TRANSITIONS TO LOW CARBON SHIP PROPULSION TECHNOLOGIES INCLUDING WIND, SIMULATED WITH AN AGENT-BASED MODEL USING EVOLUTIONARY APPROACHES

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ABSTRACT

International shipping represents around 3% of global GHG emissions and is one of the fastest growing sources. Various technologies are available that have the potential for major emissions reductions. Among these, wind assistance has the major advantage that it requires no fuel and is therefore being examined as a possible contributor to ship propulsion. (Smith et al., 2014; Traut, 2014). However, shipbuilding is dominated by a few shipyards who compete globally and respond to fuel price increases and climate chang issues by incorporating incremental innovation in their designs, rather than radically new configurations such as wind power. As shown in earlier work (Senger and Köhler, forthcoming), an agent-based model has been developed, using genetic mechanisms from evolutionary economics, to simulate the distribution of different engine technologies in ships with a focus on investments in efficiency enhancements.

The technologies offered by the engine manufacturers are modelled as genes with different alleles representing a kind of “dna-code” containing production characteristics and determining the fitness of the particular engine offered. Fitness here means how well the offered engine suits the needs of the logistics companies in terms of operating costs and emissions. Engine manufacturers have the opportunity to innovate through investments which stochastically improve the characteristics of the alleles and can also imitate their competitors through knowledge spillovers to a certain extent. The shipyards then decide for a certain manufacturer. The shipyards follow different strategies yielding different amounts of investment in capacity enhancement or R&D. By the latter, yards can improve the design of ships to reduce costs over lifetime and emissions. These benefits determine decisions by the logistic companies to adopt new technologies. The investment decisions of the logistics companies depend on the global demand for shipping. The results of earlier work show potential transition pathways to low carbon propulsion technologies for ships under constraints following from different developments of world economy, fuel prices and political emission standards. In the work presented here, we add the opportunity for shipyards to include sails in the ship design and improve them through research and development. We ran different scenarios of global economic growth and development of fuel prices and international emission standards and show here how evolutionary pressure yields different pathways to low carbon shipping, focussing on those where a significant number of vessels use wind for propulsion support.

Since wind propulsion has nearly zero energy costs, it can take a significant share of the market. However, maximising the potential of wind technologies requires a change in operating patterns, to maximise favourable winds and to operate at slower sppeds to maximise the contribution of the wind companent of the propulsion.

Keywords: wind propulsion, agent based modelling, transitions

1. INTRODUCTION

International shipping represents around 3% of global GHG emissions and is one of the fastest growing sources (IMO, 2014). Various technologies are available that have the potential for major emissions reductions. Among these, wind assistance has the major advantage that it requires no fuel and is therefore being examined as a possible contributor to ship propulsion. (Smith et al., 2014; Traut, 2014). However, shipbuilding is dominated by a few shipyards who compete globally and respond to fuel price increases and climate change issues by incorporating incremental innovation in their designs, rather than radically new configurations such as wind power. The decision process in developing and adopting new engines and propulsion systems is complex, because it involves a chain of decision makers. Shipyards and propulsion system manufacturers must invest in R&D and then sell their designs to operators. Operators respond to demand for transport services from the logistics and tourist industry. There are already a range of low emission propulsion options and a wide range of designs for low carbon ships incorporating e.g. LNG, low sulphur diesel and wind technologies. This complexity means that simulations of this ‘innovation system’ are required to assess the market prospects for different technologies and their potential cost and performance improvements. As shown in earlier work (Senger and Köhler, 2015), an agent-based model has been developed, using genetic mechanisms from evolutionary economics, to simulate the distribution of different engine technologies in ships with a focus on investments in efficiency enhancements.

2. DEVELOPMENT OF THE CLEANSHIP MODEL TO INCLUDE WIND TECHNOLOGIES

The CLEANSHIP model simulates these decision chains, using an agent-based model (ABM) approach. It is not a market forecast model, but illustrates potential pathways of technology development over time, given the market demand, the willingness to invest in new technologies and the success of R&D efforts in imitating other manufacturers or in taking a technology lead. ABMs look at the actors of a system and the interactions between them from the bottom up, to represent the complexity of a stochastically evolving system with structural change. Winter et al (2003) amongst others made a proposal for a baseline evolutionary industry model. By following that approach and by developing a model of the shipping sector, modelling explicitly, but in a simplified manner, the basic actors – engine developers, shipyards and shipping companies - as agents acted according to market constraints.

That logic was extended by the insights of the works of Köhler et al. (2009) and Frenken et al.(1999), with our agents performing a research process in a “technology space”. This evolutionary research process consists of innovation and imitation steps as proposed by Hayek, changing the genetic code representing our technology, similar to the work by Kerber et al.5 There are three types of agents in the CLEANSHIP model: engine developers, shipyards and shipping companies. The engine developers are implemented according to an evolutionary logic: they produce engines according to orders they get from ship yards, with a certain propulsion technology. This is represented by analogy with biological evolution, where genes, consisting of a series of characteristics called alleles determine the system performance in the competitive environment.

In this model, these alleles represent parts of the engine such as system design, prime mover, ancillaries or the control system. The capabilities of the engine developers in these different aspects determine the overall engine system efficiency and hence fitness (i.e. competitiveness compared to the most efficient product on the market) of the engine produced. This version of the fuel consumption model is used as the only ‘fitness’ parameter in the shipbuilding market, assuming that production costs are a dependent variable. The operational costs also depend on the costs of the fuel used by the particular technology, so the optimal costs of one technology compared to another can change over time, dependent on the fuel price development. In every time step, the developers perform a process of stochastic innovation for their current technology alleles or imperfect imitation of a competitor’s technology alleles. The first stands for research, where the values of the alleles are changed stochastically corresponding to a search over the technology space. The developers next stochastically choose whether to develop their current technology or switch to a new technology and keep the new configuration, if the new engine operation costs (taking into account current fuel prices) are lower than the current technology configuration. The second stands for a process of copying the best performer in terms of operation costs, where the allele values are changed partly in the direction of the values of the developer with the lowest engine operation costs. The probability of switching the technology depends on the distance in technology space: e.g. the distance between Diesel direct drive and LNG is smaller than between Diesel direct drive and gas turbine. Again, the new values are kept, if the new engine operation costs are lower than the current ones. The shipyards offer six classes of ships: bulker, tankers, ro-ro ferries, container ships, cruise ships and special vessels. Depending on the offer of the developers, they equip them with one of the five technologies in the technology space: diesel direct drive, diesel electric drive, LNG, gas turbine and steam turbine. The choice of technology is made in order to produce ships, which have optimal engine costs over its lifetime, taking into account production costs, fuel consumption and current fuel price. The costs of the whole ship over its lifetime are not solely dependent on the engine costs; to improve production and operating costs of the rest of the ship, yards have the possibility to invest in R&D. Every yard is led according to one of two managing philosophies: being a pioneer or being a follower. Following this, yards decide whether they invest more of their budget in improving their ship designs by R&D or in increasing their capacity. The third and most simplified type of agents are shipping companies. There is no distinction here between shipowners and charterers. These agents own and operate their fleets and change their composition to meet the demand of the world economy. They take different prices for the different parts of their fleet depending on class, technology and technological level, the latter effectively means operating costs, and changes them due to changes in demand.

A time step of the simulation, which corresponds to two years, consists of the following processes: first, for every ship class, the ships of all companies are sorted according to their prices and then ships are chosen as long as there is demand from the economy remaining. For simplicity it is assumed that these ships are then operated constantly during the entire time step. The budget of the companies is decreased by the running costs of the ships in use (taking into account current fuel prices in that time step) and by the costs caused by the ships not in use and increased by the price the particular company demands for those in use. Afterwards, every company loses the ships that reached the end of their lifetime and then analyses which of the ships that has not yet reached the end of its operational life, were not in use and decreases the prices of these ships as long as they can still operate at a profit; if this is no longer possible, it puts them out of service. The company then analyses for every ship class, if there has been unsatisfied demand during this time step and calculates the share of this demand, it tries to meet, according to the relation of its budget to the budgets of the other companies and orders ships until either the budget, remaining after decreasing it by the ship price, falls beyond a certain threshold fixed at the beginning of the simulation or the number of ships is high enough. Ordering a ship works as follows: to choose a ship, the company collects the offers of all shipyards whose unused capacity is still high enough to deliver the ship within the next time step and arranges them according to the ship costs over lifetime with respect to the current fuel prices. If there is no yard with sufficient capacity, the same procedure is repeated with those yards whose unused capacity in the next time step is going to be adequate. This process is repeated twice at most, before the company decides to delay the ordering of the ship to the next time step. If the company succeeded in finding yards, it selects the one that offers the ship with the lowest costs over its lifetime and makes an order; automatically the yard orders the engine. During the entire ordering process the companies making the orders and the offers from the yards change. Whenever a yard operates at full capacity, it raises the prices; whenever the yard’s favourite engine developer operates at full capacity, it selects the best of those with enough remaining capacity and offers ships with changed costs and correspondingly changed prices.

After the companies finished this step, the yards decrease their budget by the building costs of the ships started in that time step and the running costs corresponding to yards' capacity (energy, staff etc.). Any ship that has been finished in this time step is delivered to the company that ordered it and the price for it is transferred from the company to the yard. Further on, the yards check if their current favourite developer offers the best engine costs over the vessel lifetime and change it, if not. Eventually, a decision about investing in an increased capacity or more R&D is made, regarding budget, kind of managing philosophy and degree of capacity utilisation (investing in more capacity is only an option, if the yard is working to full capacity, if not, the yard will automatically drop prices). Then, the developers proceed with their step: they decrease their budget by the building costs of the engines, they start to build and the running costs corresponding to their capacity, deliver engines finished to the yards that ordered them (here again the price is transferred in this time step from the yard to the developer) and make a decision about investing in a capacity increase depending on their budget and capacity utilisation. Finally they perform their process of innovation and imitation as described above.

In general, every agent, whose budget has become too negative, is considered bankrupt and therefore deleted from the simulation context. Because the yards and developers do not get paid before delivering the ships/engines, they are allowed to draw a higher debt than the shipping companies.

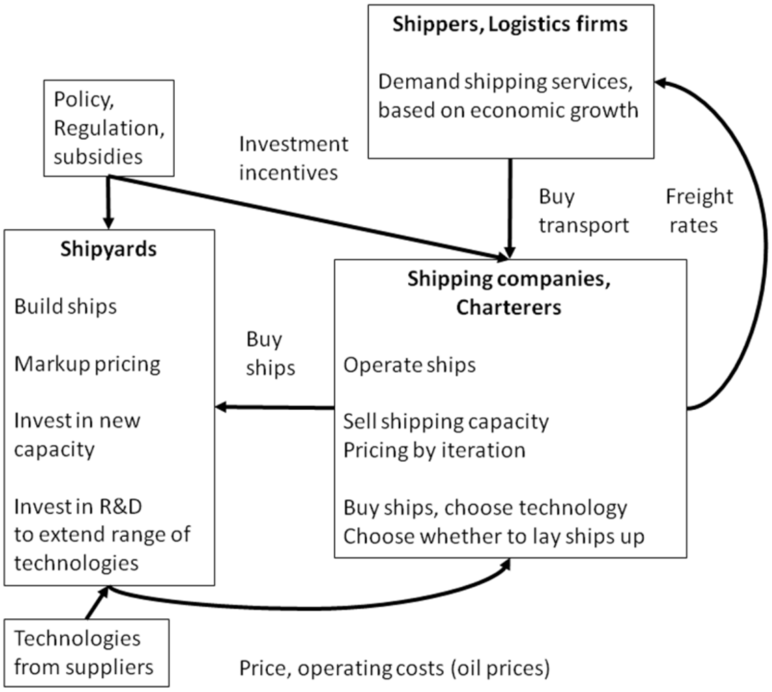

Figure 1: Structure of the CLEANSHIP model

MAIN PARAMETERS AND EXTENSION TO WIND TECHNOLOGIES

To include wind technologies to support the main propulsion technology, the yard agents get the opportunity to explore and further enhance wind technologies during their research and development process; wind technologies are explored when the benefit in terms of operational costs are bigger than the benefits achieved through research in ship design. As soon as the particular agent explored the wind technologies, they offer bulkers with wind supported propulsion which are more expensive in terms of building costs and which, if operated on favourable routes, have lower fuel consumption than those without, as well as cheaper ships without wind support. The shipping companies, while ranking the offers of the yards, now take into consideration if they operate on wind favourable routes and how wind support influences the costs over lifetime of the offered ships.

The effect of lags in expectations has also been investigated, using a system dynamics approach to modify the model. The SD-model was adapted from [11]. It is based upon an exponential smoothing of observed input data and calculating a trend function where there are distinct time delays for recognizing the trend. The behavior of the agents is thus derived from adaptive expectation and not perfect (or even rational) foresight; however, all agents share these ‘naïve’ expectations and are thus homogenous. The two parameters which constitute input data for the expectation formulation are supply and demand of ships.

The following simulation runs were all performed with an initial configuration of 10 shipping companies with an average fleet size of 50 vessels, equally distributed over all ship classes, 10 yards with an average capacity of 100000 tons, none of them offering ships with wind support in the beginning and 10 engine developers with an average capacity of 100000 tons, 8 of them offering diesel direct drives in the beginning and one each offering diesel geared electric drives respectively steam turbines.

3. CENARIOS AND RESULTS

The economic scenario for all of the simulation runs was the same: starting from 2015, global demand for shipping increases by 2% p.a. in average, fuel prices with an increase 2-5 % p.a. with an exceptional sharp increase for diesel till 2020 due to policy regulations. We performed runs for a configuration were 10%, 20%, 50% and all of the shipping companies operated their ships on wind favourable routes. Figs 2 - 5 show the number of ships equipped with wind based propulsion support systems compared to the overall global fleet size. As one can see, a lack of fleet potential around 2025 due to decommissioning of old and/or inefficient vessels yields overcompensation, which at the end of the 2030’s leads to a consolidation phase, where one of the companies goes bankrupt and therefore the global fleet size again temporarily decreases.

Figure 6 shows the impact of including adaptive expectations. The scenario starts with a slight oversupply of ships; so by using the SD-model to make an estimate for future supply-demand-gaps, the shipping companies make more conservative estimates. That yields economic cycles with much lesser amplitudes compared to the run without SD estimates and thus less orders of wind supported ships in the beginning due to more hesitant investment behaviour. The yards begin adapting these technologies as early as in the other run, because there is still an early demand due to rising diesel prices, but during the first years it stays a niche, the yards are now lacking innovation pressure for some time. Towards the end of the run, the more cautious investment behaviour assures that all companies survive the temporary consolidation phase and the diffusion of wind technologies eventually catches up compared to the other non-SD run.

Meanwhile, the number of ships with wind support increases in all scenarios. As can be seen in Fig. 6, the yards very quickly develop the necessary knowledge to equip ships with wind technologies, so the availability is high already in 2020, but the diffusion of ships with wind support strongly depends on the routes of the companies.

While in the 10% scenario, there are only very few ships with wind support, this is higher by a factor of 10 for the 50% scenario. This shows very well the non-linear effects of the technology diffusion in our model.

The development of the market share follows the same pattern: it describes a kind of s-curve as in the theory of technology diffusion (Rogers et al. [6]). Then it reaches a plateau at the end of the 2030's while total fleet size decreases, which leads to an interesting conclusion: during the phase of consolidation, in the harder competition, the companies operating ships with wind support always survive.

Figure 2: 10% of Shipping Companies operating on routes favourable to use of wind support systems

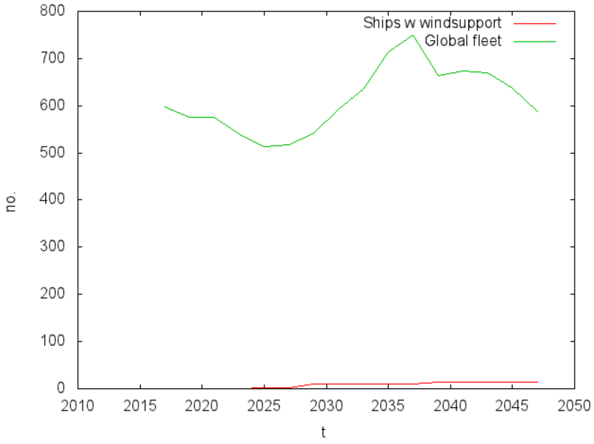

Figure 3: 20% of Shipping Companies operating on routes favourable to use of wind support systems

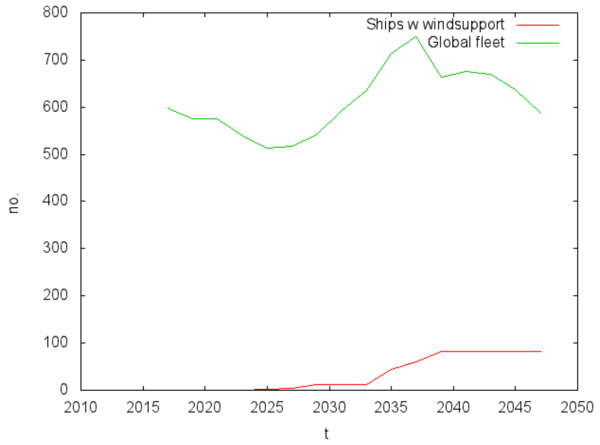

Figure 4: 50% of Shipping Companies operating on routes favourable to use of wind support systems

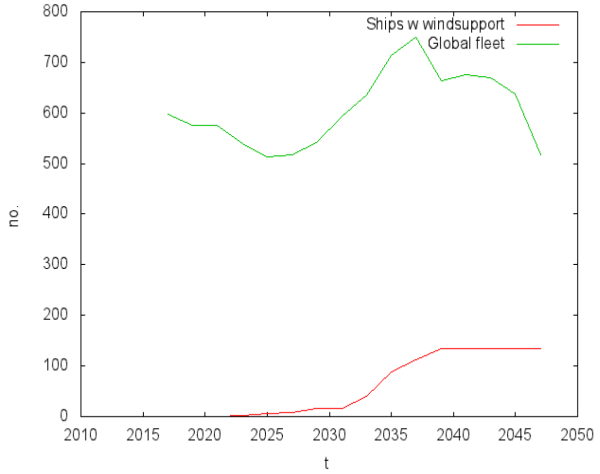

Figure 5: 100% of Shipping Companies operating on routes favourable to use of wind support systems

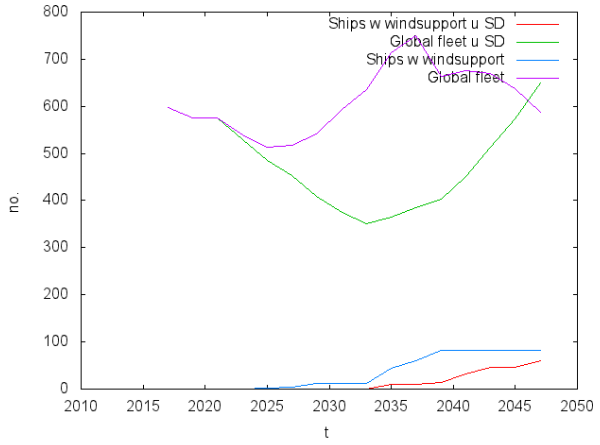

Figure 6: 50% of Shipping Companies operating on routes favourable to use of wind support systems, with adaptive expectations modelled using SD

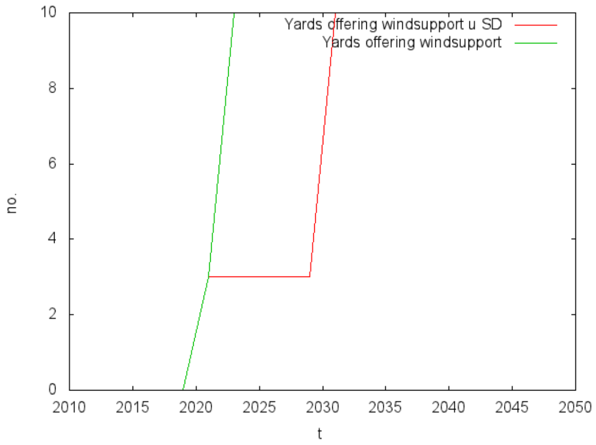

Figure 7: Typical adoption rate for yards in all scenarios (SD tested for 50% case only)

4. CONCLUSIONS

As we see, adoption of wind propulsion technologies by yards can happen very quickly, if the costs for developing the corresponding skills are low.

Since wind propulsion has nearly zero energy costs, it can take a significant share of the market, if the implementation costs are not too high and especially if costs for diesel rise significantly. However, maximising the potential of wind technologies requires a change in operating patterns, to maximise favourable winds and to operate at slower speeds to maximise the contribution of the wind component of the propulsion.

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