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D 5.A.1
Scenario development for wind propulsion technology adoption: A theoretical model for agent-based modeling

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Acronyms and Abbreviations

ABM	Agent-based model
CO_2	Carbon dioxide
EU	European Union
GHG	Greenhouse gas(es)
IMO	International Maritime Organization
LNG	Liquified natural gas
NOx	Nitrogen oxide
SME	Small and medium enterprises
WASP	Wind assisted ship propulsion – Interreg North Sea Region Project
WPT	Wind propulsion technology

Executive Summary

Purpose of this report

This report is the first deliverable of activity 5a, WP4 – Policy and Viable Business of the WASP Project. The objective of the report is to provide a theoretical basis for a model of wind-assisted ship propulsion technology (WPT) adoption by shipowners.

The answer to the question of why shipowners would choose to install WPT will serve as a basis for the development of an agent-based model (ABM) of WPT adoption (activity 5a, report 2). There is thus a close relationship between both reports. This report will thus focus on the model and its theoretical foundations, while report 2 will focus on the model's empirical basis and use in simulations. For the preparation of report 2, Nord University will collaborate with an external consultant, primarily to support researchers with the programming aspects linked to the development of the ABM.

Methodological approach

This report has been prepared using a combined systemic/inquiry approach. This approach suits the topic as it supports an interactive cycle of theoretical development incorporating the specific case of WPT adoption, eco-innovation adoption in shipping more broadly, ABM methodologies in eco-innovation and shipping, and the empirical context of the WASP Project. The systemic/inquiry strategy allows a theoretical model to be refined as the basis for the ABM.

The systemic/inquiry approach we have employed is comprised of the following elements:

i) Theory; literature review of the drivers of eco-innovation.

WPTs are part of a larger category of eco-innovations. This report thus incorporates a literature review on the drivers of the adoption of eco-innovations to understand the factors prompting maritime firms to adopt green innovations (including both products and processes). We also review existing literature about maritime business, with particular emphasis on shipping firms' cost structures and the decision drivers behind operational and technological upgrades.

ii) Framework; ABM methodology as an approach to the adoption of WPTs.

We also introduce a methodology for developing agent-based models, with a particular focus on theoretical model development. Existing ABMs which focus on transportation eco-innovations and WPT are reviewed.

iii) The case; understanding the shipping industry's expectations towards WPTs

Based on the literature review, we identify drivers prompting shipping companies to adopt WPTs, and report the results of a survey conducted with practitioners and experts to rate these drivers and determine the key factors to include in the theoretical model.

In parallel with this survey, during spring 2020, the WASP Project organized a business case workshop, which provided valuable inputs from the shipowners involved in the WASP Project.

Findings

With the growth of international trade volumes, the environmental impact of the shipping industry has increased significantly. The International Maritime Organization is expected to adopt stricter policies and encourage the shipping industry to become more environmentally friendly. Wind-assisted ship propulsion technology has the potential to reduce ship emissions dramatically. This paper aims to model shipowners' installation of different types of WPT over time, and the relationships between adoption of WPT and market segments, geographical scope, oscillating markets, and regulatory conditions. By conducting this agent-based modeling research, we aim to identify the diffusion speed of different WPTs under a range of business and policy conditions.

An agent-based model is developed using the methodology discussed in Section II. Based on the research question, the authors propose a model to simulate the decision-making process of shipowners, regarding the installation and use of WPT on their ships. There are four mobile agents in the model, including shipowners and the technology providers for Flettner rotors, Ventifoil, and fixed wing rigs. The model includes two general properties for both shipowners and technology providers, namely location and actor-direction in the model ('heading'), and two more properties for shipowners, namely available cash and monthly growth of capital. We also include two environmental agents: market situation and regulatory condition. These are defined, respectively, in terms of the change rates of fuel prices and fuel switching costs.

In this shipowner-technology provider model, we define a timeline of behaviors for each agent which can help readers and programmers to understand how agents interact with each other and with business environments. This timeline is as follows: (1) shipowners and technology providers move throughout the simulating software's space; (2) shipowners interact with shipowners and technology providers; (3) update and check confidence level of shipowners on the new technology; (4) shipowners check cash availability; (5) shipowners decide whether or not to install WPT devices; (6) shipowners install WPT devices; (7) shipowners decide whether or not to use the equipped WPT devices; (8) ships use WPT devices; (9) shipowners update confidence level and cash availability; and (10) fuel prices change.

Two parameters are included in the model: (1) initial cash available and (2) initial confidence level. These two parameters enable us to see how different initial situations influence the diffusion of WPT. Considering the purpose of this study, we use the following measures for each studied ship type: (1) the percentage of ships with fixed wing rigs, Flettner rotors, and Ventifoils installed over time; (2) the percentage of ships with these technologies in active use, over time; and (3) oil prices over time. These measures are examined under a variety of scenarios for different ship types in order to illustrate WPT diffusion over time.

1. Introduction

The maritime industry is seeking solutions to mitigate greenhouse gas (GHG) emissions, air pollution, and other climate impacts (Hermann, 2017). At present, numerous options such as energy efficiency improvements, renewable energy sources (including wind propulsion), liquified natural gas (LNG), and emissions reduction technologies (e.g., scrubbers, carbon capture and storage) are being considered and implemented to transition the industry towards a low-carbon future (Rehmatulla, Calleya, et al., 2017).

Several recent and ongoing technological developments in the shipping industry align well with the concept of eco-innovation, which refers to the process of developing and introducing new products, processes and services that, once introduced, lead to positive change in an organization's environmental impact (Rennings, 2000).

Wind energy has been a key source of propulsive power for millennia, although in recent times, despite its status as an abundant and free renewable energy resource, it has not been adequately utilized in the shipping industry (Talluri et al., 2016). Wind propulsion technologies (WPT) are promising options among renewable energy sources for maritime use (Karslen et al., 2019), and are designed to reduce fuel consumption, thus decreasing costs while also cutting emissions. The first research output of WP4 in the WASP Project provides a good overview of the recent technological development of WPT (Chou et al., 2021)

The extant literature on eco-innovation includes a significant stream of research on the determinants of eco-innovation. This research has primarily been concerned with the interaction of public policies, market incentives, and characteristics of businesses in driving the adoption of eco-innovations (F. Boons & McMeekin, 2019). As a result, the literature has provided illustrative cases of the adoption of eco-innovation in different industry sectors, including the maritime (Rivas-Hermann et al., 2015), automotive (Christensen, 2011), agriculture (Hasler et al., 2016), and construction (Zabalza Bribián et al., 2011) industries.

In general, these studies tend to connect eco-innovation processes with the interactions between driving factors such as market pull, regulatory push/pull, and technological push (Kesidou & Demirel, 2012). Market pull is generally understood as the impact of consumer choices that incentivize research into and the development of greener technologies. Regulatory push/pull describes the standards, policies, regulations, and laws administered to address environmental impact. Technological push refers to industry-specific processes, practices, and operations (Horbach et al., 2012; Kesidou & Demirel, 2012; Rennings, 2000). Recent findings have shown that these drivers catalyze operations to exploit opportunities stemming from new regulations, market leanings, and technologies (Díaz-García et al., 2015). Meanwhile, multi-sectoral studies within countries have analyzed what drives companies to adopt eco-innovations through quantitative methods and large samples (Bossle, De Barcellos, et al., 2016; Cuerva et al., 2014; Kesidou & Demirel, 2012).

Overall, the eco-innovation studies highlighted above indicate that sectoral characteristics play an important role in the diffusion and adoption of eco-innovations. The normative characteristics of a given sector thus play a role in understanding the context in which firms opt for the adoption of eco-innovations (Horbach, 2019). While a wide variety of methodological approaches have been used to understand the micro-economics of a firm’s eco-innovation adoption (Bossle, Dutra de Barcellos, et al., 2016), modeling and simulation methods appear particularly suited to capturing the complex and changing environments in which firms decide to adopt eco-innovations (Köhler, 2019).

Among these modeling and simulation methodologies, agent-based modeling (ABM) is quite popular among researchers. ABM is a computational methodology with origins in the modeling of complex systems. A key characteristic is the presence of agents, computational entities with defined properties ,such as predicted actions in a given set of circumstances, e.g. the decision on whether to invest. The behavior of each agent can be modified by adjusting programmed rules; therefore, multiple scenarios can be modelled based on predefined instructions that respond to theoretical models (Wilensky & Rand, 2015).

Zhang et al. (2011) relied on ABM to understand the impact of public policies on consumer choices for the adoption of the eco-innovation of electrical cars. In an ABM study of socio-technological change in shipping, Karslen et al. (2019) modeled the influence of imperfect agent information and split incentives using a case study of Flettner rotors as a form of WPT. The focus of this study was, however, focused on climate-energy policies.

As these studies show, although ABMs are not the most frequently used methodology in eco-innovation research, they are often used to answer questions related to the interaction of multiple drivers and the role of these drivers in focal firms' (i.e., agents') decisions regarding adoption of new technologies. ABMs' ability to simulate whole systems with multiple interacting agents can provide potential insight into the external and firm-specific conditions under which diffusion of WPTs is likely.

1.1 Purpose of the report, contributions and structure

This report, as an output of the WASP (Wind Assisted Ship Propulsion) Project, addresses the following research questions:

1. Can an ABM-focused theoretical framework be applied to develop a model of eco-innovation (WPT) adoption in the maritime shipping industry?
2. What drivers motivate shipping firms to adopt eco-innovations in general, and how do micro-economic conditions influence these decisions?
3. How do external and internal driving factors influence the adoption of WPTs by shipping firms in the North Sea Region?
4. How do these different factors interact with each other in an ABM?

This report is the first of two deliverables in *WP4 Policy and Viable Business, activity 5a: Scenario development for WPT market uptake*. A more detailed overview of WPTs is available in the WASP article (Chou et al., 2021). The first deliverable develops a theoretical model for ABM simulation, which is subsequently implemented, calibrated, and validated in report #2.

The remainder of the report is structured in the following sections:

- Section II presents the methodology along with a discussion of the empirical data collected.
- Section III addresses the question: "*Can an ABM-focused theoretical framework be applied to develop a model of eco-innovation (WPT) adoption in the maritime shipping industry?*". This section reviews the key tenets of the ABM methodology as well as the previous implementation of ABM in both eco-innovation and the shipping industry.
- Section IV summarizes the analytical framework, and provides a detailed review of the drivers for eco-innovation and shipping firms' operational economics (research question 2). This section proposes a set of likely drivers for eco-innovation in the adoption of WPTs in shipping.
- Section V presents an empirical look into the adoption drivers of WPTs in the shipping industry (research question 3).

- Section VI combines the main inputs of Sections II to V to propose an ABM-based theoretical framework for WPT adoption by shipping firms (research question 4)
- Section VII presents conclusions and frames the terms for the follow-up report as part of WP4 of the WASP Project.

2. Methodology

In this report, we seek to explain the potential drivers influencing a firm's decision to adopt WPT, and the connections between internal and external drivers. The research presented here is explanatory in nature, as it aims to i) explain patterns related to the phenomenon in question and ii) identify relationships shaping the phenomenon (Marshall & Rossman, 2006). We rely on abductive inference in formulating new ideas and analytical approaches without drawing on preliminary theoretical premises (Meyer & Lunnay, 2013). Abductive inference is characterized by generating alternative explanations for data that does not fit the expected theoretical propositions (Meyer & Lunnay, 2013). We adapt the abductive methodology known as systemic combining (Dubois & Gadde, 2002), which repeatedly adjusts theoretical lenses and methodological approaches through an interactive approach to better respond to the characteristics of the empirical world. Systemic combining is also used when carrying out complex case studies which require the researcher to have a deep understanding of organizational dynamics. We can thus strategically use systemic combining as a way to connect theoretical framing with empirical data and a specific case study (Dubois & Gadde, 2002). Figure 1 visualizes the systemic combining process. This study was carried out in four phases, as further described in Figure 2.

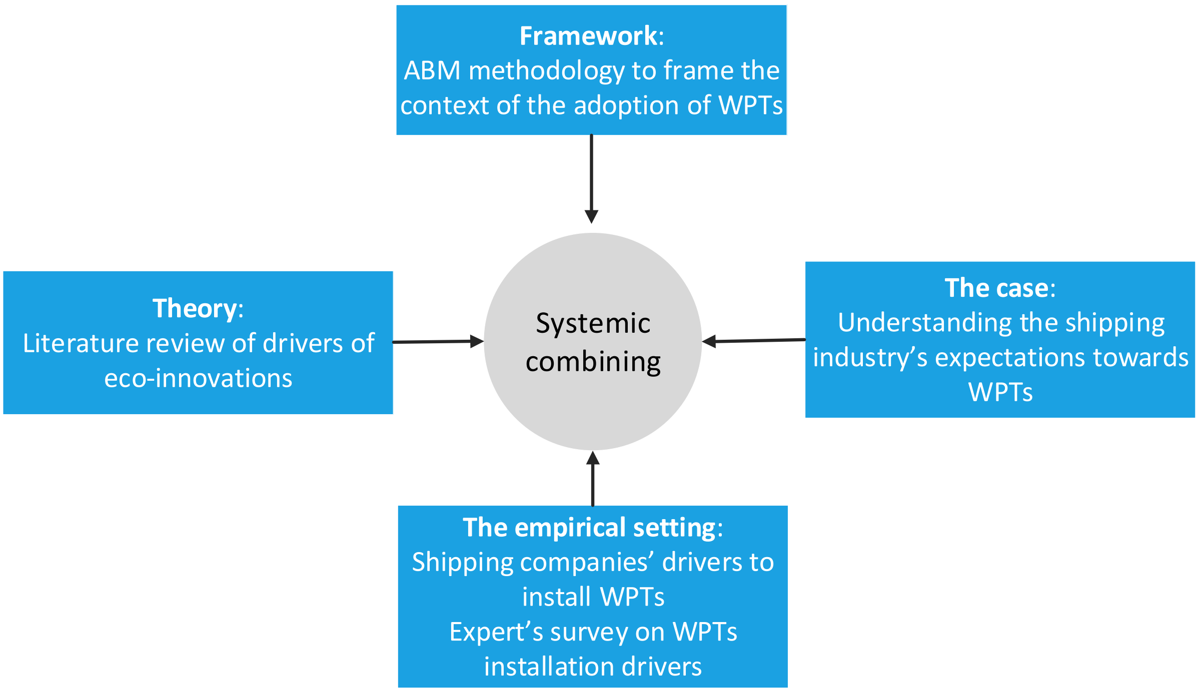

Figure 1 Systemic combining approach to developing a theoretical model of WPT adoption in shipping firms

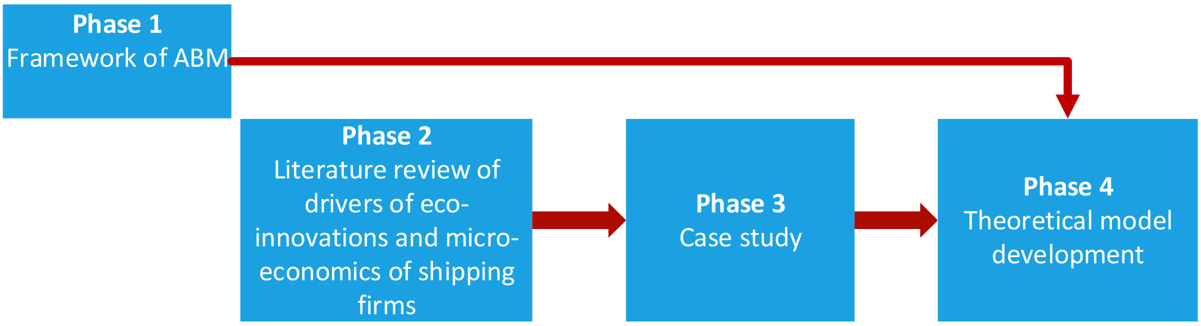

Figure 2 The four phases of the systemic combination process

2.1 Phase 1: Technical requirements of the ABM methodology

In Phase 1, we conduct a review of the technical requirements in designing an ABM. ABMs are programmed using computational rules; in this case, these rules are based on the factors we identify as drivers in agent decisions (Wilensky & Rand, 2015). Section III of this report reviews previous ABMs in both eco-innovation and shipping research to understand data needs, agent definitions, ABM process flows, and overall software requirements. The purpose of Phase 1 is not to provide a lengthy or technically intensive presentation of ABM, but to highlight how theoretical models for running ABM should be developed.

2.2 Phase 2: Literature review on the drivers of eco-innovation adoption, with a focus on the maritime industry

Phase 2 consists of a systematic literature review with a focus on the drivers of adoption of eco-innovations. The purpose of such a review is to provide a reliable and reproducible synthesis of key thematic discussions within a given academic field (Easterby-Smith et al., 2018). A systematic review in the context of eco-innovation is primarily concerned with identifying primary drivers, motivations, and barriers that have been shown to lead firms to either adopt or not adopt eco-innovations. Following Bossle et al. (2016), the literature review on eco-innovation drivers was organized according to the elements highlighted in Figure 3.

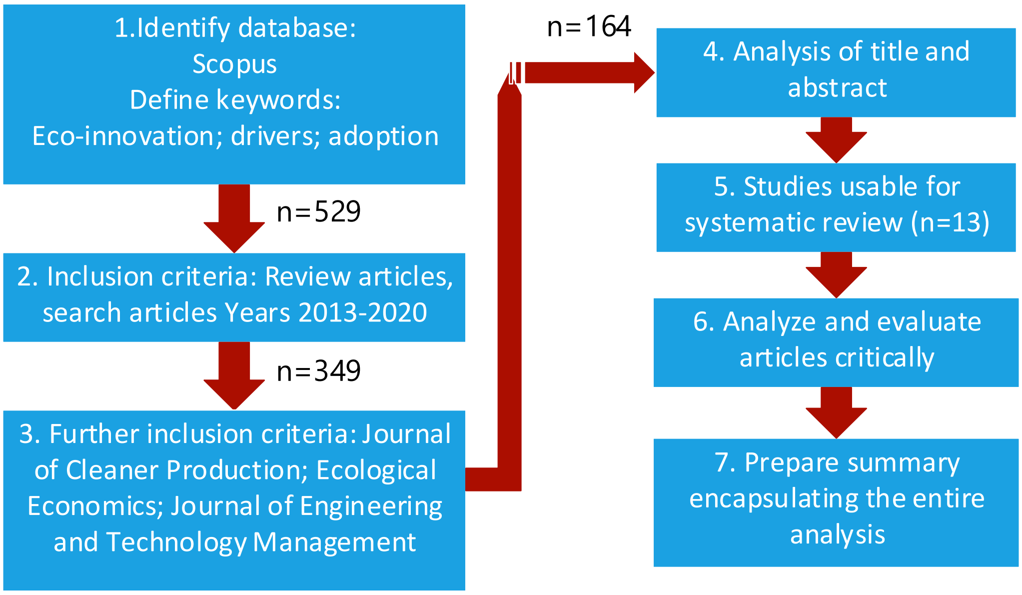

Figure 3 Overview of the systematic literature review process on the drivers of eco-innovation adoption. Adapted from Bossle et al. (2016)

The starting point in the systematic literature review process is the guiding research question, which is formulated as follows: *What mix of eco-innovation drivers higher adoption rates of WPT in the shipping industry?*

Based on the guiding research question, articles were selected for inclusion in the literature review based on a seven-step process. In step 1, keywords were identified by consulting previous systematic literature reviews (Díaz-García et al., 2015). Articles relevant to the topic were then located in the Scopus database using these keywords; Scopus was chosen due to its repository of relevant high-quality research. We carried out a preliminary inspection of previous reviews on "innovation" and "eco-innovation". Subsequently, we broadened the search to also include other search terms, such as "adoption" OR "drivers", and to include other qualifiers such as "innov*" and "eco-innov*". The results from this search were then used to create a final list of key terms to cover all possible existing literature relating to eco-innovation and the underlying drivers that catalyze adoption rates.

A set of exclusion criteria was established in step 2, including temporal criteria, as the focus was on the most recent academic contributions (2013-2020). In step 3, we identified research focused on the discussion of eco-innovation within three key journals of technology and environmental management: Journal of Cleaner Production, Ecological Economics, and Journal of Engineering and Technology Management. In step 4, a detailed analysis of the titles and abstracts of candidate articles in connection with the research question resulted in a preliminary list of 13 articles for further inclusion.

The selected academic literature was complemented with industry-driven articles derived from the shipping magazine Lloyd's List. These articles were included to analyze the industry consensus on eco-innovations and how it is being discussed by industry insiders. The query used keywords such as "clean technology", "eco-technology", "green innovation" and "wind propulsion technologies" to identify the articles to be used. This search returned 47 mentions of the above terms in various articles dating back to the year 2008. These articles were utilized as an industry-centric counterbalance to the academia-focused systematic literature review on eco-innovation.

Academic literature and industry articles were analyzed critically to prepare a summary leading to the set of propositions summarized at the end of Section IV. These propositions were subsequently integrated into the survey in Phase 3.

This systematic review was complemented with a review of the literature on micro-economic decisions in shipping firms. The combination of the two reviews provides an initial theoretical understanding of the factors that influence the likelihood that shipping companies will adopt WPTs.

2.3 Phase 3: Case study of the drivers of WPT adoption by short sea shippers

Stage 3 follows a single case study design. The purpose of this case study is to tackle research question 3: "*How do external and internal driving factors influence the adoption of WPTs by shipping firms in the North Sea Region?* "

Phase 2 developed the theoretical framework which is necessary to analyze the single case (Yin, 2018). The theoretical framework also provides inputs for the data collection instruments used in Phase 3, which are summarized in Table 1 below. The case study focuses on WPT adoption drivers in the short sea shipping sector, mainly within the North Sea Region.

Table 1 Relationship between the guiding research question, context, and case study

Guiding issue	Method of data collection	Section in the report
Internal drivers of WPT adoption: Why do shipping companies install WPTs?	Focus group with shipping companies installing WPTs; business case workshop	Section V
Validation of the key eco-innovation drivers as applied to WPTs	Survey with WPT stakeholders	Section V

2.3.1 Survey with WPT stakeholders

The survey was designed to gather information on the driving factors of eco-innovative behavior and performance, and comprised ten questions relating to the various identified drivers, including technology push, regulatory pull, and market push. The questions adapted the theoretical propositions resulting from Phase 3 of the study (Appendix 3). The participants were asked to respond to all ten questions using a five-point Likert scale ranging from 1 = Strongly Disagree to 3 = Do Not Agree or Disagree to 5 = Strongly Agree.

The survey respondents were eco-innovation practitioners with business, education, industrial, or research backgrounds. They were identified and recruited in two ways. One group of participants had previously been involved with the WASP Project and or EU-backed shipping demonstration initiatives; these individuals were deemed suitable due to their knowledge of the shipping industry in general, prior experience with shipping eco-innovations, and commitment to fostering sustainable development as signified by their involvement in previous demonstration projects. The other group was recruited from among the authors of academic articles pertaining to innovation, eco-innovation, green innovation, WPT, and the shipping industry. It was deemed necessary to expand the scope of participants beyond past participants in related projects to ensure a wide population of competent and knowledgeable individuals.

Participants represented a number of countries, including Belgium, Brazil, Denmark, France, Germany, Italy, the Netherlands, Norway, Portugal, Spain, Sweden, Turkey, and the United States. These participants held positions in educational institutions, governmental organizations, shipping companies, and consultancies; their job titles included professor, researcher, head of research unit, port logistics director, dean, special projects manager, director, consultant, and CEO. From a sample of 111 selected participants, 11 could not be contacted due to old, expired, or malfunctioning e-mail addresses. Of the remaining 100, 19 respondents completed the survey, representing a response rate of 19%.

2.3.2 Focus group with shipping companies installing WPTs

In collaboration with WASP Project partners, we held a focus group on 11.05.2020. This focus group was conducted virtually due to the COVID-19 restrictions. It included 16 participants, including two shipping companies participating in the WASP Project. The focus group was organized into three parts:

1. The business problem/opportunity and the operational environment
2. Benefits of WPT technologies versus challenges/risks
3. The cost factors

2.4 Phase 4: Model development

Phase 4 involved the development of the ABM theoretical model (Figure 2). It was directly linked to the inputs provided by Phases 1, 2 and 3. Phase 1 identified the technical requirements, including an overview of previous ABM models of eco-innovation in transportation and the type of data requirements. Phases 2 and 3 will, on the other hand, adapt the specific conditions of WPT adoption by shipping firms and align these with the requirements established in Phase 1.

We have developed the ABM model for this project through an exploratory process involving the definition of agents and behaviors and subsequent exploration of emerging patterns (Wilensky & Rand, 2015).

3. An ABM framework to model WPT adoption in short sea shipping

This section describes the agent-based model and the logic of the associated theoretical framework. The use of agent-based modeling is gaining popularity across a range of academic subjects in both the natural and social sciences (Wilensky & Rand, 2015). In the social sciences, ABM is used to model the behavior of individual or group actors in dynamic adaptive systems; these systems can take the form of marketplaces, organizations, or other systems that can be analyzed via the combined actions of large groups of individuals (Garcia, 2005).

In an ABM approach, agents are autonomous decision-making entities that interact with each other and/or their environment based on specific rule sets which dictate their behavior and choices (Zhang et al., 2011). This methodology is a useful tool to understand eco-innovation and new product development, specifically in the shipping industry, because the process of innovation, imitation, and enhancement is not deterministic, and thus the system being modeled is highly non-linear (Debenham & Wilkinson, 2006). ABM allows for detailed examination of the full range of actor-specific strategies during the innovation process.

Utilizing external knowledge sources is a vital product development strategy, which is why innovation benefits from collaborative partnerships within innovation networks through the dynamic and heterogeneous unit nexuses, because each part harnesses different collections of expertise (Gilbert et al., 2007).

The development of ABM occurs in three broad phases (Garcia, 2005, 2007; Wilensky & Rand, 2015): theoretical model development, simulation in ABM software, and validation with empirical data. The last step in this sequence ensures quality of results and allows the empirical calibration of the model (Figure 4).

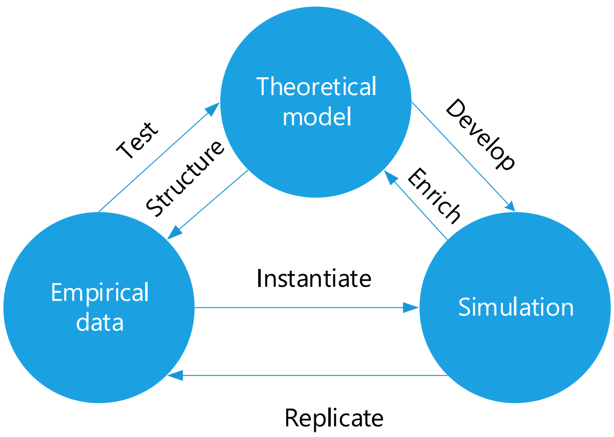

Figure 4 Process of ABM. Source: (Garcia, 2007)***.***

3.1 Developing a theoretical model in ABM

Garcia (2005)'s widely cited paper on the application of ABM in innovation management models exploration and exploitation mechanisms at the firm level as a way to help an organization's managers make decisions about investments in new product development portfolios. The conceptual model includes six steps in the development of ABMs, starting with the definition of a research question that will subsequently guide the ABM process. These steps and key considerations of each are listed below:

Step 1. Theory operationalization

- Involves creation of a cognitive map
- Simple; the goal is to determine the allocation of resources for exploration or exploitation

Step 2. Agent specification

- The behavioral state of each individual: characteristics of the degree of relation to other agents (early adopter versus late adopter)

Step 3. Environmental specification

- Environments may be modeled as closed or open; open environments are those altered by events outside of the modeled system
- Implications for model development in the WASP Project context include fuel price/market scenarios

Step 4. Rules of behavior

- Both agent-agent rules and agent-environment rules must be established
- Implications for model development: What conditions will influence a shipowner to install/not to install a WPT? What is the role of charterers, government, and WPT manufacturers?

Step 5. Decisions regarding measurement of results

- Decisions include which type(s) of data to record, on what scale to measure this data, and what format results will be displayed or recorded in (e.g., figures, maps, or tables).

Step 6. Runtime specifications

- Decisions must be made regarding the number of iterations to run in order to properly model the system.

Specifications are based on interview feedback and the analysis of other qualitative data sources. The theoretical model development process synthetized above reflects that of other more generalist methodologies, such as the approach proposed by Wilensky and Rand (2015).

3.2 ABM applications in the shipping industry and eco-innovations

Several publications focusing on the application of ABM within the maritime transportation field were identified. A number of these publications model the impact of policy instruments, such as the sulfur cap on maritime fuels (Holmgren et al., 2014; Vierth et al., 2015). Holmgren et al. (2014) relied on an ABM developed as part of the EU-funded SKEMA project and applied the TAPAS tool to model decision-making processes in transportation chains, with a focus on high-value goods.

We identified two studies focusing on research questions similar to those of this report, i.e. drivers for the adoption of eco-innovations or cleaner technologies in the transportation sector (Karslen et al., 2019; Zhang et al., 2011). The details on both models are presented in Appendix 1 and 2, respectively.

Zhang et al.'s (2011) model focuses on the diffusion of electric vehicles (EV) as an eco-innovation. The aim of this ABM study is: “We focus the study on the impact of three specific mechanisms on the diffusion of AFVs: technology change, consumer interactions, and regulatory policies" (Zhang et al, 2011, p. 153). "

The theoretical framing encompasses several theories connected to the drivers of eco-innovation, including technological push, regulatory push, and market pull (see the next section for a more detailed presentation of how these drivers influence WPT adoption). In addition, the ABM accounts for the characteristics of the different agents involved in the development and diffusion of EVs, including car manufacturers. The parameters in the ABM evaluate different EV designs, their acceptance by consumers, and how different policy combinations affect EV designs. The authors use this model to run three different experiments drawing on the eco-innovation model and the agent parameters.

Another ABM model developed by Karlsen et al. (2019) focuses on the diffusion of a specific type of WPT called Flettner rotors. The model answers questions concerning the effects of shipping firm participation in learning networks and pilot projects relating to the installation of WPTs, along with the effects of imperfect information or split incentive barriers and technology providers' interaction with shipowners. Key properties of the environment include fuel prices. The model incorporates several simplifications of the inherent characteristics of ABM to avoid an overwhelming model complexity: focus is narrowed to a single WPT technology and supplier, a limited number of policies (e.g. CO_2 pricing); impacts on shipping firms' adaption of WPT are examined only for one type of ship; and the cost calculation is limited to the case of a single long-distance deep-sea shipping route (Rotterdam to Shanghai). The model is also constrained to 100 shipowners and 100 model runs. In addition, to contribute to the simplification, equipment failures and catastrophes are assumed to be non-existent in the model.

4. Drivers of eco-innovation and the micro-economics of shipping firms

This section of the report summarizes Phase 2: Literature review of the drivers of eco-innovation and the micro-economics of shipping firms.

4.1 Drivers for the adoption of WPT: Four theoretical propositions

Proposition 1: Due to the dynamics of short sea shipping, regulatory measures will be most effective driver for the adoption of WPT

Regulations have historically been emphasized as an important driver of eco-innovation due to their two-fold effects on the environment and technical upgrades (Rennings, 2000). Particularly in the shipping industry, it has been observed that a mutual reinforcement relationship between *economic market pull* and *self-regulatory instruments* stimulating eco-innovation. However, due to the challenges of current market circumstances, shipowners are not sufficiently incentivized to install less environmentally damaging technologies (Hermann, 2017). It has also been shown that *technological push* and *regulatory push* are closely linked as eco-innovation drivers due to technological suppliers' lobbying of regulators to ensure certain technologies continue to be included in regulatory measures (Hermann, 2017).

Previous research on WPTs and regulations indicate that if a CO_2 taxation policy were to be implemented, the use of Flettner rotors in conjunction with diesel propulsion would provide an economic benefit. Conversely, in a scenario with no CO_2 taxation policy in place, the use of Flettner rotors on ships would provide little to no economic benefit for certain routes (Talluri et al., 2018). Another study (Talluri et al., 2016) concluded that the installation of vertical axis wind turbines or Flettner rotors could provide significant benefits on ships crossing the Atlantic Ocean because these routes are characterized by high fuel consumption and, more importantly, particularly strong wind conditions.

Karslen et al. (2019) suggest that improvements in the eco-innovation process require more stringent regulatory frameworks, including new standards and limits on access to existing subsidies and fiscal incentives; options include carbon taxation, which would directly impact the shipping sector. Additionally, after a period of carbon taxation and demonstration programs, a cost-effective policy could enhance the diffusion rates of rotor technology and reduce the need for this carbon taxation. A policy focus on routes with favorable wind conditions (e.g., Atlantic routes), forming naturally protected innovation niches would lead to learning, reduced barriers, and lower costs, thereby offering more benefits for shipowners operating on routes with less favorable wind conditions (Karslen et al., 2019).

Proposition 2: To stay competitive, once the first firm adopts, others will follow

There have been several studies showing a positive correlation between eco-innovation and a firm's economic performance (Cai & Li, 2018; Hojnik & Ruzzier, 2016). Firms that apply eco-innovation in their business models generate greater revenue per employee than those that do not (Doran & Ryan, 2012). These benefits are seen primarily in operational economies, through cost savings and higher levels of resource productivity along with more efficient logistics and the subsequent commercialization (Sarkar, 2013). Furthermore, Cheng and Shiu (2012) found positive correlations between a firm's performance and its focus on eco-innovations in products, processes, and organization. Chen et al. (2017) and Cruz-Cázares et al. (2013) showed how innovation focusing on technological efficiency is also positively linked to firm performance. Other studies have demonstrated that environmental innovation (i.e. the optimization of a firm's use of natural resources in terms of energy consumption per output unit) yields significant improvement on competitiveness and business performance (Bossle, Dutra de Barcellos, et al., 2016; Eiadat et al., 2008; Tseng et al., 2013).

Additionally, investments in eco-innovation have been shown to spawn an iterative cycle wherein firms' investment in eco-innovation leads to greater competitive advantages on the market (Hojnik & Ruzzier, 2016). This also supports the notion that firms that seek opportunities while maintaining open collaboration with other players in the market tend to develop eco-innovations at a higher rate. Firms that excel at recognizing opportunities engage in greater eco-innovation, and these firms also tend to have customer and market orientations that enable them to accurately identify consumer preferences and evolve their business models to further reinforce eco-innovation development (Sáez-Martínez et al., 2016). Other market-based benefits of the development and implementation of eco-innovation include improvement in the firm's image, cost savings, local community outreach improvement, broadened access to green markets, and further competitive advantages (Shrivastava, 1995). Furthermore, Sáez-Martínez (2016) indicated that path dependency is highly prevalent in eco-innovation development: firms with high levels of innovation development capacity are more likely to experience continued eco-innovation in the future. Thus, within the shipping industry, it can be surmised that WPTs have the potential to provide this kind of benefit, and with their expected cost savings of up to 20% (Talluri et al., 2018), this makes them extremely attractive. Even before this analysis, as far back as 2013, Scandlines implemented a long-term vision to incorporate hydrogen, Flettner rotors, and other environmental improvements into concept vessels to lure both potential buyers and customers who are seeking ways to cut their fuel consumption (Eason, n.d.).

Proposition 3: Technological push will be the least important factor because shipowners purchase WPT and do not develop it themselves

Technological push refers to industry-specific processes, practices, and operations that motivate firms to upgrade their current technological capacity (Horbach et al., 2012; Rennings, 2000). Market pull and technological push are interlinked and complementary, and a firm's capacity to capitalize on R&D influences its trajectory (Kemp et al., 1992). Firms' technological research and development capabilities tend to show a positive relationship with eco-innovation because of their role in facilitating the technological adaptations that are necessary to evolve clean technologies (Bitencourt et al., 2020). Firms have started increasing their investment in environmental innovations to better compete in the marketplace, however, to rationalize these investments in R&D and implementation, an appropriate prospect of future market relevance must be present (Azzone & Noci, 1998). Another aspect of technological push is the drive to develop potential benefits of knowledge spillover within industries; as other firms in the market innovate, firms with strong technological competence are able to benefit from the knowledge gained in order to advance their own eco-innovation (Cai & Li, 2018).

Del Río et al. (2016) concluded that firms in low-tech sectors (slow movers/adopters, mature industries, high polluters) have a higher proclivity to eco-innovate when catalysts in the business environment necessitate for change. For example, innovation may be required to stay within regulations, and thus a low-tech firm which may not have otherwise chosen to eco-innovate would be forced to do so.

In the shipping industry, if shipowners want to eco-innovate, they may send an order to shipyards to build or retrofit ships with existing eco-innovations, or invest in R&D. However, the consequent improvements in emissions and energy efficiency are dependent on the type of technology, as are the costs (both capital investment and operational). Thus, shipbuilders and suppliers make financial decisions during the innovation phase within this industry which are felt throughout the shipping markets (Köhler & Senge, 2012). The impetus from shipowners to innovate tends to come from demonstration projects that highlight the effectiveness of new technologies. The underlying supposition is that the results from demonstration projects, including both successes and failures, should not reduce shipowner expectations but instead emphasize that learning accumulates during each period, and thus expectations can increase over time (Karslen et al., 2019). It can therefore be argued that technology push is not as significant a driver in adoption as the market push from consumers and the cooperation with authorities in demonstration projects. However, in a recent shipping magazine (Osler & Farley, 2019) it was stressed that WPTs, such as kite sails and Flettner rotors, require a cost-benefit analysis predicated on a vigorous dataset before shipowners are sufficiently well-informed to make large commercial decisions on future adoption.

Proposition 4: Upfront retrofitting costs will be the biggest barrier to adoption

For shipowners, the installation of Flettner rotors is still not profitable enough to justify their cost on all routes with current fuel prices and regulatory policies. Although the environmental gain is substantial, the economic reality is that this technology does not currently make financial sense in situations where wind conditions are less than optimal (Talluri et al., 2016). Additional barriers within the shipping industry include imperfect information on technological performance and the split incentive structure which exists in the short-term time charter market. This last point, for example, implies that shipowners' investments in novel technologies are not rewarded with charter premiums, unless WPTs can become part of the negotiation between the shipowner and the (long-term) user. Other barriers relate to capital access (or a lack thereof), incompatible infrastructure, technical risks, and geopolitical risks such as oil price volatility or lower fleet utilization (Karslen et al., 2019; Rehmatulla, Parker, et al., 2017; Rojon & Dieperink, 2014). These limited charter premiums, as well as low fuel costs and low expectations for benefits, have led shipowners to view rotor technology as uneconomical, leading to low adoption rates and limited learning and to continuing high capital costs. The imperfect information and split incentives barriers prevent knowledge diffusion by stalling positive feedback loops between experiments, learning, and expectations (Karslen et al., 2019). Due to the inadequate mobilization of functional resources, the financial support provided for technological development has primarily been funded through public innovation initiatives, while actors seeking to receive financial support have struggled to obtain it (Rojon & Dieperink, 2014).

Many players in the shipping industry struggle for commercial vitality and oftentimes lack the requisite financial means to invest in, adopt, and subsequently install novel technologies. Within the current market climate, liquidity is more vital to firm survival than profitability, and thus firms tend to avoid investments in which the capital costs would not be recouped for years; thus, any long-term competitive advantage from WPT is overshadowed by the interim capital restrictions (Rojon & Dieperink, 2014).

Given this economic context, one key approach to improving overall adoption rates of WPT may be to decrease capital costs. Centralized approaches such as one-stop retrofit harbors are one possible approach to achieving this. In a 2017 interview, Per Winther Christensen, Deputy Technical Director of the Danish Shipowners' Association, stated that

> "I see increasing interest in the Flettner rotor, and Maersk Tankers will install two rotors on a vessel this year. The expected savings on the rotor systems vary and are particularly

> dependent on the vessels' trade patterns and which wind systems they meet on the voyage. Savings could be up to 10%, which is significant. Few Flettner rotors are installed and in operation today, but high growth seems likely; if 500 are installed in 2050, that would represent 100-fold growth over 30 years." (Kinthaert, 2017).

While retrofitting costs may be expensive, it may make more sense for new ships to implement WPT, such as Flettner rotors, in the coming decades.

4.2 Economics of shipping firms' operations

In this section, we review the microeconomic decisions of an individual shipping company. The shipping market experiences periods of boom, recession, and depression based on changes in supply and demand. Good microeconomic decision-making means maximizing returns on investment and growth in boom periods, while keeping control of the business when surplus capital is moving out of the industry during a recession. The challenge is to create sufficient profit for the company when times are good to be able to avoid undesirable situations when times are bad. Good decisions give a company a positive cash flow and enable it to implement new technologies to increase profit in future operations. In this section, we review a classic decision-making tool – the return-on-investment model – supporting shipping firms to decide on whether to invest in a set of new wind-assisted propulsion devices.

Return on investment (ROI) provides a snapshot of profitability and can provide a simple quantitative measure of whether or not WPT-equipped ships economically outperform traditional ships. In business, ROI is commonly used to measure rates of return per period for capital invested in an economic entity to decide whether or not to conduct a specific investment. It can also be used as an indicator to compare different investment opportunities. In our case, each shipowner faces the choice between three different technology providers, providing fixed wing rigs, Flettner rotors, or Ventifoils. The investment with the largest return is typically given priority. The ROI can be estimated using equation (1) below (Friedlob & Plewa Jr, 1996). In our study, we rewrite this as equation (2); this will be further developed based on the case study in Section VI.

$$ROI = \frac{Profit}{Investment} \tag{1}$$

$$ROI = \frac{R_{Invest.} - C_{Invest.}}{C_{Invest.}} \tag{2}$$

Where $R_{Invest.}$ denotes revenue/gains of the investment or reduction of operational costs. $C_{Invest.}$ denotes the cost of the investment.

5. Empirical insights into WPT adoption drivers in the shipping industry

This section presents the case study conducted in Phase 3 of the research, following the theoretical work undertaken in Phases 1 and 2. This case study, which follows the methodological framework set out in Section II above, aims to understand in context how the shipping industry adopts WPTs by presenting the results of a business case workshop and survey of WPT industry and academic experts. The purpose of this section is therefore to understand how WPTs are perceived by shipping stakeholders and to contextualize the shipowners' decision to install them. Phase 3 is a preliminary step in the development of a conceptual model of the adoption of WPT, which is presented in Section VI of this report.

5.1 Business case workshop

The WASP business case workshop was held in May 2020, with the participation of WP4 partners and shipping companies installing WPTs. The summary below sets out the connections between this workshop and the theoretical model development.

The business opportunity

The first part of the workshop addressed the expectations of the shipping companies participating in the WASP Project. A clear concern raised by Shipping Company 1 the learning effects of the installation of WPT in the overall operation of the ship's costs in the longer term. Fuel-saving aspects are therefore critical, especially the possibility to earn back the investment in the long-term (i.e. ten years) (as raised by Shipping Company 2).

Cost-saving concerns go hand in hand with recent regulatory changes in the North Sea Region that require the use of low-sulfur fuels. WPTs are perceived as an emerging alternative that will help achieve both regulatory compliance and fuel cost-savings in the long term (Shipping company 1):

Participation in pilot projects on cleaner technology development is considered a strategic bet by participating companies. Pilot project participation allows a company to build on the learning they have achieved through participation in previous similar projects (Shipping Company 1). Areas where continued learning may be necessary include, for example, the operation period of the technology during voyages (Shipping Company 1). Alongside the technical learning connected to the project, shipping companies value the effect of the cooperation that accompanies participation: “We can help other shipowners through our installation of wind power technology” (Shipping Company 1). Firms also value learning regarding the operational environment once the WPT is installed, in particular, better understanding of the consequences of WPT installation on crew training and cargo handling (Shipping Company 1).

Potential business benefits also exist for the shipping firms in connection with the added brand value of installing WPT on board. Visibility and customer awareness of the investment is important: “The visibility is important, our customers know who you are and know that you are a sustainable carrier, complying with environmental regulations” (Shipping company 1).

Firms expect the installation of WPTs, even to generate financial benefits, even if this installation is only done in the context of pilot projects, as it serves to: “attract more customers and thus impact revenues” (Shipping company 2).

Customers are increasingly demanding that the environmental impacts from shipping operations be addressed (Shipping Company 2). As the participants in the workshop outlined:

> "Transport companies ask for CO_2 calculations. They also ask to integrate hybrid propulsion systems. We have many customers asking questions about wind propulsion technologies." (Shipping Company 1)

Challenges, risks, and costs associated with WPT adoption

Participants expressed some concerns about the effects of the COVID-19 pandemic on green transition in the shipping industry. It is not surprising that this context emerged during the workshop, as it took place in May 2020, during the early stages of the pandemic, when lookdowns and uncertainty were on the rise. These uncertainties were connected to fluctuating fuel prices, which made it more difficult to predict costs. This and other conditions resulting from the pandemic led to changes in how much companies were able to prioritize investment in green technologies.

> "The current situation is not really stable, due to the COVID-19 pandemic, and our company will postpone investments for at least the next year." (Shipping company 1)

> "The current context has a negative effect – green technology is not a priority now. However, this situation may change soon. We perceive that the price [of fuels] is very volatile right now." (Shipping company 2)

In addition to the contextual factors highlighted above, the shipping companies involved in this workshop identified the broader challenges and risks of WPT uptake. The most commonly mentioned was often referred to as "internal" and connected to bunkering costs (Shipping company 1). As discussed in relation to the effects of the pandemic, fuel costs are included in the long-term financial planning of operations, and ongoing uncertainty about these costs implies extra risks. As the participants clarified:

> "The challenge right now is the market and low prices paid to freight companies, which extends the length of time taken to recover initial investment" (Shipping company 1).

> "The bunker cost is really important and volatile. There is an upward trend in prices over the long term, but in the last few years, prices have gone down. These changes change the business case, especially when the investment in WPT has a payback period of 3 to 5 years" (Shipping company 2).

The installation of WPT incurs additional costs, including costs relating to integrating the routine learning of the new technology into existing procedures: "Operational costs are a major factor when choosing a new technology to install on board ships. Certainly, challenges remain to integrate new technologies with mature ones"(Shipping company 1). In comparison to conventional technologies, in particular fossil-fuel-based solutions, maintenance costs were not considered a key concern (Shipping company 1 and Shipping company 2). However, the associated risks of the installation and potential failures were raised, and one of the shipping company representatives discussed the need for these to be addressed in contracts with WPT providers: "When preparing the contract with the suppler, it is important to leverage the risk and liabilities with respect to the performance of the new technologies" (Shipping company 2).

Another factor to include in consideration of costs is resale value: "WPT can be put on deck, so it will be easy to remove. The resale value of a specific piece of equipment depends on the market acceptance" (Shipping company 1).

5.2 Survey results

The survey results are summarized below according to the questionnaire sections (see Appendix 3).

5.2.1 Environmental performance

Survey questions one, two, and three were used to ascertain the extent to which shipowners embrace environmental performance measures. Question one asked the participants if eco-innovations such as WPT are necessary to achieve high levels of environmental performance. A resounding 18 of the 19 individuals responded with complete agreement, while one neither agreed nor disagreed. This result is unsurprising since the essence of eco-innovations is their capacity to impact the environment in a positive way. However, it is interesting to note that this question was constructed in such a way as to imply the environment as a stakeholder as opposed to simply an externality. This concept is embedded within the concept of sustainable development and facilities the transition from a utilitarian framework to an ecologically responsible one. Especially for an industry such as shipping, where GHG emissions are a major concern, a major transition is needed if vital climate goals such as those expressed in the Paris Climate Agreement are to be achieved. Eco-innovations such as WPT will go a long way towards reducing fuel consumption and ultimately the amount of pollution caused by this industry.

Question two asked whether WPTs should be adopted by shipowners to strengthen a firm's environmental management strategy. 18 of the 19 respondents either agreed completely or somewhat, while only one neither agreed nor disagreed. Placing this in the context of the analysis of question one, it is increasingly becoming imperative for firms, particularly heavily polluting firms, to develop and implement environmental management strategies. This is not only necessary only from an environmental standpoint but also from an economic perspective; the more proactive firms are, the more they can decrease the amount of catch-up they will eventually have to undertake when more stringent regulations are implemented. WPTs can thus provide an economic benefit but also signal to regulators and industry assessors that shipping firms are taking sustainable development seriously.

Question three addressed the potential of WPTs compared to other available solutions. Roughly 79% of the 19 respondents either completely agreed or somewhat agreed that WPTs have the greatest potential of the existing alternatives to provide immediate environmental relief for the shipping industry. There are several options to shipowners that all provide various levels of environmental relief, however, the allure of WPT is the predicted amount of fuel savings, which acts as a double incentive. Thus, WPT seems more attractive than end-of-pipe technologies that only reduce the amount of pollution, and while a combination of different eco-innovations would be ideal, WPTs offer the most immediate environmental relief considering the financial limitations of shipowners. Furthermore, eco-innovative behavior has been shown to facilitate a positive, albeit indirect, influence on the economic performance of firms. This is because while firms need to adapt to environmental changes and regulations, the spillover from investments such as WPT has the potential to improve economic performance. The associated collaboration within cluster networks also leads to more eco-innovations because firms that have a larger cache of environmental knowledge are better positioned to utilize that knowledge in the future through the development of new products and services.

5.2.2 Regulatory push

Questions four and five centered on regulatory inquiries to determine their potential influence on eco-innovation. Question four asked if governments should provide subsidy schemes to shipowners to increase the proliferation and adoption of WPT in the industry. Of the 19 respondents, 16 were either in complete agreement or somewhat agreed, while two neither agreed nor disagreed and one participant somewhat disagreed. Governments around the world often provide subsidies for both mature and emerging industries. More stringent environmental regulation will lead to greater environmental costs in shipping industry operations because shipowners and operators will need to implement environmental management systems as well as invest in emissions-reducing technologies. Market-based instruments instituted by governing bodies may be useful in providing fiscal incentives to achieve the desired pollution reductions while also increasing the proliferation of eco-innovations to improve adherence to the new standards. If the ambitious emissions goals of the Paris Agreement are to be reached, the decarbonization of the shipping industry must accelerate in the coming decades.

Subsidies could benefit the entire industry, but also specifically entice early adopters and disincentivize fence-sitting. Addressing a related point, the fifth question asked whether there would be an increase in adoption following stricter environmental regulations within the shipping industry. Roughly 90% of the respondents completely agreed or somewhat agreed that there would be, while the other 10% neither agreed nor disagreed. Harsher and more stringent environmental regulations would force the hand of slow-moving shipowners into adopting emissions-reducing technologies like WPT. One option would be universal eco-rating schemes, which can be utilized as a benchmarking instrument for buyers, users, and regulators to make better-informed decisions based on the performance of a given product or service. However, it has been shown that firms can use eco-rating schemes in complicated or obfuscating ways to deflect regulation and/or provide irrelevant information to the marketplace (Poulsen et al., 2018).

A potential countermeasure would be a universal rating scheme that is legislated and overseen by a consortium of national governments. Such a consortium could include the EU and IMO working collectively in the EU as a test region, with the scheme extrapolated and implemented around the world. This scheme should allow for third-party verified data to benchmark the environmental performance of ships to provide reliability. A novel implementation of this could take the form of a decentralized ledger or blockchain to ensure transparency. The potential for regulatory avoidance further emphasizes the necessity for firm regulations. If regulations are definite, then the first-mover advantage is viable, but if regulations are unclear or lax, then a first mover may be at a disadvantage due to premature capital expenditure. This occurred in 2013, when the head of regulatory affairs at AP Moller-Maersk, Niels Bjørn Mortensen, stated that “early movers are getting penalized and all those laughing on the fence are getting rewarded” (Eason, 2013). In this instance, legislation was implemented with a five-year rollout window before being enforced; however, due to lobbying, that deadline was pushed back, thus rendering Maersk’s retrofit unnecessarily premature and causing a disadvantage. The spillover from stricter environmental regulations can thus have a positive impact on reducing emissions in the shipping industry, while also proliferating the adoption of eco-innovations such as WPTs.

5.2.3 Market pull

Questions six, seven, and eight were designed to assess market drivers from the perspective of shipowners. Question six asked whether, if one shipowner were to retrofit their ship with WPT, others in the industry would follow; 14 respondents either completely or somewhat agreed that they would, while four respondents saw no impact, and one somewhat disagreed. While this result aligns with the existing literature, it contradicts the series of events outlined above, in which Maersk invested in NO_X-regulation compliant engines in some vessels, only to have competitors sit on the sidelines while the regulatory organization pushed back the deadline for compliance (Eason, 2013). In this scenario, the rivals did not follow, and as such experienced an advantage due to foregoing capital investments. Although these investments will need to be made at some point if compliance is to be maintained, pushing the investment off gives the advantage to late adopters. They benefit because their ships will not sit idle during retrofitting and they will have more time to secure financing for these retrofits, or even receive subsidies if these were to become available. However, shipping companies may want to push forward with the adoption regardless to differentiate themselves from competitors and take advantage of the public relations benefit of "greening" their operations. In any case, NO_x-regulation compliant technologies do not provide enough of an economic incentive to companies for them to invest in this technology early on the basis of direct economic benefits alone. WPTs, on the other hand, offer the incentive of reduced fuel consumption under certain conditions.

Question seven asked if the upfront costs of retrofitting older ships with WPT outweighed the future environmental and financial cost savings. Eight participants either completely agreed or somewhat agreed that they did, ten respondents were not swayed either way, and one person completely disagreed. Due to many respondents not agreeing nor disagreeing, it is difficult to assess the implications of the responses to this question.

Question eight asked the participants if eco-innovations such as WPT give shipowners a competitive advantage over their rivals; 13 either completely agreed or somewhat agreed that they do, while four did not agree nor disagree, and two somewhat disagreed. The responses to this question suggest that WPT adoption does indeed increase competitiveness. This advantage can take the form of more attractive contract terms with charters due to enhanced fuel efficiency. In any case, this is one of the aspects that the WASP Project aims to investigate. To facilitate generalization, the responses should be triangulated with additional data emerging from the WASP Project in the future,

Furthermore, the public's perception of the shipping industry moving in a "greener" direction bodes well for future business and industry wellbeing. An added positive externality would be the environmental restoration achieved through decreased fuel consumption and increased environmental sustainability.

5.2.4 Technology push

Questions nine and ten were designed to measure technological driving factors. Question nine asked if shipowners' decisions were influenced more by market demands than by technological capabilities; 17 of the 19 respondents completely agreed or somewhat agreed that they were, signifying that while the availability of technology may be important, market conditions and regulatory frameworks have greater influence for decision-makers. Consequently, participation in demonstration projects may be attractive because the exploration costs are shared by numerous parties, as are the potential benefits. In mature industries like the maritime shipping industry, resistance to change is a possibility (Makkonen & Inkinen, 2021), so as a mitigation solution, fewer resources are focused on new and upcoming technologies if development comes at the cost of further market concentration. Ships taken out of service for retrofitting or technological upgrades are rendered idle, causing the firm to lose out on contracts and service time.

Question ten asked if respondents felt WPTs were more suited to short sea routes than long-haul routes. Just under half felt that they are not; only five agreed that they are, while six neither agreed nor disagreed. This somewhat contradicts that prior literature stating that, from the perspective of adoption, short sea route ships should adopt WPT before longer routes (Rehmatulla, Parker, et al., 2017).

The technology-focused survey questions showed that the capabilities of firms would not significantly impact the adoption rate of WPT. One of the reasons for this is that certain barriers surrounding the implementation of WPT are predicated on a lack of knowledge of the technology itself in practical settings. Demonstrations and trials are therefore vital to the entire network of the maritime industry. While innovation and technological developments play an important role, the awareness that these innovations may present environmental and societal benefits is rapidly increasing, making the economic case stronger than the technological one. The competitiveness between firms in "greening" their operations is contingent upon firms attempting to maintain a solid public reputation with stakeholders and also gaining an advantage over their competitors at both the regional and national levels (Bossle, Dutra de Barcellos, et al., 2016).

6. Proposed theoretical model of WPT adoption in shipping

The development of the agent-based model within this report follows the method discussed in section III. Based on discussions with the programmer overseeing the model coding, a top-down design is used in this project, meaning the entire conceptual model was developed before coding. In the top-down design process, the research question is chosen first, then the agents are identified, and finally, their properties and the rules of their behaviors are designed.

6.1 Choosing the research question

The objective of this report is to provide a theoretical basis for a model of the adoption of wind-assisted ship propulsion technology by shipowners. There are two keywords in this objective: *wind-assisted ship propulsion technology* and *shipowners*. Several WPT technologies are available on the market; in this report, we consider fixed wing rigs, Flettner rotors, and Ventifoils. This decision to model multiple WPT suppliers is analogous to Zhang et al.'s (2011) approach, which modelled the characteristics of different alternative vehicle fuels. Our approach to modeling also incorporates multiple types of shipowners operating in different segments; RoPax ferries, bulk carriers, and general cargo vessels are considered for installation of WPTs. We also attempt to integrate the need for shipowners to consider the future market situation (e.g. oil prices) and regulatory conditions (e.g. change in fuel switching costs). Together, these considerations enable us to redefine the research question to *"Can we model the installation of different types of WPT over time by shipowners in different segments with a geographical scope through oscillating market and regulatory conditions?"* To generate results for different market segments, the model may need to run several rounds based on different inputs.

6.2 Choosing mobile agents

The model simulates the decision-making process of shipowners in terms of whether to install and use WPT on their ships. In order to model this complex process, a number of assumptions are made. We assume that each shipowner owns only one ship. Lobbying from technology providers and feedback from other shipowners who use or have used WPT influence the attitude of a shipowner towards WPT. When the attitude reaches a threshold, the shipowner starts to consider whether they need the new technology. When making their decision, the shipowner is driven solely by seeking the highest return on investment. Considering the three types of WPT considered in this report, we include three types of technology providers in this shipowner-technology provider model. Each technology provider promotes one type of WPT. Therefore, in total, four types of agents interact in this model: shipowners and the technology providers for the Flettner rotor, the Ventifoil, and fixed wing rigs.

6.3 Choosing mobile agent properties

Our model includes two general properties which apply to both shipowners and technology providers: (1) location, which records where a single shipowner or technology provider is in the simulation, and (2) heading, which shows the direction of movement of a single shipowner or technology provider. When a shipowner meets a technology provider, the latter attempts to persuade the former to install WPT, and when two shipowners meet, they share their perspectives on WPT. When two technology providers meet, nothing happens. WPTs differ in their technical properties, as summarized by a previous WASP report (Chou et al., 2021). Therefore, we also consider the WPT technical properties as analogous to Zhang et al.'s (2011) characteristics of EVs. Shipowners have two more properties. The first is if cash is not enough to install WPT. Cash available determines whether a shipowner has enough money to install WPT. If the cash is not sufficient, they may save money during operation. Therefore, we have the second shipowner property, growth rate, which describes the difference in cash available between two consecutive months for a single shipowner if WPT is not in use.

6.4 Choosing environmental agents

In this section, we define the economic environment in which the mobile agents operate. There are two environmental agents included in our model: market situation and regulatory condition. The "fuel price changing rate" used to define the market situation. This is because the main advantage of WPT is cost savings in terms of fuel consumption. Regulatory condition is signified by the change rate of fuel switching costs, in order to simulate the impact on running costs of future regulatory changes (e.g., the possibility that the IMO may expand the area of the Arctic heavy fuel ban)

6.5 Choosing agent behaviors

In this shipowner-technology provider model, we define several behaviors for each agent. These behaviors are necessary for users and programmers to understand how agents interact with each other and the business environment.

Shipowners and technology providers move. The shipowners can turn randomly and move forward. This behavior simulates the social activities of shipowners. Two shipowners or one shipowner and one technology provider moving into one single grid cell in the model signifies that they meet either physically (e.g. participate in an industrial conference) or virtually (e.g. phone calls, online meetings with video link, etc.).

Shipowners interact with shipowners and technology providers. Each shipowner has an initial confidence level regarding WPT. This confidence level will be influenced when a shipowner exchanges information with other shipowners or with technology providers.

Shipowners make decisions on whether to install WPT devices. If the confidence level of a shipowner reaches a threshold, the shipowner consults three technology providers consecutively to choose the most suitable WPT for their ship. One month is considered a reasonable time interval for a shipowner to assess one type of WPT. After-decision making, one year is required to install the WPT equipment[1]. The confidence level is expressed on a scale from 0 to 1, with the threshold for installation of WPT set at 0.5. ROI is a commonly used decision-making tool before any type of investment; to calculate ROI, we modify the formula set out earlier in equation (2). Gains from investment, in this case, fall into two categories: total fuel cost savings during the use period of a WPT device (V_{FS}) and the WPT scrap value at the end of life (V_{SV}). Cost of investment also includes two sub-items: the initial amount of investment (C_{IVI}) and the total maintenance cost during the whole use period (C_M). The service life of a WPT device is assumed to be around 30 years[2]. After estimating the present value (PV) of all the future benefits and costs to make all the future cash flows at different times summable, we can calculate the return on investment according to equation (3) below.

$$ROI = \frac{\sum_{t=1}^{T} PV(V_{FS_t}) + PV(V_{SV}) - C_{IVI} - \sum_{t=1}^{T} PV(C_{M_t})}{C_{IVI} + \sum_{t=1}^{T} PV(C_{M_t})} \quad (3)$$

[1] This period of time was clarified as part of the WASP business case workshop discussion and it is taken as time reference for the theoretical modeling.
[2] https://www.stormgeo.com/solutions/shipping/articles/flettner-rotor-sails-for-ship-propulsion/

Where $PV(V_{FS_t})$, $PV(V_{SV})$ and $PV(C_{M_t})$ are the present values of V_{FS}, V_{SV} and C_M, respectively, in month t. the model runs from month 1 to month 360 over 30 years. T=360. The shipowner will install the WPT devices with the highest ROI.

Shipowners make decisions on whether to use the equipped WPT devices. While WPT reduces ships' energy consumption, it increases shipowners' maintenance costs. Considering that the maintenance cost may decrease if the WPT devices are used less frequently, we split C_M into two sub-items: $C_{M-basic}$ denotes the fixed part of maintenance cost that has to be paid by the shipowners even if the devices are not in use, and $C_{M-marginal}$ denotes the extra cost when the WPT devices are in use. In addition, because fuel prices are not static, shipowners need to estimate V_{FS} at the beginning of each month. They use WPT devices if V_{FS_t} is greater than $C_{M-marginal_t}$; otherwise, they leave the devices idle.

Update cash available. The cash available to a shipowner changes during operation. Therefore, we need to update cash available (CA) at the end of each time interval (t). Regardless of whether WPT devices are installed, shipowners make profits and increase cash available during operations at the speed of ρ_{Growth}. This is the only method for shipowners to save money if their initial cash available is not enough to install WPT devices. After WPT devices are adopted, CA is also influenced by fuel cost savings and maintenance cost. In the year of installing WPT devices or the month of selling the scrap, we also need to subtract C_{IVI_t} or add V_{SV_t}.

$$CA_{t+1} = CA_t \times (1 + \rho_{Growth}) + V_{FS_t} - C_{M_t} - C_{IVI_t} + V_{SV_t} \quad (4)$$

Update confidence level. Shipowners' confidence level will increase if shipowners decide to use WPT devices during the following month or meet technology providers or shipowners who are using WPT; they decrease if shipowners meet other shipowners who have installed WPT devices and do not use them now. They may also undergo small random changes if shipowners meet other shipowners who have never used WPT.

6.6 Designing a time step

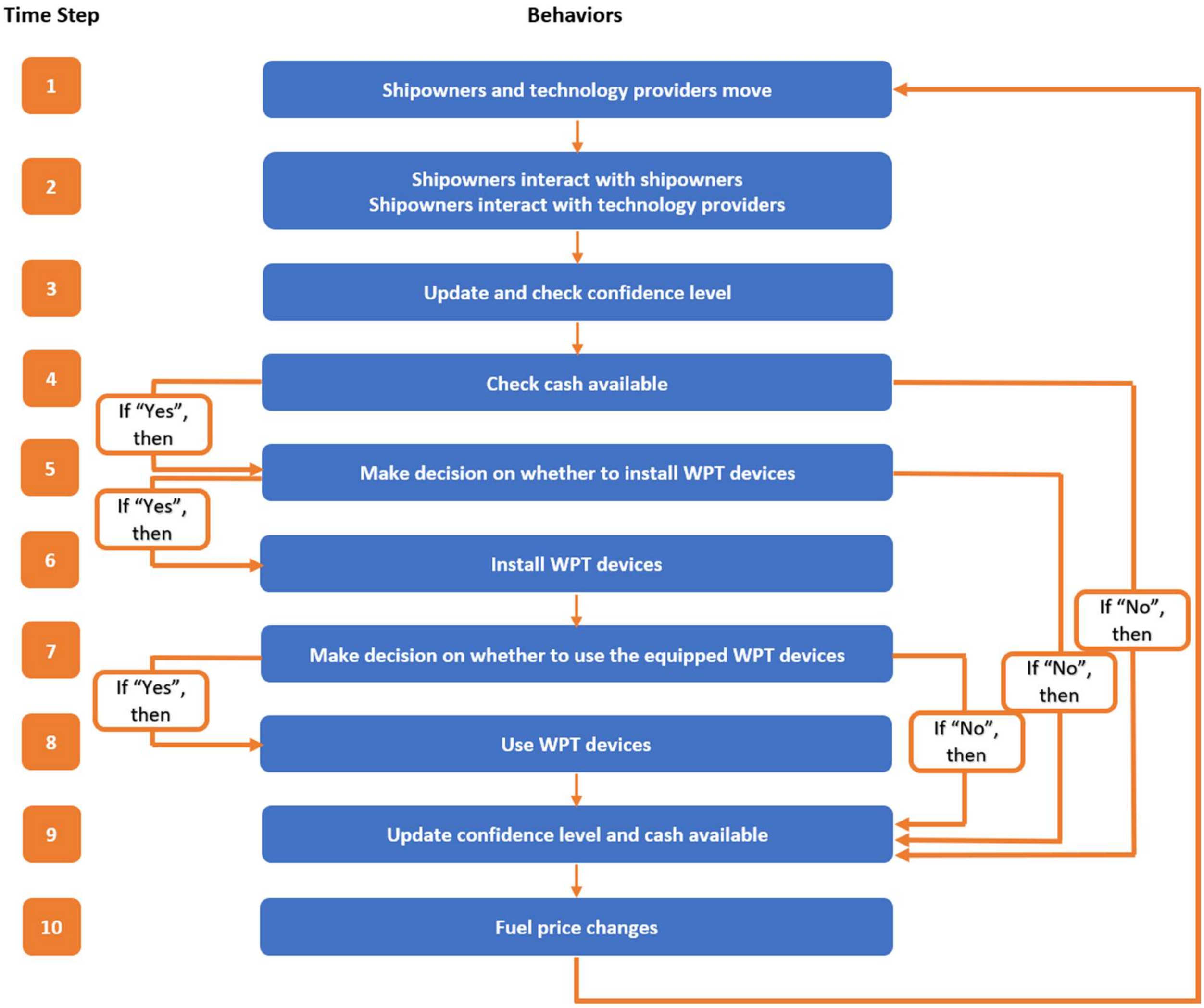

Figure 5 Time steps of the interval

6.7 Defining the parameters of the model

We define two parameters in the shipowner–technology provider model: (1) the initial cash available and (2) the initial confidence level. These two parameters enable us to see how different values of the initial setting influence the diffusion of WPT.

6.8 Defining measures

Considering the research question, we define the following measures for each studied ship type:

- The percentage of fixed wing rigs, Flettner rotors, and Ventifoils installed over time under the different scenarios.
- The percentage of fixed wing rigs, Flettner rotors, and Ventifoil in use over time under the different scenarios.
- The fuel price over time under different scenarios.

Stricter regulations in the future may require the use of cleaner types of fuel. Cleaner fuel typically means higher cost, which is reflected by the "change rate of fuel switching costs" in the model. According to the corresponding time interval of a specific fuel price, we are able to check the fuel type from the model. Based on these measures, we can explore the influence of fuel price and regulations on the diffusion and use of WPT.

7. Conclusion

This report addressed two interrelated needs of the WASP Project:

- Designing a theoretical framework to explain wind propulsion technology (WPT) adoption
- Influence of WPT drivers in the context of short sea shipping in the North Sea Region.

This report is part of the WP4 – Business and Policy, activity 5a of the WASP Project, and it will be the basis for the development of an ABM to simulate the adoption of WPT in the context of short sea shipping in the North Sea Region under a range of policy and socio-economic scenarios. The results of this simulation will be delivered in a follow-up report (development of WPT adoption scenarios, simulation, and validation).

The follow-up report will constitute the final deliverable of activity 5a and will take place between May 2021 and June 2022. As a result, the theoretical model presented in Section VI as a result of this report is still subject to further development and can be assessed as the key input to the follow-up report.

Beyond the concrete application of the results to the next stage of the WASP Project, the findings presented here have external validity on their own. In the field of sustainability and socio-technological studies, there are growing calls to introduce simulation methodologies, including ABM, to understand the adoption of eco-innovation in different sectors.

This report extends previous research on the adoption of eco-innovations in the shipping industry by focusing on the microeconomic decision-making aspects of installing WPT. While previous research has already used ABM in the context of the diffusion of eco-innovations, including WPT, in transportation, we have identified certain gaps and opportunities to extend the existing knowledge.

First, the results and methodology presented here fill a gap in the literature on the ABM methodology, primarily relating to the development of the theory underpinning the models. In this report, we present an example of the abductive approach to theory development in ABM using multiple details and a combination of qualitative and quantitative methodologies.

Second, in the emerging literature on eco-innovation, growing attention is being paid to patterns of sustainability transition in specific industrial sectors. Previous research has analyzed the effects of regulations in air pollution abatement technology, green retrofitting of ships, ballast water treatment technologies, and more recently, adoption of cleaner fuels in shipping. This report contributes to knowledge about the driving factors behind the adoption of wind propulsion in shipping, and in particular to improved understanding of the participants involved in the pilot installations co-financed by the WASP Project (North Sea Region).

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Appendix 1 – Summary of reference ABM on transportation eco-innovation. Source: Zhang et al. (2011)

Process	Agent	Agent properties	Environment	Other parameters	Data/equation referred to	Useful in WPT model
1. Manufacturer calculates profit	Manufacturer	Profit function of manufacturers, including an engineering design optimization model that will be used to validate the ABM later. Profit is calculated following the equation based on game theory (1), which includes profit as a function of the quantity (q) of each vehicle sold per manufacturer, multiplied by the difference between the price of the vehicle and the manufacturing costs of the vehicle. The result of this product is subtracted from the investment costs to set up a product line. This equation also includes a value of government penalty (in case standards are not met).		The price per vehicle (p) is set as a function of the manufacturing cost (z) and the value of manufacturing parameters (m). As a result, each model includes specific parameters connected to the vehicle design and small changes to its design, including specific pieces, technology, etc.	Michalek et al.'s (2014) equation for engineering performance, consumer demand and manufacturing costs' "simulated annealing" to seek equilibrium among market agents. Vehicle cost data comes from AVCEM.	Validation equation
2. Equilibrium among manufacturers	Manufacturer	Market (Nash) equilibrium among manufacturers/ competitors. Simulated annealing. This algorithm implies that each individual manufacturer keeps optimizing its profit, yet competitor manufacturer decisions remain constant.				
3. Manufacturer designs vehicle agent	Vehicle	Design parameters based on AVCEM (advanced vehicle and energy-use model). This is an analysis package of EV and traditional vehicles. Four parameters on AVCEM: vehicle design, fuel type, engine power, aluminum content). AVCEM not directly used in the ABM, but the costs			AVCEM (Deluche, 2005)	

		associated with each vehicle design are hard-coded into the ABM.				
4. Consumer chooses an EV	consumer	Purchase decision based on customer preference. The equation models the consumer preference for a particular vehicle from product set (C). The equation implies the exp of the utility of consumer for each vehicle, which is particular for each vehicle design, including fuel use, type of vehicle, charge period (partworth)			Based on Garcia (2007). Choice-based conjoint data	
5. Word of mouth influencing the consumers' network	Consumer	Parameters are estimated using hierarchical Bayes (HB). Continuous heterogeneity, each individual parameter is estimated. MCMC parameters estimated. 10 000 iterations are used to derive individual partworths. Each one of the 10 000 individual agents is initiated according to the partworths emerging from the survey results.	Word of mouth (WOM), value is included in the mode through conjoint data analysis and a large-scale survey targeting 20 000 automobile experts (subscribers to a specialized magazine), which received 9504 answers. In the survey, a question was included about frequency in which experts talk to their network about EVs. Partworth is modelled as a function of WOM, knowledge about fuel, knowledge about maintenance, and knowledge about price. WOM is modelled to determine whether this has indeed an effect on consumer preferences, and whether, as a result, government policies and manufacturer decisions should consider WOM into their decision making. One simplified assumption was made, considering each individual agent to be affected in the same way by the WOM effect.		Word of mouth knowledge (Lenk et al 1996)	
6. Government policies	Government	Government creates policies that influence the consumer or the producers (either to increase consumption of EV or to produce more EV). One policy package is investigated (CAFE: corporate average fuel economy). CAFE sets rules about maximum fuel use for new vehicles, therein targeting mainly manufacturers. On the other hand, CAFE also targets consumers because the incentive to reduce costs associated with fuel consumption. In the ABM, the government				

		agent is therefore modeled as direct costs to the manufacturing as part of equation (6), "total cost of manufacturing for manufacturing agent". The equation includes a difference between the CAFE standard and the fuel economy of the vehicle. in this case, the government is considered an external agent and is not involved in optimization functions.				

Appendix 2- Summary of reference ABM on WPT diffusion. Source: Karslen et al. (2019)

Process	Agent	Agent properties	Environment	Other parameters
1- Setup	Shipowner/Dry bulk	Each shipowner is assumed to have a homogenous best practice in relation to rotor technologies.	Market risks are considered constant.	Technical risk is used as a variable to determine the adoption of WPT and reflected into the ABM model through a grid implementation model. It addresses the technical risk associated with structural factors, as well as stability and cargo handling
1- Setup		Each shipowner moves 2.5 cells in a random direction as a result of calculated risk.		All ships chartered during the same period
2-Networking between shipowners	Shipowners	Shipowner expectations (EX) in regard to rotor technology. Measured from 0 (no interest) to 1 (complete interest). If an EX threshold is reached, the shipowner starts networking with other interested shipowners.		Knowledge spillover occurs after the shipowner starts to network with other companies
3. Shipowner interaction with technology providers	Shipowner and technology providers	In addition to networking between shipowners, this process models the interaction between technology suppliers and shipowners. The result is increased interest in the WPT (EX). After the threshold is reached (0.5) the shipowner becomes a "supporter" of WPT and increases networking to support WPT adoption		
4. Shipowner fuel costs			Paid by the time charterer	Ship fuel cost (F)
5. Decision to install WPT	Shipowner	If E(NPV) >0, then the shipowner will install WPT		Calculated using expected net present value (E(NPV)).
	Charterer	Incremental revenues		First element in NPV, Incremental revenues to the shipowner (FPT). This function calculates fuel saves resulting from installing the WPT, passed from charterer to the shipowner as a charter premium.

	Shipowner	Maintenance cost	Second element in NPV is E(C), which represents additional maintenance cost to the shipowner from rotor technology adoption, and represents costs multiplied by 2, and deducing shipowner expectations.
	Shipowner	Capital cost	In the case of shipowners, NPV also includes E(K) to account for the shipowner's capital of adopting rotor technology.
	Shipowners	Operational profit	E(OP) represents the operational profit and is calculated as the shipowner charter revenues and the operational costs (constant). The equation also includes the deduction of the potential incremental rotor revenues and incremental maintenance costs from the rotor technology installation. This parameter assumes a dry bulk charter regime; it is assumed that OP is positive if the expected incremental operating profit from rotor technology is greater than conventional propulsion OP.
6: Shipowners determine to use rotor technology	Shipowners	Repeating OP condition over several cycles to ensure profitability over time. The rotor technology can be used if it is profitable, or shipowners can decide to take down rotors from the ships, even if the structure stays there if profitability is proven later.	
7: Realized operating profits of shipowners in a period	Shipowners and charterers		Focuses on realized OP for each period. Parameters in equation (6). This equation includes two possibilities. In the first one, the ABM model indicates rotor technology failure for the specific shipowner modelled. In this case, FTP is excluded, which is the incremental shipowners' revenues, and the value "claim" is introduced to specify underperformance as stated by the charterers. In the second possibility, the rotor does not fail; therefore, the realized operational profit will be equal to the FPT, incremental revenues to the shipowner, and the deduced operational costs.

				In equation (6), the value of FPT is also given by an equation that includes monthly cost of fuel (F), charterer expectation of the rotor technology (EX), shipowner expectations (EX) and realized fuel efficiency (RE). RE is adjusted to reflect a percentage of fuel costs to capture the uncertainty of wind propulsion.
8.Shipowners update knowledge through experiments		Shipowners improve their knowledge about rotor technology, barriers, and infrastructure onboard. This is done through experiments reflected through the variable (KN). Similarly, there is networking between shipowners that implies spillover effects among shipowners connected with each other. As a result, other factors are included in the equations including KN incr (increase of knowledge of experimenting shipowner). In each period, the knowledge increases for each shipowner, capturing this value as KN (total spillover), summing up knowledge spillovers from all experimenting shipowners having a link with the focal shipowner.		
9. Shipowners' interactions with demonstration projects	Demonstration projects/ shipowners	Demonstration projects are provided with the property to move around a predefined grid. If these projects move along the grid, they generate expectations among shipowners. "Dradius" defines the degree to which the demonstration project increases knowledge about rotor technology. Other properties include the increase in expectation and knowledge of shipowners fitting within the demonstration project radius (DEX incr). Other properties include the assumptions that demonstration projects are successful once implemented, thus assuming they do not decrease shipowners' interests and expectations		
10. Technical risk update	Shipowners			This focuses on the risk associated with the rotor technology and is given by an inverted s-shaped curved equation 9 in the model. The risk factor is calculated according to the difference to the KN factor (shipowner

				knowledge about rotor technology). KN increases if the shipowners interact in a network together with other actors involved in demonstration projects.
11. Rotor technology capital costs			This process captures an environmental characteristic, namely that of the installed capacity of the rotor technology. This implies that as more ships install rotors –also as demonstration projects – then the capital cost installation of one rotor piece will also decrease proportionally. The model assumes a double capacity to account for a reduction of the capital cost (LR) of a new installation.	
12. Shipowners and charterers update expectations	Shipowners			The shipowner's expectation (EX) is updated after niche experiments following the original expectation and realized operational profit (OP).

Appendix 3- Survey with experts

Online Survey

a. What is your name? (First and surname)
b. What is your email address?
c. Country
d. Type of organization
e. Position or title within the organization *(optional)

On a scale of 1-5, to what extent do you agree with the following statements?

Environmental performance

1. Eco-innovations in the shipping industry, such as wind propulsion technologies, are necessary to achieve high levels of environmental mitigation performance.
2. Wind propulsion technologies should be adopted by shipowners to strengthen a firm's environmental management strategy.

3. Of the solutions available, wind propulsion technologies have the potential to provide the most immediate environmental relief for the shipping industry.

Regulatory push

4. The government should provide subsidy schemes to shipowners to increase their adoption of wind propulsion technology.
5. Stricter environmental regulations within the shipping industry would lead to an increase in wind propulsion technology adoption by shipowners.

Market pull

6. If one shipowner retrofits with wind propulsion technology, others within the industry will follow.
7. In regard to retrofitting older ships with wind propulsion technologies, upfront costs outweigh future environmental and financial cost savings.
8. Eco-innovations like wind propulsion technologies improve shipowners' competitive position in the market over rivals.

Technology push

9. Shipowners are more influenced by market demands than the technological capabilities of the firm.
10. Wind propulsion technologies are more suited for short sea routes than long hauls