen, the literature on environmental sustainability in maritime shipping (circle A) has seen the fastest growth among the three areas: from non-existence prior to 2005 to the largest area at the present time. In the next rank, the literature on MOO for maritime shipping (circle C) has seen a significant growth in the past years with increasing overlap with environmental sustainability (AC). The literature on DSS for maritime shipping (circle B) has witnessed considerable growth until 2010 and continued to grow at a lower rate afterwards. With the emergence of the literature on environmental sustainability after 2005, the literature on DSS has reflected the inclusion of sustainability as part of the DSS for the maritime industry, as can be seen in

[2] Until August 2014.

Table 5
The summary of research on MOO for maritime shipping.

Reference	Objectives	Solution technique	MOO approach
Without sustainability considerations			
Grabowski and Hendrick (1993)	Trade-off analysis between crew size and shipboard safety	Heuristic method	What-if analysis
Imai et al. (2006)	Maximizing ship stability and to minimize number of container re-handling	Genetic algorithm	Weighting method
Wong et al. (2010) and Wong et al. (2009)	Minimizing total repositioning cost and dissatisfied demand	Immunity-based evolutionary algorithm	Population based Pareto front evolution
Homayouni and Tang (2013)	Minimizing total traveling time of the vehicles and delays of cranes	Genetic algorithm	Weighting method
Sheng et al. (2014)	Optimize overall cost and service level (or failure rate)	Rolling horizon method	ε-constraint
With sustainability considerations			
Corbett et al. (2009)	Optimizing fuel emission and service level	Algebraic equation optimization	ε-constraint
Song and Xu (2012a) and Song and Xu (2012b)	Trade-off analysis between CO_2 emissions and port handling rates	Service activity-based method	Scenario analysis
Qi and Song (2012)	Analyzing trade-off between fuel consumption and service level	Simulation optimization	ε-constraint
Palacio et al. (2013)	Minimizing total cost and the environmental impact of the network	AHP	ε-constraint
Brouer et al. (2013)	Trade-off analysis between bunker consumption and customer service level	Mixed integer programming	ε-constraint
Chen et al. (2013)	To minimize both truck waiting times and truck arrival pattern change at ports to reduce emissions from idle trucks	Genetic algorithm	Population based Pareto front evolution
Hu et al. (2014)	Minimizing fuel consumption and emissions of the vessels	Second-order mixed-integer cone programming	Weighting method

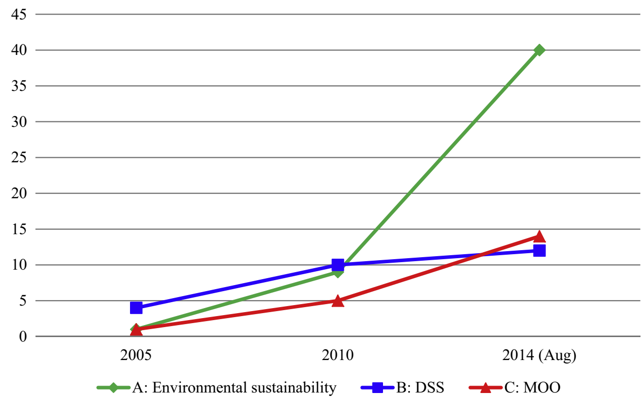

Fig. 8. Cumulative trend of publications on maritime shipping in the three areas.

the overlapped area between circles A and B. Apart from the earliest attempt to develop DSS with MOO capabilities by Grabowski and Hendrick (1993), the overlap between these two areas (B and C) has remained unchanged.

With the growing interest in environmental sustainability and MOO in maritime shipping, it is expected that the next generation of DSS will be developed with MOO capabilities. This trend is likely to happen with a lag once multi-objective models and solution techniques for maritime shipping are developed to a reasonable level. The realistic nature of the models and the efficiency of the solution techniques are crucial in order to enable DSS developers to embed the associated models in commercial software packages for maritime shipping. In addition to development in modeling and solution techniques, particular emphasis should be placed on developing comprehensive yet simple user interfaces as emphasized by Fagerholt (2004). This is of particular emphasis for MOO based DSS in light of the fact that the decision process requires close interaction with the user to guide the search and to explore preferred areas of the Pareto frontier.

Based on the literature review of DSS for maritime shipping, we identify the following future research directions for maritime DSS. Firstly, the current state of the art of maritime DSS is in the initial stages, and most of the DSS are in prototype or experimental use apart from TurboRouter. As illustrated by Fagerholt (2004), user acceptance factors need to be considered for the practical deployment of DSS in real world settings. While there are large number of studies on information systems (IS) acceptance (Davis et al., 1989), the unique features of maritime DSS that involve complex relationships among engineering (ship characteristics), weather (sea conditions), and regulation (GHG and ship speed) factors may require different

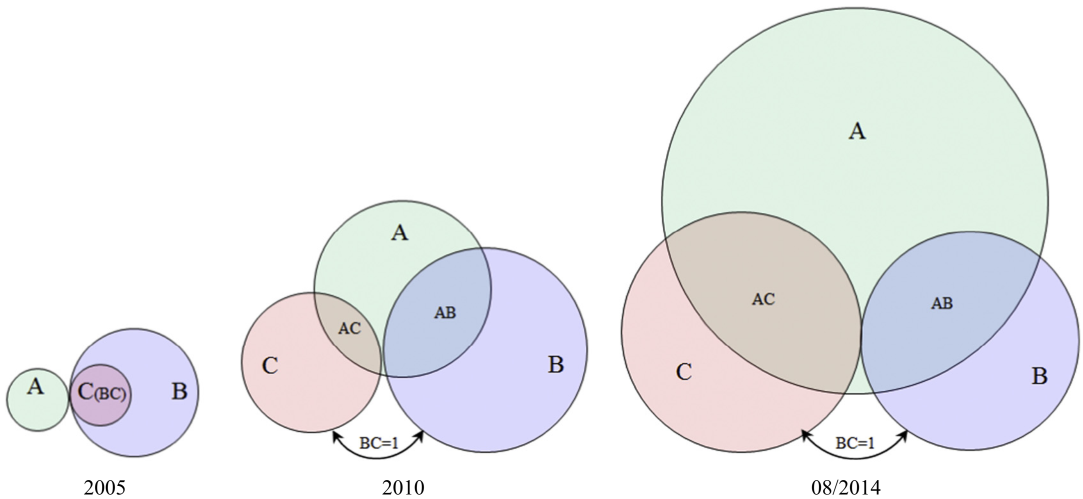

Fig. 9. Growth of the literature in maritime shipping in the three areas surveyed (A: Environmental sustainability, B: DSS, C: MOO).

motivational factors of end users from those for general IS. Studies on the user acceptance of maritime DSS will contribute to the wide deployment of the DSS in the real world. Secondly, an ideal DSS should have a model base that manages different types of optimization models and provides its users with different models according to different contexts of decision making problems. End users are most likely not to be experts on such optimization models, therefore an interactive recommendation of one or more models to the users will increase the usability of the DSS. Thirdly, maritime DSS require data from various sources, including ships, ports, weather and economic (fuel price for example) data for decision making. Most of the current maritime DSS obtain such data manually and this may hinder the timeliness of the decision making, in particular in the middle of voyage. As argued by Ballou et al. (2008), the integration with existing instrumentation and specialized sensors (see Beirle et al., 2004 as an example) will improve timely decision support by a maritime DSS.

Our survey indicates that the research on MOO for maritime shipping is in the rapid growth stage. In light of the rising attention to sustainability in operational and strategic decisions in maritime shipping and likely conflicts between environmental and the other pillars of sustainability, MOO appears to be a viable approach to the modeling and optimization of operational and strategic decisions in this domain, so we expect a significant growth in the body of literature in this domain. New multi-objective models are needed to analyze the trade-off between the true cost of emissions on financial and operational performance as two and three objective models, incorporating fuel emission as an explicit objective (and not merely its cost). There are papers that have considered performance metrics such as service level as a constraint (e.g. Qi and Song, 2012). Extension of these models to consider such performance measures as explicit objectives provides a better opportunity to explore trade-offs and to support informed decision making. As such, it is expected that more MOO based models will be developed in coming years. The majority of the current research have focused on emissions as an indicator of environmental sustainability and analyzed the likely impact of slow steaming on the aspects of service level such as longer transit time and larger fleet size to respond to the global demand to sea transport. Given the complexity of the problems in this area and the uncertainties involved in port and transit times, more research is needed to develop fast and scalable solution techniques to handle the uncertainties involved in the respective decision problems. This will need implementation and the theoretical development of crisp and fuzzy stochastic models and solution techniques for fast and real time trade-off analysis of problems involving uncertain and/or fuzzy parameters as well as subjective criteria.

Simulation optimization is one of the promising approaches to address the resultant problems in maritime transportation. It is a flexible approach for solving stochastic decision problems that involve a large number of scenarios, which makes it prohibitive to use scenario-based and robust optimization approaches (Better et al., 2008). A number of recent articles have used this approach in relevant problems in the maritime sector (Qi and Song, 2012) and urban transportation (Osorio and Bierlaire, 2013). Further research is needed to develop scalable simulation optimization methodologies that can be embedded in commercial DSS for maritime transportation. Examples of such research include real time speed decisions, given the delays in ports of calls and trade-offs between fuel emission and total cost of delays. The majority of the extant literature has focused on environmental sustainability; future research in MOO is needed to develop metrics and objectives for economic and social sustainability in order to analyze the trade-offs among the different pillars of sustainability.

The role of ports on enhancing the sustainability of maritime shipping needs more attention to balance the interests of the port operators and ship liners. Port time uncertainty has been highlighted as one of the main factors affecting slow steaming and thereby emission from vessels (Kontovas and Psaraftis, 2011). Further research is needed to develop decision models to incorporate the preferences of port operators and shipping companies in integrated models to aid the negotiation, mediation and decision making between port authorities and shipping companies based on the real time data of the port and vessels' status. Finally, there is no research addressing the overlap among the three areas (ABC) that are surveyed in this paper. This is one of the major gaps in the literature that needs further research and development, both in theory and the application of MOO based DSS to help improve the sustainability of the maritime supply chains.

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