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MarPEM: An agent based model to explore the effects of policy instruments on the transition of the maritime fuel system away from HFO

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ABSTRACT

To lower the emissions of deep sea shipping, policymakers aim to decrease the use of heavy fuel oil (HFO) as a maritime fuel. Multiple alternatives for HFO exist, but despite new regulations, their use is still limited. To stimulate shipping companies to replace HFO by one of the alternatives, policymakers can use a variety of policy instruments. In this paper, we present a comprehensive system perspective of the maritime fuel system and agent-based model (MarPEM) that can be used to study the effects of policy instruments on the transition away from HFO. In contrast to existing studies on reducing maritime emissions, our system perspective captures the relations and dynamics between different components of the maritime fuel system. Thereby, it can account for the feedback and non-linear dynamics in the system. We illustrate the use of MarPEM to assess the effect of three policy instruments that each influence the maritime fuel system differently. The outcomes of the experiments are in line with previous studies and the opinion of industrial experts. The model is thus a valid representation of the maritime fuel system. By presenting a sufficiently detailed representation of the marine fuel socio-technical system, listing clear and detailed assumptions, and publishing the source code, future studies can use this work as basis to study the effects of other policy instruments. Thereby, this research enables future detailed studies of the maritime fuel system's transition.

1. Introduction

The continually increased globalisation of the economy has led to a growing demand for transport. Over 80% of this transport is carried out by sea-faring vessels (United Nations Conference on Trade and Development (UNCTAD), 2015), of which the vast majority use heavy fuel oil (HFO) for their propulsion (Corbett and Koehler, 2003). Together, those vessels emit around 3% of global CO_2 emissions, 15% of global NO_x emissions, and 13% of global SO_x emissions (International Maritime Organization (IMO), 2014), exacerbating a range of environmental issues.

To reduce the emission of sulphur oxides (SO_x), recently introduced regulations prohibit the use of fuels with a sulphur content above 0.10% in the coastal waters of the United States and North-West Europe. Outside those sulphur emission control areas (SECAs), the sulphur content of maritime fuels is currently limited to 3.50%, but is scheduled to be lowered to 0.50%

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in 2020 (IMO, 2015). HFO has a sulphur content of 2.7% and thus can currently still be used outside the SECAs (IMO, 2014). However, after 2020 shipping companies need to start looking for alternatives to HFO. A variety of those alternatives have been identified, such as liquefied natural gas (LNG), marine gas oil (MGO), or scrubbers to clean the emissions. However, the adoption of those alternatives has been very slow (Moirangthem, 2016). For instance, as of July 2015, there are 65 LNG-powered vessels in operation and 79 are scheduled to become operational in the coming years (DNV-GL, 2015): only 0.3% of the total of 55,000 sea vessels (IMO, 2012).

There are multiple factors underlying the limited replacement of HFO as maritime fuel (Wang and Notteboom, 2014). One of those factors is that the infrastructure to supply the alternative fuels is less developed than that to supply HFO. This is especially an issue for LNG, which needs to be stored and distributed at temperature below −162 °C and thus requires special infrastructure (Wang and Notteboom, 2015). While this infrastructure is not developed, shipping companies will not invest in LNG-powered vessels; and while there are no LNG-powered vessels, no fuel supplier will invest in the infrastructure (Danish Maritime Authority, 2012): a classic example of a chicken-and-egg problem (Adamchak and Adede, 2013). Furthermore, Wang and Notteboom (2014) identified factors related to the regulatory framework, the economic viability, the technical feasibility, and the public-social awareness.

Policymakers have a variety of means to mitigate those limiting factors and stimulate the transition of the maritime fuel system away from HFO. For instance, subsidising the retrofitting of vessels to use another fuel, fining offenders of the emission regulations, or stimulating the availability of alternative fuels in ports. However, the effects of those policy instruments on the fuel adoption in the maritime fuel system are in many cases unknown.

So far, there have been a number of studies that assessed means to reduce the emissions of maritime transport. The majority of those studies compared the economic and environmental performance of different maritime fuels and propulsion technologies (e.g., Brynolf et al., 2014; Eide et al., 2013; Jiang et al., 2014; Ren and Lützen, 2015), studied the barriers for vessel owners to improve their energy efficiency (e.g., Johnson et al., 2014; Jafarzadeh and Utne, 2014), or researched the economics of the required LNG bunker infrastructure (e.g., Danish Maritime Authority, 2012; Harperscheidt, 2011; Semolinos et al., 2011). All those studies have in common that they assess the (economic or environmental) micro-performance of a certain technology or fuel isolated from the rest of the maritime fuel system. While this work is very important, it does not take into consideration that LNG adoption emerges from behaviours and interactions within the elements of maritime fuel system over time. So, in order to assess the dynamics of the transition away from HFO, a study of policy instruments needs to consider the multitude of maritime fuel system elements and their interactions.

In this paper, we present a comprehensive system perspective of the maritime fuel system that can be used to study the effects of policy instruments on the transition away from HFO. This system perspective is implemented in an agent-based model: Maritime Fuel Policy Exploration Model (MarPEM). This model allows us to study the possible development of the maritime fuel system and the emergence of a transition for a variety of policy instruments. MarPEM represents the maritime fuel system as a set of heterogeneous agents that decide autonomously and interact with each other and their environment (Shalizi, 2006). Agent-based models have been used often to study how the transition of a system may be stimulated – such as the transition to other automotive fuels or the adoption of plug-in hybrid electric vehicles (Van Vliet et al., 2010; Eppstein et al., 2011). To demonstrate the functioning and illustrate the use of MarPEM, we apply it to explore the effect of three policy instruments that each influence the maritime fuel system in a different way. Thereby, those experiments show that MarPEM can be used to assess a variety of policy instruments and thus can be applied in future studies.

2. The maritime fuel system

The system perspective that we propose for this study considers a much wider system scope than is common in transition studies. The goal is to capture the feedbacks between different parts and the subsequent non-linear system behaviour (Bar-Yam, 2011). By capturing that non-linear system behaviour, we can obtain a thorough understanding of the consequences of studied policy instruments. As a consequence, the system perspective is fundamental to technology change and sustainability transition research (Ulli-Beer, 2013).

The maritime fuel system (covered by the system perspective) comprises the physical assets that produce, distribute, and consume fuels, as well as the organisations that interact with each other to arrange the physical handling of those fuels. This system is a socio-technical system, and thus can be described as a system of tightly interwoven technical and social subsystems (Hughes, 1987; Ottens et al., 2006). Fig. 1 gives an overview of the system's social and technical systems, which are discussed in further detail in this section.

2.1. Technical system

The technical system consists of the physical entities that handle maritime fuels and are connected to each other via the flow of those fuels. *Vessels* are the entities that consume maritime fuel to transport cargo between ports. Vessels use different propulsion technologies, which determine the type of fuel they use, their fuel efficiency, and their emissions (Danish Maritime Authority, 2012).

The vessels bunker their fuel in a port via *distribution infrastructure*, which can consist of bunker barges, trucks, or pipelines (De Buck et al., 2011). To ensure sufficient availability, maritime fuels are temporarily stored in *bunker storage tanks* that

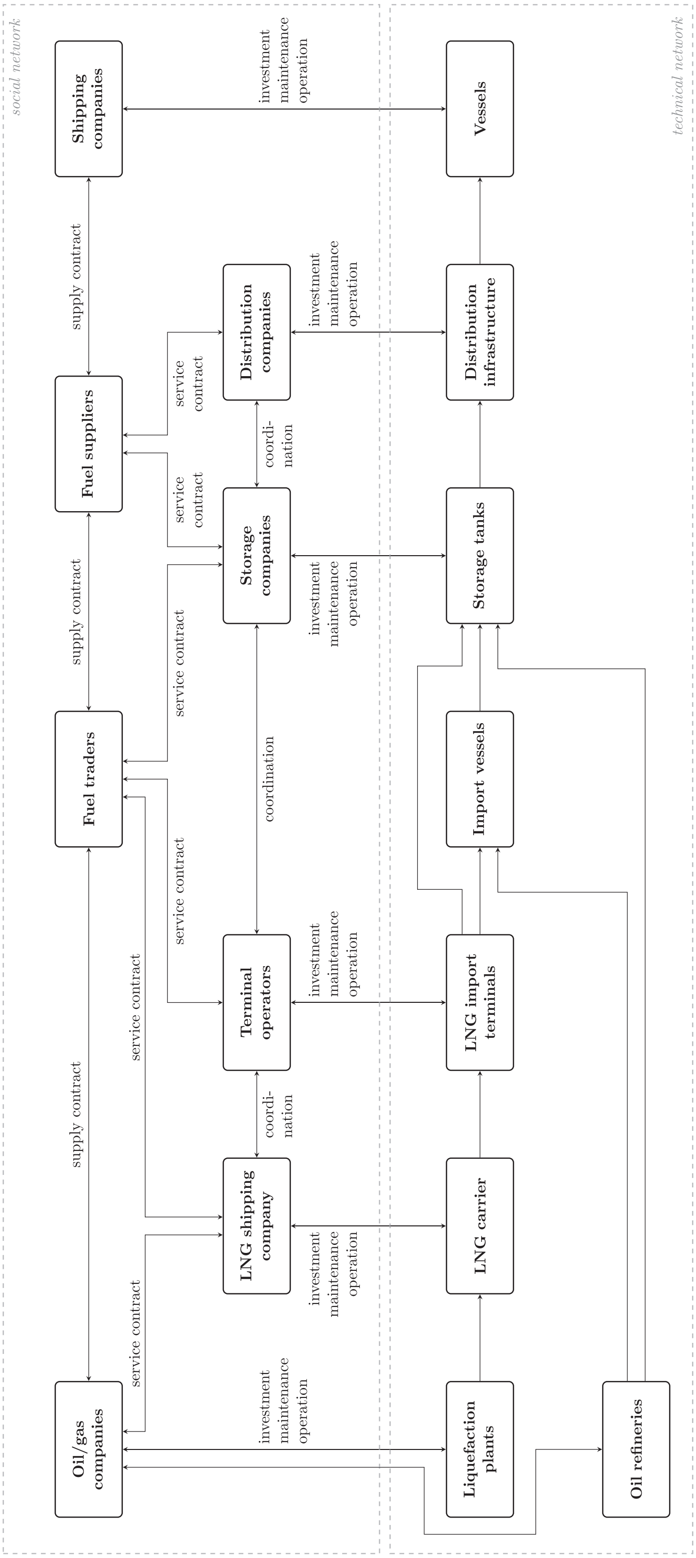

Fig. 1. Socio-technical structure of the maritime fuel system.

are situated in the port. Unlike the traditional fuels (i.e., HFO and marine gas oil (MGO)), which are stored and distributed at ambient temperature, LNG needs to be kept at a temperature below −162 °C. Hence, the storage and distribution of LNG requires special storage tanks and distribution infrastructure (Danish Maritime Authority, 2012).

Both HFO and MGO are petroleum-based, which implies that they are produced in an *oil refinery*. This refinery may be situated in the port where the fuel is distributed, in which case the fuel can be stored directly in the storage tanks. However, when the refinery is not situated in the port where the fuel is distributed, the fuel is first transported to that port with an *import vessel* (De Buck et al., 2011).

LNG is not produced in an oil refinery, but by liquefying natural gas in a *liquefaction plant* located at or near a gas source. Liquefaction plants are located all over the world, with most liquefaction capacity installed in Qatar, Indonesia, Australia, and Algeria (International Gas Union, 2015). Once the LNG is liquefied, it is shipped in an *LNG carrier* to an *LNG import terminal* where it can be regasified to natural gas and injected in the natural gas network (International Gas Union, 2015). However, when LNG is used as maritime fuel, it is not regasified but stored temporarily before it is distributed to a vessel. As for petroleum-based fuels, if a port does not have an LNG import terminal, the LNG may need to be transported with an import vessel from a nearby terminal.

2.2. Social system

The social system consists of the independently operating organisations that arrange the production, distribution, and consumption of maritime fuels. *Shipping companies* operate one or more vessels in order to execute the shipping assignments of their customers. Shipping companies have to schedule the operation of their vessels, which involves the sequence of ports the vessel is going to visit, and where it is going to bunker fuel (Agarwal and Ergun, 2008). This scheduling decision is influenced by a variety of factors, such as the availability of vessels, the (expected) demand for transport, port dues, fuel availability, and fuel prices (Notteboom, 2009). On a longer timescale, shipping companies invest in new vessels or retrofit existing vessels. In both cases, the shipping companies have to decide about the vessel's propulsion technology (amongst other properties), for which they consider factors such as the initial investment costs, the fuel expenses, the emission regulations, and the fuel availability (Acciaro, 2014).

Shipping companies purchase the maritime fuel for their vessels from *fuel suppliers*. Those suppliers operate in one or more ports, where they offer certain maritime fuels. Each supplier aims to maximise its profits within the possibilities that are set by the market conditions. For that purpose, it can change the price its asks for its fuel. When the market conditions are unfavourable, it can happen that those maximum profits are very low, but are simply the best the fuel supplier can realise. On a longer timescale, the fuel suppliers reconsider the range of fuels they offer. The decision to offer a particular fuel depends on the expected profit that the supplier can obtain from this fuel and on the availability of infrastructure to supply the fuel in its port. This infrastructure is not necessarily owned by the fuel supplier, in which case it contracts *storage companies* and *distribution companies* to store and distribute the fuel.

The fuel suppliers buy their fuel from *fuel traders* (which can be integrated with the fuel supplier) that participate in the global fuel markets to purchase fuel (De Buck et al., 2011). The fuel trader negotiates with the *oil/gas companies* that own refineries and thus can supply the petroleum-based fuels. Oil/gas companies are also heavily involved in the production of LNG and often (partially) own the liquefaction plants (International Gas Union, 2015). So, for both types of fuels, a fuel trader negotiates with oil companies about the supply of a maritime fuel. To transport the LNG to the port where it is needed, oil/gas company contracts an *LNG shipping company* to transport the LNG and the fuel trader contracts a *terminal operator* to import the LNG into the port.

2.3. Socio-technical connection

The technical and the social system are connected to each other through the different organisations in the social system that own and operate physical assets in the technical system. As a consequence, developments in the technical system influence the social system, and vice versa. The social system is influenced by the technical system through the physical availability of fuels that influence the market interactions and the social relations that emerge from them. For example, a fuel trader cannot sell more fuel than is available in the port, and thus its negotiations with fuel suppliers are influenced by the physical constraints of the technical system. The same applies for negotiations about service contracts; a storage company cannot store more fuel for a fuel trader than its storage tanks allow. More upstream, this influences the quantity of fuel that the fuel trader can purchase from the oil companies.

The other way around, the social system also influences the technical system, as the supply contracts and service contracts control the physical flow of fuel in the technical system. For instance, the supply contract between a shipping company and a fuel supplier specifies the intended supply of a certain quantity of fuel. Together with the service contract between the fuel supplier and a distribution company, this determines what quantity of fuel is going to flow through the distribution infrastructure to a vessel. Likewise, the supply contract between an oil company and a fuel trader, combined with the service contracts of that fuel trader with an LNG shipping company and a terminal operator, determines what quantity of LNG is shipped from a liquefaction plant to an LNG import terminal.

3. Model description

The system description provides an overview of the maritime fuel system, its elements, and their relations. However, for it to be used to explore the effects of policy instruments on the transition away from HFO, we implement this system perspective in an agent-based model: MarPEM. The main problem we wish to model is the lack of understanding of the effects of policy instruments on the adoption of different maritime fuels. This adoption of fuels follows from the simulated global consumption of the maritime fuels, which themselves emerge from the market interactions among the agents in the model. In this section, we describe how the elements and interactions of the maritime fuel system are conceptualised as types of agents and objects in MarPEM (Section 3.1). Hereafter, we discuss how those elements are initialised – i.e., the creation of instances of the agents and objects – to represent the organisations and assets in the global maritime fuel system (Section 3.2).

Since any model is a simplification of reality (to the extent needed to study a particular problem), the agent-based model is a simplified representation of the maritime fuel system. Some elements of the maritime fuel system are combined into one type of agent, while some other elements are not included in the model. The shipping companies and their vessels are combined in a number of 'vessel' agents. Even though this reduces the heterogeneity in the model and excludes some interactions from the model, the aggregation of vessels is expected to hardly influence the model outcomes. The vessels are included to cause the (geographically dispersed) demand for fuels, which materialises similarly when the vessels are aggregated.

The traders and suppliers of a fuel in a port are integrated in a 'fuel supplier' agent, as the model is not concerned with intra-port dynamics. This also causes us to exclude the distribution infrastructure and storage tanks in the ports from the model. Given the maturity of the HFO and MGO markets, they are represented as centralised global fuel markets and we assume that each port has the infrastructure to supply those fuels. The market for maritime LNG is still developing, which means that it is more geographically differentiated and is more easily influenced by the behaviour of individual agents. Therefore, we represent the LNG market as a set of decentralised market interactions among autonomous agents.

Fig. 2 presents an overview of the agents and objects in MarPEM, along with their connections and interactions. More details on the implementation and initialisation are given in the detailed model description, which is presented in Appendix A. The source code of MarPEM is available at https://www.openabm.org/model/5681.

To verify MarPEM, the guidelines of Van Dam et al. (2013) have been followed. We performed single-agent testing, minimal model interaction testing, and multi-testing experiments. Those experiments enabled us to fix programming errors that could influence the model behaviour and experimental outcomes, provided us insights into the volatility of the model behaviour, and showed us the sensitivity of the model behaviour to changing parameters. This verification resulted in a changed implementation of our model and – as discussed in the following section – caused us to exclude the (endogenous) decisions of bunker terminals to offer new fuels.

3.1. Model specification

3.1.1. Vessels

The vessels sail between ports (via a shipping lane that specifies the distance and allowed emissions), in order to execute shipping assignments. Depending on their propulsion technology, the vessels use a certain quantity of a particular fuel. Once the vessel arrives in a port, it unloads its cargo and selects a new shipping assignment. The assignment is selected on basis of the availability of its fuel, the fuel costs, the utilisation of the vessel, and the possible fine for exceeding the allowed

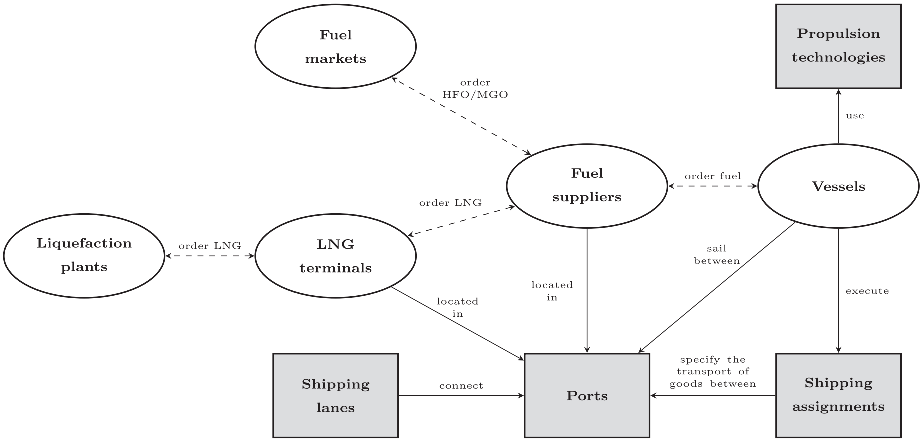

Fig. 2. Agents (ellipses) and objects (rectangles) in MarPEM, along with their connections (solid lines) and interactions (dashed lines).

emissions (which includes the probability of being inspected). Subsequently, the vessel compares the price of the fuel supplier in its current port to the price of the fuel supplier in the next port. If the fuel is cheaper in the current port, the vessel bunkers fuel here; otherwise, it will bunker in the next port.

Once a year, each vessel that exceeds its economic lifetime considers replacing its propulsion technology. This implies that it selects the propulsion technology that has the lowest combination of installation expenses, costs of fuel, expected fines, and risk of fuel unavailability. For that purpose, the vessel computes the net present value of the investment in a new propulsion technology. The initial investment is only needed when the propulsion technology differs from the current technology, and the annual expenses consists of the costs of fuel and the expected fines. The period of time over which the net present value is computed is equal to the number of years until the vessel reaches the end of its lifetime. So, the closer the vessel is to the end of its lifetime, the bigger the annual savings need to be to let the vessel decide to replace its propulsion technology. This net present value is corrected for the risk of fuel unavailability through dividing it by the percentage of ports that offer the technologies fuel (weighted by the vessels risk aversion). Hereafter, the vessel selects the technology with the highest net present value. If this is another technology than its current technology, it will replace its current technology.

3.1.2. Fuel suppliers

Each fuel supplier offers one type of fuel to vessels in a port. Consequently, the fuel availability in a port is defined by which fuel suppliers are located in that port. A fuel supplier uses a Q-learning algorithm (Watkins, 1989) to learn from previous experiences what price to ask for its fuel to maximise its profits. Q-learning is a reinforcement learning algorithm that enables agents to autonomously learn what actions to take in a certain state of its environment. This algorithm has a wide variety of applications, among which a number of transport related studies (e.g., Abdulhai and Kattan, 2003; Tamagawa et al., 2010; Jacob and Abdulhai, 2006). Q-learning can be used to enable agents to learn what price to set – given a state of their market environment – in order to obtain the highest profits possible (Tesauro and Kephart, 2002). When Q-learning is used for that purpose, each agent receives feedback on its action in the form of the profits it receives from selling its fuel at a certain price. Over time, it learns what price results in the highest profits in the current market conditions. By enabling all agents to set their price using Q-learning, the market environment of each fuel supplier is changing, forcing them to continuously adapt their price setting behaviour to the new environment. Through their interactions, the agents influence each other and collectively cause the emergence of a market. This market has no centralised marketplace, but is decentralised and defined through the volumes and prices of the traded fuels. This decentralised nature of the market enables us to capture geographical differences in the markets, as well as account for market power. Agents can learn that they have the market power to ask a higher price in a geographical subset of the market or in the market as a whole. That way geographical differences can emerge or one agent can impose its will on the entire market.

The decisions of fuel suppliers to offer new fuels in a port are not included in the model, but are represented exogenously through scenarios. Initially, we included those decisions as part of the fuel suppliers' behaviour to capture the mutual feedback between the demand for LNG and the supply of LNG. We executed experiments to assess the effects of this feedback on the development of the maritime fuel system (which are presented in Appendix B) and we found no substantial differences for either the fuel demand or the fuel prices. Combined with the substantial computational expenses of including the decisions of offer new fuel endogenously, this was reason to exclude those decisions from the model. That way we could perform more detailed experiments without missing important dynamics.

3.1.3. Fuel markets

The model contains one HFO and one MGO fuel market. The fuel market is conceptualised as a double-sided auction that is used to determine the price where demand matches supply. A double-sided auction represents a market as a centralised marketplace that balances supply and demand and sets a market price. Double-sided auctions are commonly used in agent-based models to represent well-established markets (Marks, 2006). The supply curve of a fuel market is exogenously specified, while the demand curve is constructed on basis of the fuel suppliers' orders. If the market finds a price where demand meets supply, the market is cleared and the sellers are told what quantity they can supply and the buyers are told what quantity they receive.

3.1.4. LNG terminals

The LNG terminals are situated in ports throughout the world, where they receive LNG that they either inject (regasified) in the network or sell to fuel suppliers. The injection of LNG into the network is represented by a demand-curve for LNG, which specifies what quantity of (regasified) LNG is demanded at different prices. The remainder of the terminal's LNG (constrained by its capacity) can be supplied to the fuel suppliers that order from the terminal. Like the fuel suppliers, the LNG terminal uses a Q-learning algorithm to learn what price to ask for its LNG to maximise its profits. The LNG that is sold by the terminal needs to be replenished, for which it orders LNG from the liquefaction plant(s) that can supply it at the lowest expenses (i.e., plant's price + carrier costs × distance).

3.1.5. Liquefaction plants

The liquefaction plants produce LNG. Each liquefaction plant has a supply curve that specifies how much LNG it is willing to supply at a certain price. Based on the demand of the LNG terminals, the liquefaction learns – through a Q-learning algorithm – which price it should set to maximise it revenues.

3.2. Model initialisation

Table 1 gives an overview of how the model's agents and global variables are initialised to represent the global maritime fuel system. Given that MarPEM is developed in collaboration with the Port of Rotterdam, the model is initialised with a focus on North-West Europe. However, developments in that region are influenced by developments in other regions of the world. To limit the model's computational expenses, the agents in the other regions have been aggregation into a single regional agent with the aggregated characteristics of the initial agents. For instance, all liquefaction plants in the Middle East are aggregated in a single plant with a production capacity that equals the summed capacities of the original plants. As the model concerns global market interactions, the effects of this aggregation are expected to have little influence on the fuel adoption patterns that we set out to study.

To aggregate the vessels and shipping assignments, we made the size of the shipping assignments proportional to the quantities shipped between ports. The largest quantities of goods are shipped within the Far East, and consequently the shipping assignments within that region have the largest size. Therefore, the vessels of the largest classes (i.e., that can ship the largest assignments) mainly sail on the shipping lanes with the highest shipped quantities, while the vessels of smaller classes mainly sail on lanes with lower shipped quantities. Generalised, the size of shipping assignments (and thus the deployment of vessel classes) can be grouped into four categories, ranked from largest to smallest: (1) *huge:* Far East and Middle East; (2) *large:* North America, Europe, and South America; (3) *medium:* Rotterdam, Antwerp, and Hamburg; and (4) *small:* Amsterdam, Le Havre, and Zeebrugge. Although this distribution of shipping assignments and vessels is not necessarily in line with the real-world distribution, this assumption does not influence the quantity of consumed fuel and thus is expected to have little influence on the global fuel adoption patterns.

Each vessel uses one out of four available propulsion technologies: HFO, MGO, LNG, or HFO with a scrubber. Those technologies are only a selection of all measures available to vessel owners to meet the emission regulations. We selected those technologies as they are considered viable propulsion technologies and thus are likely to be selected by the vessel owners. We thereby follow other studies, such as (Danish Maritime Authority, 2012; Brynolf et al., 2014).

MarPEM is designed to be easily adjustable, to enable future studies to change the geographic or functional focus, or study a variety of policy instruments. To make those changes, one only has to alter the initialisation of the model. For instance, to introduce a different fuel, the modeller only has to add fuel suppliers that offer that fuel and a propulsion technology that uses that fuel. More fundamental changes to the model – such as introducing new behaviour or changing the underlying assumptions – require changes to the code. Given the availability of the code, the modular design of the code, and the detailed documentation in Appendix A, those changes can be made with relative ease by modellers that were not part of MarPEM's development.

4. Experimental design

To demonstrate how MarPEM can be used to explore the effects of different policy instrument, we perform a number of experiments. In those experiments, we vary the implemented policy instruments, simulate the maritime fuel system, and measure the adoption of the maritime fuels. The explored policy instruments are selected so that they influence the maritime fuel system in different ways and, thereby, show the versatility of MarPEM. In this section, we present the design of the simulation experiments, by discussing the indicators used to measure the fuel adoption and the different policy instruments that are studied.

Table 1
Initialisation of the agents and variables in the agent-based model (∗ = agent is an aggregation of multiple agents).

Agent/variable	Initialisation
Vessels	73 vessels, 8 capacity classes, 4 technologies: HFO, MGO, LNG, scrubber
Fuel suppliers	HFO and MGO in all ports, LNG differs per experiment
LNG terminals	France, Netherlands, United Kingdom, Belgium, (South) Europe*, Far East*, Middle East*, North America*, South America* (capacities based on International Gas Union (2015))
Liquefaction plants	Africa*, Australasia*, Far East*, Middle East*, North America*, Norway*, South America* (capacities based on International Gas Union (2015), supply curve based on Satapathy et al. (2014))
Fuel markets	HFO costs: 800 \$/mt, MGO costs: 1780 \$/mt, LNG costs: 728 \$/mt
Ports	Amsterdam, Antwerp, Hamburg, Le Havre, Rotterdam, Zeebrugge, (rest of) Europe*, Far East*, Middle East*, North America*, South America*
Shipping lanes	Distances based on Sea-Distances.org (2015), allowed emissions based on (International Maritime Organization (IMO), 2014)
Propulsion technologies	HFO, LNG, MGO, HFO with scrubber
Shipping assignments	Shipped quantities between ports based on Seabury Group (2015), size of individual assignments proportional to shipped quantities
LNG transport	Carrier costs: 0.0095 \$/nm, import costs: 0.08 \$/nm

4.1. Indicators

The adoption of fuels in the maritime fuel system is measured by two indicators: (1) the percentage of vessels that use a certain propulsion technology and corresponding fuel (*technology adoption*), and (2) the consumption of the different types of fuels (*fuel demand*). The technology adoption of a propulsion technology is computed by counting the number of vessels that use that technology and divide that by the total number of vessels. This is an indicator of the strategic decision of vessels to invest in a certain technology. However, this only covers a part of the adoption of a fuel, as idle vessels contribute very little to the use of a fuel. Therefore, the demand for a particular fuel measures what quantity of that fuel is supplied to vessels and how this relates to the total quantity of supplied fuels. This indicates to which the extent the fuels are actually used and thus also how the SO_x-emissions develop.

4.2. Policy instruments

In the experiments, we vary the use of policy instruments, in order to observe their effect on the adoption of maritime fuels in the simulated maritime fuel system. We consider three different policy instruments: (1) enforcing emission regulations, (2) stimulating LNG availability in ports, and (3) stimulating retrofitting of vessels. We are aware that this selection of policy instruments is just a subset of all possible policy instruments. However, this paper does not aim to study all possible instruments to determine what policy instruments should be used to stimulate the maritime fuel system's transition. We perform the experiments to demonstrate the model's ability to study the effects of policy instruments. For that purpose, we decided to study policy instruments that influence the maritime fuel system in different ways: through regulation, through the supply of fuel, and through the demand for fuels. That way we illustrate the diversity of policy instruments that can be explored with our model, which can be used in future studies as basis to study the other policy instruments.

Due to the focus on three policy instruments, the experiments are divided into three parts, with each part assessing the effect of different implementations of a policy instrument. For each implementation of a policy instrument, the simulation is ran 10 times to explore the effect of stochasticity in the model. A single simulation run simulates the maritime fuel system over a period of 15 year, during which the fuel adoption is measured by the indicators we discussed before.

Enforcing emission regulations. The enforcement of emission regulations is implemented in the model by varying the inspection probability. This is the probability that the emissions of a vessel are inspected when it arrives at a port. Together with the fine that needs to be paid when a vessel is caught offending the emission regulations, the inspection probability determines the expected fine of exceeding the emission limits.

This influences a vessel's selection of shipping assignments and assessment of propulsion technologies. To assess the effect of this policy instrument, the experiment regards five different inspection probabilities: 0%, 25%, 50%, 75%, and 100%.

Stimulating LNG availability in ports. The availability of LNG in a port is implemented in the model through the presence of an LNG fuel supplier in that port. The vessels consider the availability of fuel in their shipping assignment selection, bunkering decision, and propulsion technology assessment. Thereby, the fuel availability can substantially influence the fuel adoption. To assess the effect of stimulating the LNG availability, four fuel availability scenarios are considered.

1. *None*: no additional LNG fuel suppliers, and LNG availability limited to Zeebrugge.
2. *3MP*: additional LNG fuel suppliers in the 3 main bunker ports: Far East, North America, and Rotterdam.
3. *SECA*: additional LNG fuel suppliers in the ports in the current SECAs: Amsterdam, Antwerp, Hamburg, North America, and Rotterdam.
4. *All*: LNG fuel suppliers in all ports.

Stimulating vessel retrofitting. Retrofitting a vessel concerns replacing its propulsion technology, without renewing any other aspects. Given the large number of relatively young vessels (UNCTAD, 2015), the retrofitting of vessels is likely to be important to change the fuel adoption in the maritime fuel system on a relatively short notice. Stimulation of vessel retrofitting is implemented in the model by lowering the economic lifetime of vessels, so that retrofitting is considered at a lower age. To assess the effect of stimulating the vessel retrofitting, the experiments concern different economic lifetimes: 5 year (1825 days), 10 year (3650 days), and 20 year (7300 days).

In the experiments where the enforcement of emission regulations is not studied, we set the inspection probability to 50%; when the LNG availability is not studied, we make LNG available in all ports; and when the retrofitting of vessels is not studied, we set the economic lifetime of vessels at 3650 days. Those parameter values are chosen so that we can optimally study the effects of the policy instruments that are studied in the experiments.

5. Experimental outcomes

The experimental outcomes show how the policy instruments affect the fuel adoption in the simulated maritime fuel system. In this section, we present those outcomes per policy instrument. We will start with the enforcement of emission regulations (5.1), then discus stimulating the LNG availability in ports (5.2), and finish with vessel retrofitting stimulus (5.3). Those outcomes are used in the next section to discuss the ability of MarPEM to explore the effects of policy instruments.

5.1. Enforcing emission regulations

The enforcement of emission regulations is implemented in MarPEM as the inspection probability of the emission of vessels. Fig. 3 shows, for the different inspection probabilities, how the technology adoption and fuel demand develop over time. The solid lines in the graphs represent the median demand (of the 10 different runs) for a particular fuel, and the dashed line represents the median percentage of vessels that have adopted a certain technology. The gray area around the lines represents the interquartile range of the different runs.

The figure indicates that the inspection probability had very little effect on the development of the fuel adoption. For each inspection probability, the HFO adoption (both in terms of fuel demand and technology adoption) decreased quickly and was replaced by LNG. So, even when the emission regulations were not enforced, HFO was replaced by LNG as dominant maritime fuel. Neither MGO nor scrubbers played a substantial role in any of the enforcement scenarios.

Given the limited LNG use in the real world, these outcomes may be unexpected. However, they can be explained by the price of LNG that is 90% of the HFO price. This is low enough to recover the higher initial investment of the LNG propulsion technology, even when there is no penalty for exceeding the emission regulation. Due to the high LNG availability, the vessels compare HFO and LNG solely on economic terms. This causes them to switch to LNG and the LNG adoption to increase. This is in line with the studies that concluded that LNG is an economically viable alternative for HFO (e.g., Danish Maritime Authority, 2012). The reason that we do not observe this transition to LNG in the real-world may be due to the lacking LNG availability in ports (Wang and Notteboom, 2015) or the energy efficiency gap (Jafarzadeh and Utne, 2014). Even though LNG is an economically viable alternative for HFO, those two factors prevent shipping companies from investing in LNG-powered vessels.

5.2. Stimulating LNG availability in ports

To assess how the LNG availability in ports affects the fuel adoption, the maritime fuel system was simulated with four different LNG availability scenarios. Fig. 4 shows, for each of the scenarios, how the use of the technology adoption and fuel demand developed during the simulations. Although the development of fuel adoption differed considerably per scenario, the 'None' and 'SECA' scenarios had substantial similarities, as did the '3MP' (three main ports) and the 'All' scenarios.

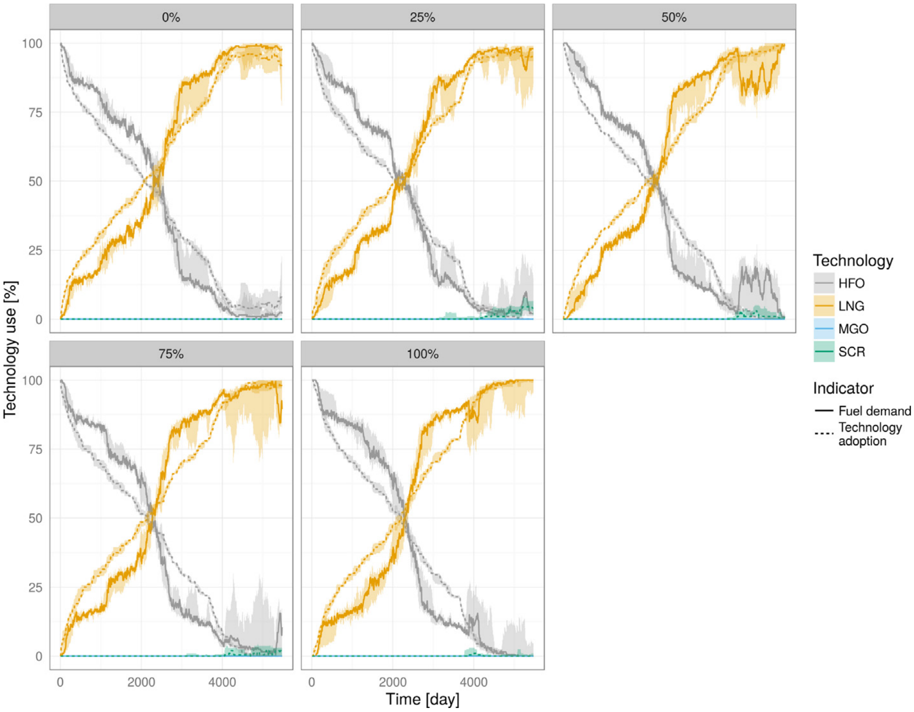

Fig. 3. Use of different technologies (HFO, LNG, MGO, and scrubber (SCR)), measured in terms of fuel demand and technology adoption, for each of the assessed inspection probabilities (0%, 25%, 50%, 75%, and 100%).

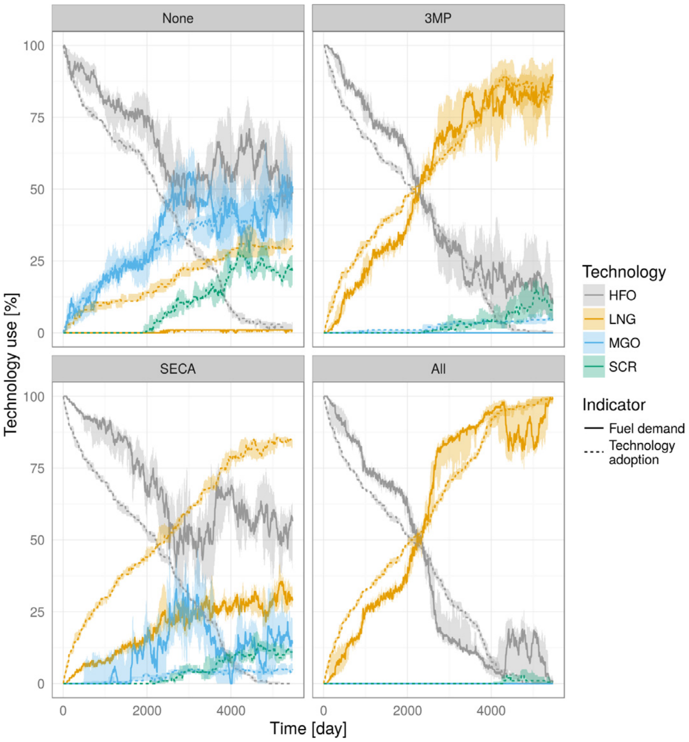

Fig. 4. Use of different technologies (HFO, LNG, MGO, and scrubber (SCR)), measured in terms of fuel demand and technology adoption, in different LNG availability scenarios (None, 3MP, SECA, and All).

In both the '*None*' scenario and the '*SECA*' scenario, the HFO technology adoption decreased to a low percentage, while the HFO fuel demand stabilised around 50%. The stabilisation of the fuel demand was caused by the use of scrubbers that still use HFO, and by the high fuel consumption of a few large vessels in the Far East that kept using HFO. The 'None' and the 'SECA' scenarios differed from each other in terms of which fuel replaced HFO. In the 'None' scenario, MGO was the main replacement of HFO, whereas the LNG adoption was negligible due to the availability of LNG that was limited to Zeebrugge where few vessels moored. In the 'SECA' scenario, LNG was available in North-West Europe and North America and thus was adopted more extensively. In the Middle East and Far East, where LNG was not available, HFO was still replaced by MGO and scrubbers.

The fuel adoption in the '*3MP*' scenario and in the '*All*' scenario differed considerably from the other two scenarios. In both the '3MP' and the 'All' scenario, the HFO adoption decreased, both in terms of fuel demand and technology adoption, to a low percentage and was almost exclusively replaced by LNG. This rise of LNG adoption was possible because LNG was available in all major bunker ports, enabling most vessels to bunker LNG. However, in the '3MP' scenario, the LNG adoption peaked at around 90%, while it reached near 100% in the 'All' scenario. The lower LNG adoption in the '3MP' scenario was due to LNG not being available in all ports and thus preventing some vessels to use LNG.

Overall, these experimental outcomes indicate that the availability of LNG had a substantial effect on the fuel adoptions in the maritime fuel system. For LNG to become the dominant maritime fuel, it needed to be globally available in (at least) the main ports. Only then, the vessels considered LNG a potential alternative for HFO and considered switch their fuel.

5.3. Stimulating vessel retrofitting

The willingness of a shipping company to retrofit its vessels is implemented in MarPEM through the economic lifetime of a vessel, above which retrofitting – and possible a new propulsion technology – is considered. Fig. 5 shows, for the three considered economic lifetimes, how the fuel adoption developed during the simulations.

At first sight, the economic lifetimes appeared to lead to different patterns of fuel adoption. However, the fundamental pattern was the same for each of them. For all three economic lifetimes, the adoption of HFO decreased and was replaced almost completely by LNG. So, over time, for all three economic lifetimes, LNG would eventually become the main maritime fuel. The three graphs appear so different because each had a different speed at which HFO was replaced by LNG. The shorter the economic lifetime, the earlier vessels started considering the replacement of their technology, and the faster the system transitioned from HFO to LNG. This pattern was also observed for any other combination of inspection probabilities and LNG

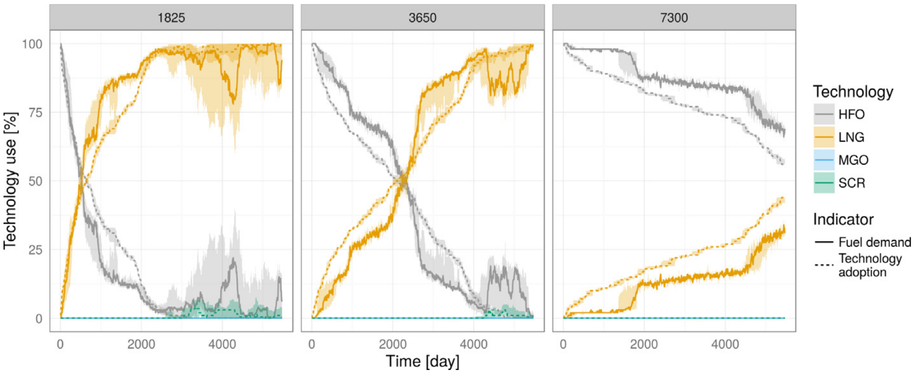

Fig. 5. Use of different technologies (HFO, LNG, MGO, and scrubber (SCR)), measured in terms of fuel demand and technology adoption, for the different economic lifetimes of vessels (1825, 3650, and 7300 days).

availability scenarios. Therefore, we can conclude that, in the long run, the economic lifetime did not lead to fundamentally different fuel adoption. However, the economic lifetime did influence the speed at which those fuel adoptions materialised.

6. Discussion

6.1. The model's functioning

The experiments illustrated how MarPEM can be used to study the effects of policy instruments on the maritime fuel system's transition away from HFO. The maritime fuel system is a complex adaptive system, which means that the system behaviour (i.e., the adoption of maritime fuels) emerges over time from the (inter)actions of heterogeneous agents that make autonomous decisions on basis of their perception of their environment. The policy instruments can influence those decisions directly, indirectly, or a combination of those two. For instance, a policy instrument that makes LNG available in ports influences the vessel owners' decisions both directly and indirectly. Availability of LNG directly influences the decisions by lowering the risk of not being able to bunker LNG and thereby making LNG more attractive. Next to that, the availability of LNG changes the market dynamics over the exchange of LNG, which can influence the LNG. Thereby, stimulating the availability of LNG indirectly influences the decision to select a type of fuel and the fuel adoption that emerges from that decision. Those indirect effects of a policy instrument can only be assessed if the system is studied as a whole (and not as isolated components). Therefore, the system perspective – fundamental to MarPEM – enables a more thorough analysis of the policy instruments' effects on the transition of the maritime fuel system.

6.2. Observed dynamics

A second objective of the experiments was to demonstrate the ability of MarPEM to study the effects of policy instruments that influenced the maritime fuel system in a variety of ways. We found that the dynamics observed in the experiments are in line with the conclusions of other studies and the economic rationale. For instance, Danish Maritime Authority (2012) and Adamchak and Adede (2013) concluded that LNG can be an economically viable alternative to HFO and over time will become a substantial alternative to HFO. Even more critical studies, such as Lloyd's Register Marine (2014), conclude that over time LNG will start to play a more substantial role as a maritime fuel. Moreover, Danish Maritime Authority (2012) and Wang and Notteboom (2015) identified the availability of LNG as an important factor for the transition from HFO to LNG. The experimental outcomes were also discussed with industrial experts of the maritime fuel markets. In those discussions, the experts confirmed that our experimental outcomes are in line with the general consensus concerning the transitioning of the maritime fuel system. So, the experiments confirm that the (inter)actions of autonomous entities simulated in MarPEM cause the emergence of dynamics that are recognised by experts and are in line with other studies. MarPEM thus can be considered a valid representation of the maritime fuel system and thereby can be used to explore the effects of policy instruments.

6.3. Extension of the model for future studies

Due to the focus of this paper on presenting the system perspective and the model, the studied policy instruments were necessarily a subset of the instrument available to stimulate the maritime fuel system's transition. The studied policy instruments were selected to demonstrate the model's ability to explore the effects of instruments that influence the maritime fuel system in different ways. Using the detailed description of the system perspective and the model, future studies can explore the effects of other policy instruments that can stimulate the transition of the maritime fuel system. Examples of such policy instruments are subsidies in retrofitting vessels with LNG-powered engines, reduction of port fees for LNG-powered vessels, subsidising maritime LNG, or different forms of regulation. The model may need to be extended or adapted to study the effects of some of those instruments. For instance, to study the effects of reduced port fees, the model needs to be extended to enable vessels to account for port fees in their scheduling decision and their selection of propulsion technology. Some directions in which the model can be extended are: representing the global system in more detail, including the market dynamics of the shipping sector, or adding the behaviour of port authorities. The detailed description in this paper and its appendices, the availability of our source code, and expandable model design provide a substantial basis for future studies that can provide more insights into the effects of policy instruments with unknown effects.

7. Conclusions

In this paper, we set out to present MarPEM: an agent-based model of the maritime fuel system that can be used to study the effects of policy instruments on the transition away from HFO. To assess those policy instruments, MarPEM focuses on the system as a whole. Therefore, we first described the maritime fuel system from a socio-technical system perspective. This provided insights into the components that make up the system, their properties, and how they are interconnected. Using those insights, we developed our model with which we can simulate the development of the maritime fuel system. In the experiments, we showed that MarPEM can be used to explore the effects of policy instruments on the transition of the maritime fuel system away from HFO. The three policy instruments that were studied in this paper were selected to demonstrate the model's ability to explore policy instruments that influence the system in a variety of ways.

The effects of the studied policy instruments were well-studied using qualitative reasoning and modeling studies. The experiments performed with this model confirm the impact of the policy instruments on the transition of the maritime fuel system. By comparing the experimental outcomes to the insights derived from other studies, and through expert consultation we conclude that MarPEM provides a valid representation of the maritime fuel system for purposes of policy impact assessment. Future studies thus can use our description of the maritime fuel system and our simulation model to study policy instruments of which the effects are unknown. This may require the model to be extended or have some assumptions relaxed. By discussing the system perspective and model in detail and by publishing the source code of MarPEM, we provided a substantial basis for future research into the transition of the maritime fuel system. Thereby, this research hopes to enable further deeper study of the maritime fuel system's transition.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.trd.2017.06.017.

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