Agent Based Modelling of the Dry Bulk Shipping Sector

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Signed Declaration

I, Eoin O'Keeffe confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

This thesis presents an agent based model of the dry bulk shipping sector. The model is highly disaggregated, representing all voyages and cargoes transported through to 2050, including approximately 500 shippers and 750 shipowners with a total fleet of greater than 1000 vessels. In multiple projection scenarios, 2700 trade flows are modelled. The purpose of the approach is to identify a high fidelity representation of the system to gain a greater understanding of how aggregate level properties, for example total fuel consumption, are generated from individual company based decisions such as when to transport cargo, what vessels to use, and what technology to invest in. Contracts of affreightment, the spot market and time charter market are represented within the model to create, where possible, a realistic representation of actual contractual conditions. The model is deployed to investigate the impact of climate change on the sector. Specifically, it investigated: physical impacts of climate change through the opening of Arctic sea routes; changing demand for commodities due to climate change and projected evolution of the global economy; changing fuel prices due to external projected changes in the shipping sector, and; effects of mitigation of climate change through carbon pricing and minimum standards on vessel efficiency. A key finding from the work is that endogeneous changes in the shipping system, through for example shipper preferences, create greater variability than those driven by external factors. This variability is reflected in the number of vessels in each of the size categories, the technology uptaken and the strategic approach of shippers in transporting their cargo. There remains a strong coupling of transport supply and emissions, with the regulations tested and available technology not resulting in significant improvements in energy efficiency. On the modelling of the dry bulk shipping system, clear computational and scope limits were identified. On computational limits, the system is constrained such that parallelisation is limited leading to long runtimes. To understand the effects of agents choices, the modelling of the individual voyages is necessary leading to large degrees of freedom. In addition, the work has highlighted the need for more validation data of greater granularity.

Impact Statement

This work provides a platform for further work and analysis on the dry bulk shipping sector and more generally on the shipping sector as a whole. The model is developed to be easily extended so that further work both in academia and commercially can be applied. It has a number of applications but particularly its main goals are policy testing and operational research for commercial value. The model links the more abstract higher level approaches of scenario modelling at the global scale with company level operations to allow businesses understand how their decisions impact and are impacted by the wider policy environment and, vice versa, how policy impacts are manifested at the company scale.

The model allows the physical impacts of climate change to be simulated to understand how these can effect the commercial environment. The modelling approach adopted is not restricted to those impacts tested within the thesis. The model platform can easily be extended, for example, to allow a dynamic trade model to be included so that feedbacks between the shipping system and trade can be understood better.

The model allows users to view the shipping sector in a more interactive way that goes beyond significantly abstracted representations of the sector. A typical criticism that businesses have of model representations of their sectors is that they are too complex and too abstracted. The approach in this thesis and the model generated allows shippers and shipowners to implement policies that they would directly use with very little abstraction. It therefore goes some way to bridging the gap between academic modelling and business practical problems.

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When I was about to give up on on my code altogether and instead try to simulate the behaviour of the shipping system through the medium of dance, Rob McBryde provided help towards the end to help me get the model over the line. Without him, I would still be trying to debug memory leaks!

Contents

10 An Agent Based Modelling Framework 137

List of Figures

List of Tables

Chapter 1

Part A: Context

1.1 Thesis Outline

The thesis is divided into two sections. After a glossary introduction, **Part A** begins by outlining the research questions and then provides an introduction to challenges within the industry in the context of climate change with a specific focus on the dry bulk shipping sector (DBSS). This introduction provides a context to the research questions provided in the earlier chapter. **Part B** provides the framework for the thesis and modelling along with results and conclusions.

In **Part A**, **Chapter 4** and **Chapter 5** provide an introduction to complex adaptive systems and their applicability to the modelling of the shipping sector. They also provide some analysis of existing approaches to modelling transport in the long run within the maritime field. In **Part B**, **Chapter 7** which provides an outline of the approach used in the thesis. Next a background and context for the analysis is provided through a qualitative risk assessment of the shipping industry in **Chapter 8** followed by a more indepth analysis of the DBSS in the proceeding chapter. An agent based model is described in detail in **Chapters 10** and **11** with associated verification and validation in **Chapter 12**. The scenarios used in this study are described in **Chapter 13** and their associated results focussed on the research questions in **Chapter 14**.

Chapter 2

Glossary and Formatting

2.1 Introduction

The following chapter outlines the abbreviations and terms used throughout this thesis. The terms are first introduced in the text in long format and thereafter used in their abbreviated form. Additionally, there is provided an outline of the approach used in model symbols and terms in later chapters.

The formatting used in this thesis follows the rules below:

- References to chapters, sections, figures and tables occur in **Bold** with first letter capitalised
- Abbreviations and terms occur in normal text
- References to the model on which the thesis is based, *GooFy*, and the agents and objects within *GooFy* occur in *italics*. In the chapters that deal with the structure of *GooFy*, this can result in words, such as shipper, occuring in both *italics* and normal font. When it occurs in normal font, it refers to the object in the real world rather than how it is manifested within *GooFy* (*GooFy* is not an acronym).

2.2 Glossary of Abbreviations and terms

Abbr	Full name
ABM	Agent Based Modelling
ACE	Agent Based Computational Economics
AIS	Automatic Identification System
BDI	Belief-Desire-Intention
BDI	Baltic Dry Index
BFI	Baltic Freight Index
CAS	Complex Adaptive Systems
CIF	Cost, Insurance & Freight
CoA	Contract of Affreightment
CN	Competing Nations scenario
CRP	Cargo Routing Problem
DBSS	Dry Bulk Shipping Sector
DWT	Deadweight Tonnage
EBM	Equation Based Modelling
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Index
EMF	Efficient Market Hypothesis
EOQ	Economic Order Quantity
ETS	Emissions Trading Scheme
FSM	Four Stage Modelling
FSM	Fleet size and mix problem
GA	Genetic Algorithm
GC	Global Commons scenario
GHG	Greenhouse Gas
IMO	International Maritime Organisation
LDT	Vessel Light displacement
MABS	Multi-Agent Based Systems
MAC	Marginal Abatement Cost
MEPC	Marine Environment Policy Committee
MIRP	Maritime Inventory Routing Problem
SEEMP	Ship Energy Efficiency Management Plan
SQ	Status Quo scenario
SRPTP	Ship routing problem of tramp shipping
SSP1/SSP5	Shared Socio-Economic Pathways 1 and 5
UNFCCC	United Nations Framework Convention on Climate Change
WACC	Weighted Average Cost of Capital
WPS	World Port Source

Table 2.1. Glossary of abbreviations: Matching casing and notation to traditional notation use.

Term	**Description**
Agribulks	Agricultural goods transported in the bulk sector typically grains, soya, fertiliser.
Cabotage	Coastal shipping transport within a country
Capesize	Dry bulk vessels typically greater than 200,000t
Deadweight	Typical indicator of the size of a vessel, representing its cargo carrying capacity in tonnes
Dry bulk shipping	Dry cargoes that are large enough for vessel loads, eg. coal, iron ore and grain.
Layup	This is when a vessel is anchored in a sheltered location for a period of time with no crew (or at least minimal for safety) and does not engage in market activities
Layday	The day of arrival that a vessel must be at a load port to collect cargo
Parcel size	Refers to the volume of cargo transported
Panamax	Largest category of vessels that can traverse the Panama canal. In this thesis, it is designated as 60,000 to 100,000t
Pure play	Referring to a company that focusses on a particular market segment
Retrofit	The physical alteration of an active vessel that, typically, improves its fuel efficiency
Shuttle service	Cargoes are delivered by a vessel that transits from load port to discharge in a round trip without diverting to other ports
Suezmax	Largest category of vessel that can traverse the Suez canal. In this thesis, it is designation at 100,000 to 200,00 t
Valemax	Maximum size vessels as commissioned by the Brazilian mining company Vale. These were later termed Chinamaxes
Wet bulk shipping	Liquid bulk cargoes such as chemicals, oil and petroleum products

Table 2.2. Glossary of terms

2.3 Model Symbols Glossary

2.3.1 Models for Agent strategies

Categorical and continuous variables can be superscripted to a subset. These subsets are shown as uppercase, for exampe C^{FIXED} or C^{F} indicates fixed vessels costs.

Name	**Set symbol**	**Indexing symbols**
Commodity flow between ports for a shipper	K	k
Commodity	c	c
Vessel	V	i, j
Routes	R_v	r
Vessel Type	V	v
Count of vessels	Y	v, i
Binary indicator	X	i, x
Profit	π	i
Revenue	R	v, i
Time Consumed	Z	v, r

Table 2.3. Typical categorical/discrete objects as used within equations

For agent strategies that have been deployed in *GooFy*, the symbols used in the model definitions change, particularly in the broader use of other terms such as production and consumption.

Name	**Set symbol**	**Indexing symbols**
Capacity or Demand	Q	t, r

*Table 2.4. This table shows agent strategy definition symbols that have either changed or are not covered in **Table 2.3***

Name	**Superscript**	**Example Applications**
Days at sea	$DAYS\_AT\_SEA$	$T^{DAYS\_AT\_SEA}$
Days in port	$DAYS\_IN\_PORT$	$T^{DAYS\_IN\_PORT}$
Production	$PROD$	Q_{rt}^{PROD}

Table 2.5. Superscript definition used in agent strategies

Name	**units**	**Set symbol**	**Indexing symbols**	**Example superscripts**
rate	NA	d	i, j	$RISK$,$WACC$
Speed	km/hr	S	i	LOW

Table 2.6. Continuous variables

2.3.2 Other

The notation for superscripts when referencing agents is based on a simple camel casing principle. The first letter of each word within the variable is captialised and used in the variable names with an additional letter appended if this does not create a unique variable or for further descriptive purposes. Each subscript defines association of the variable to an instance of a particular entity with superscripts providing additional information about the variable such as association to an entity type. For example, C_i^{Sh} is total costs to shipper i, while C_i^{So} defines total costs to shipowner i. By utilising the superscripts for additional definition, it allows reuse of subscript letters. Each additional entity is separated by a comma, for example, $TC_{i,k}^{Sh}$ means the total costs to shipper i for commodity k. Note that commodity is not a superscript as k is only used to denote commodity. Similarly, c is only used to denote cargo. In the example above, the first superscript Sh is matched with the first subscript i meaning shipper i. However, since there is no associated superscript with k, it exists independently.

Where possible variables in equations are shown in lower case. The following correspondence table is used for comparison.

This thesis	Typical usage	Description
P_i	$\mathbf{p_i}$	Price of item to owner i. This could also be a vector
of prices $\mathbf{P}$	$\mathbf{P}$	Matrix of all prices and all owners.

Table 2.7. Matching casing and notation to traditional notation use.

Outputs from models will also be assigned to X and Y variables. These are used as matching variables (often binary).

Name	Symbol	Definition	Units
Crop yield	CY	Crop yield per km^2 of land, typically calculated for each country	te/km^2
Factor inputs	X	Quantity of factor inputs. Typically subscripted with L for land, C for capital, and lb for labour	km^2/\$/numbers
Price	p	International price of commodity	\$/te
Production	Q	Quantity of commodity produced (typically in a country)	te

Table 2.8. Symbol glossary for commodity production and consumption

Name	Symbol	Definition	Units
Balancing Factors	A, B	Used for the calculation of the O-D matrix	
Exports	O	Commodity quantity for export from a country	te
Generalized transport cost	TC	Monetised cost of transport	$
Imports	D	Demand of a commodity of a country.	te

Table 2.9. Symbol glossary for trade

Name	Symbol	Definition	Units
Transport work	TW	Transport work	tekm
Average haul	AvH	Average haul	km
Transport demand	D	Transport demand. In other words, the volume or mass of cargo to be shipped	te
Transport cost	C	The actual cost of transport	$
Binary flow variable	x	Indicates if a cargo is transported on a particular vessel	1 or 0
Transport time	T	The calculated time for a ship from arrival at one to arrival at another port	
Number of Nodes	N	Used for network analysis	
Number of Arcs	A	The number of arcs connecting nodes (also referred to as edges or links)	
Origin	o	The origin(typically a port)	
Destination	d	The destination(typically a port)	

Table 2.10. Symbol glossary for ship operations and route network calculations

Name	Symbol	Definition	Units
Fuel Intensity	FI		
Specific fuel constant	sfc	Factor to convert tonnes of fuel to tonnes of CO_2	
Emissions	Em	CO_2 Emissions	te

Table 2.11. Symbol glossary for ship technology and efficiency

Symbol	Referring to
i, j	Agent
m, n	Location
v	Vessel. E.g. Route network optimisation
c	Cargo.
k	Commodity
s	Shipper
o	Shipowner
t	Time

Table 2.12. Symbol glossary subscripts used in equations

Symbol	**Referring to**
bid	Bid price offered by shipper for transport of cargo
ask	Ask price of shipowner for hiring their vessel
Q	Annual volume on route
q	Cargo parcel size

Table 2.13. Symbol glossary for operation, tactical and strategic models

Chapter 3

Research Question and hypotheses

3.1 Research Question and Hypotheses

This thesis seeks to outline that mitigation in the DBSS must be considered in the context of climate change and adaptation. It does this by investigating the effects, both direct and indirect, of climate change on the DBSS through to 2050. Additionally, this thesis proposes the use of highly disaggregated simulation modelling, in the form of ABM, as being a suitable tool to investigate these impacts. These will be investigated through the hypotheses:

1. The treatment of the dry bulk shipping sector as a system of heterogeneous agents allows modelling of complex behaviour not captured with existing approaches in the field.
2. Setting shipowners and shippers as learning agents creates different take up of technology as compared with treatment of these entities as having consistent homogeneous market preferences.

Hypothesis 1 seeks to show that the system behaviour should not be constrained to an equilibrium type approach where supply is matched to demand on an annual basis. In fact decisions are made on an individual company basis at a point in time, where the decision is influenced by prevailing market conditions and the expected future conditions from the perspective of that company. **Hypothesis 2** seeks to show that by encapsulating stakeholders within the model as decision making entities that learn, the emergent system technology and vessel change is significantly different to the case where these stakeholders are aggregated into groups (such as size and type) and applying a uniform technology and vessel change.

In addition to dealing with the hypotheses above, the following research questions are to be investigated:

1. Will climate change impacts be similar across the route network, as the opening of new northern routes only affects certain commodities and trades?
2. Will relative changes in demand for dry bulk commodities, potentially as a result of climate mitigation policy in other sectors, lead to significant changes in the world shipping system such as arrangement of the world fleet structure?
3. Will the impact of climate change mitigation regulations cause a change in the provision of transport thus reducing the uptake of carbon emission reducing technologies?

3.2 Brief Elucidation

Research question 1) looks specifically at the cascading effect of changes to a specific route. For example, the opening of a new shorter route may effect the economic order quantity for a trade, by reducing the gains from economies of scale. The reduction in demand for this vessel size may change the overall demand for vessels of this size. This could lead to changes in parcel size for other trades that would have been shipped in this vessel size, as the overall liquidity in this size range is reduced.

Research question 2) deals particularly with climate policy sensitivity of commodities, with a focus on coal demand. It investigates whether the change in demand will simply reduce the demand on those vessels that would have supplied this transport or, as alluded to above, whether there are cascading impacts that will affect demand in other size ranges.

Research question 3) investigates the negative feedbacks from climate change policy. Will the adoption of a price of carbon have unintended consequences.

Tesfatsion (2006) outlined four areas of understanding in ABM:

1. Empirical Understanding: Can observed global regularities be generated in an ABM simulation?
2. Normative understanding: Can we generate good economic designs for the system, for example through policy intervention?
3. Qualitative insight and theory generation: Can we gain greater understanding of the real system through a systematic examination of their dynamical behaviours?

4. Methodological advancement: Can we improve approaches in ABM?

This research focuses on 1), 2) and 3). The approach looks to gain a normative understanding focussed on the double externality problem, where the private return is not matched by the social return (Faber & Frenken 2009), and market barriers to take up of emissions reducing technology in the context of climate change.

Chapter 4

Introduction

4.1 Maritime transport and the global economy

Globalisation has transformed the world in the last fifty years. Over this period, the growth in trade has allowed increasing choice for many countries, often being responsible for improvements in health and welfare. As a result, trade is often perceived as the backbone of globalization, allowing goods to be produced and shipped in the most efficient manner to allow consumers access at their lowest price. The reduction in transport cost has been facilitated through technological innovations and has occurred at a time when there has been increased trade liberalization (Tamiotti et al. 2009).

The freight shipping sector's value lies in its ability to service global trade. The importance of the sector is borne out in the fact that growth in world GDP has been historically correlated with growth in seaborne merchandise tradeUNCTAD (2009), albeit reducing in strength in recent years Constantinescu et al. (2015), Mangan (2017). This historical coupling is something particularly apparent in the economic expansion of developed countries. Consequently, when we consider impacts on the shipping sector, it is important to consider these in terms of their key interfaces with the global economy. More specifically, the cost and reliability of transport supply and externalities, such as air pollution and greenhouse gas (GHG) emissions , are not currently accounted for in these costs (with some limited exceptions)

The transport of goods, particularly long distance transport, is dominated by shipping. Indeed, the greatest contribution of shipping to global trade has been to make sea transport so cheap that the cost of freight for non time-dependent products is in many cases negligible when considering where to source goods. This is the major reason why shipping dominates the transport of goods and this cost performance has been achieved by a combination of economies of scale, new technology, better ports, more efficient cargo handling and the use of international flags to reduce overheads (Stopford 2009).

Indeed, some authors predicted a ”death of distance” as transport costs became lower and lower. However, Carrere & Schiff (2004) found the opposite to be the case with distance of trade declining for most countries with elements such as regional integration and counter-season trade and their relative evolution to be important, and indeed distance remains a key determinant of trade (Disdier & Head 2008, Williams & Grégoire 2015). This suggests that the system is complex making it difficult difficult to extract simple causal relationships from aggregated data.

The importance of transport costs in trade is less to do with their absolute value but rather the transport cost relative to the total value of the good (Korinek & Sourdin 2009). For high value goods, such as apparel, this could be between 2-4% for maritime transported goods but for low value commodities such as iron ore it could be as high as 60% (Korinek & Sourdin 2009). Thus the importance of transport cost for low value goods (wetbulk and drybulk in particular) is crucial. As alluded to above, distance is often found not to be a good proxy for trade patterns (Martinez-Zarzoso & Nowak-Lehmann 2007). There is some discussion that time to market is a better proxy for transport costs than distance (Korinek & Sourdin 2009), but it is likely only to be the case for containerised cargoes particularly retail goods such as apparel. In many cases, particularly in the dry bulk sector, the transit time is less important than service reliability. In fact, there is surprisingly little detailed information available on micro-level trade flows to help gain greater understanding of the transport of goods.

As Anderson & Van Wincoop (2004) outline, transport costs vary by country to country pairing and indeed by commodity. Moreover, there can also be significant intra annual variation in these prices, as some commodities, particularly agribulks (such as grains and fertiliser), are seasonal in production. There is also tension between commodities that have substitutable transport. For example, coal and iron-ore both are transported on capesize (200,000t+ vessels), thus relative demand is important in determining transport cost as it is supply sensitive.

When considering long run projections of the shipping sector, it is important to fully understand how issues such as cost and service reliability can change. Cost is fundamentally dependant on the voyage cost, the demand and the supply. In an oversupplied market, transport costs move toward voyage costs: the marginal cost of transport. As demand increases above supply, the voyage cost becomes a lower bound and the price becomes dependent on the shippers willingness to pay (and ship operators willingness to offer transport at that time). Although pricing at an aggregate level is available, detailed port to port flows by commodity and vessel are not for the most part.

4.2 Maritime hazards: Past and future

The global system of maritime trade is a complex dynamic system. The derived demand for shipping is considered as the volume of cargo for transport factored by the distance over which it needs to be transported, meaning both aggregate demand and trade pattern are important. Superimposed on this are time variations due to seasonal availability and demand, short-term cycles (both endogeneously and exogeneously generated), economic cycles and long term trends.

The key drivers of fluctuations in the sector have been due to temporal, geographical and commodity inconsistencies in matching supply and demand. Vessels have a lifespan of 25 to 30 years, while demand for transport, as alluded to above, adjusts over much shorter timescales. Together with this, short term fluctuations in the cost of transport are often due to mismatching of demand location and supply location. Many vessels, particularly larger bulk vessels, spend almost half their sailing time carrying no cargo (in ballast) as they must relocate to areas where there is demand. The option of vessel substitution is also limited as many commodities are restricted by their state (liquid, gas, solid), cargo size (supply chain requirements lacking flexibility) and market related demands.

Coupled with these existing challenges, future developments include greater demand from Asia and developing countries as well as significant changes in commodities being transported having dramatic effects in the dry and wet trades. Additionally, climate change potentially will have significant direct and indirect impacts, and as such can be considered to be a ”threat multiplier”. For example, localised weather conditions can cause crop failures which in turn alters demand and supply within a region that in turn causes volatility in transport demand for that crop. In addition, due to the long life of vessels, climate change mitigation policies enacted now (or not) will have lasting effects on the maritime sectors ability to deal with changing physical climate conditions.

Together with possible impacts, the maritime sector must also cut its emissions significantly as part of a global effort to avoid dangerous climate change (Smith et al. 2014). Therefore, determining the most effective path at reducing emissions whilst avoiding increased exposure to systemic risks is important for the welfare of the industry.

As alluded to above, the shipping sector consists of several distinct sub-sectors, most notably dry (e.g. grains and iron ore), wet (e.g. oil and chemicals) and containerised. These are distinct due their product properties. Containerised trade is typically run on scheduled services so it can transport less than vessel load cargoes. Dry and wet typically carry a single cargo, and for larger vessel sizes, this involves a single drop-off. Although some vessels exist that can service more than one of these sub-sectors, they are dominated by specialised vessels that service a single sector. Although **Chapter 8** provides a sector wide assessment, the focus of this thesis is on the DBSS. As with containerised and wet, it is typically considered a distinct market and thus a hard system boundary assumed from a vessel allocation perspective. Secondly, it transports low cost cargo and is thus sensitive to changes in transport cost. Thirdly, it is a significant proportion, in mass, of the cargo transported globally and therefore significant alterations in this system would have a material affect on sector wide emissions. Finally, it carries cargo that is sensitive to climate change impacts and climate change mitigation policies, and thus allows consideration of feedbacks from climate effects.

4.3 Maritime transport modelling paradigm and its limitations

The focus in this section is on approaches that model sector-wide changes in the long run. Transport modelling of this kind is largely based on the four stage modelling (FSM) paradigm. The FSM has been adopted in regional and global models following their extensive use in passenger modelling (Ortuzar & Willumsen 2001). These are, largely, equilibrium type models, although there are many different implementations. FSM adopts the principal that trade and transport can effectively be split into four separate categories for ease of modelling:

- Trip generation: The total number of trips originating from a node are estimated.
- Trip distribution: The destinations of the trips are estimated to form an origin-destination matrix.
- Modal split: The share of modes are calculated for each origin/destination pair.
- Trip assignment: The origin/destination demand for each mode is assigned to a route.

FSMs were developed in the passenger transport sector and were adopted by freight transport modellers. Macro-level models using this FSM approach, such as STREAMS, VACLAV, SAMSGODS and TRANS-TOOLS for the European area (Kraft et al. 2010, Bergkvist et al. 2005), measure the effects of control polices. These use coarse-grained data either at the national level or disagregated to sub-national regions (typically NUT3/2 zones) resulting in up to 1300 traffic cells. It should be noted that these models are traditionally road based models, with the focus on passenger transport and not freight. However, maritime transport modelling has borrowed heavily from this FSM paradigm and in some cases has been included in these models, albeit with less granularity.

As noted by Bergkvist et al. (2005), many of these models fail to account for logistical processes and as a result fail to model at the level where the decisions regarding the actual transports are taking place. For minor changes, this may be sufficient but for large infrastructural alterations or significant changes in transport costs identification and incorporation of feedbacks and other system responses is difficult. Furthermore, Bergkvist et al. (2005) suggest that micro-level models are best placed to capture the decision making of the actors in the logistical process.

For the most part (with some notable exceptions such as ASTRA), each individual step with the FSM consists of what Parunak et al. (1998) refer to as equation based modelling (EBM), where the model is a system of equations and execution consists of evaluating them. For geographical systems, EBM models are represented as static aggregations of populations, rational aggregated behaviour and flows of information (Crooks & Heppenstall 2012), effectively assuming homogeneity within the system. Solution approaches included multiple regression, location-allocation and spatial interaction models (Crooks & Heppenstall 2012). For transport this typically takes place within the FSM framework.

In particular, EBMs substitute what Tesfatsion (2006) called “equilibrium assumptions for procurement processes”. This is reasonable for systems that have a stable equilibrium as procurement processes may not effect the long run state. Tesfatsion (2006) cites Fisher (1989)

> The theory of value is not satisfactory without a description of the adjustment processes that are applicable to the economy and of the way in which individual agents adjust to disequilibrium. In this sense, stability analysis is of far more than merely technical interest. It is the first step in the reformulation of the theory of value.

As Crooks & Heppenstall (2012) suggest, geographical systems are characterised by continual change and evolution through space and time with interactions between agents felt at different scales as well as over differing timescales. The limitations of EBM can be its assumption of equilibrium or steady state, which is an exception in the real world (Kraft et al. 2010).

As noted at the beginning of this chapter, the shipping system has radically changed over the last fifty years, therefore, as we look to project over that same magnitude of time the assumption that the system only undergoes minor perturbations is questionable.

Existing approaches have struggled to explain phenomena within the shipping system in a useful way to increase resilience. Together with this, there is a necessity to unlock investment in new technology that will reduce emission of pollutants and GHGs. As is shown by marginal abatement cost (MAC) curves, there is enormous potential here but market barriers hinder this. Unlocking these, requires an understanding of the environment in which they act at the company level.

There have been some notable exceptions to EBM within the FSM framework. Song et al. (2005) adopt a disagregated pipe-network approach to modelling the container shipping network. The transport demand and shipping are inputs to their model. As such it is serves as an assignment model in the FSM mould. Kraft et al. (2010) coupled a systems dynamics model with a static network based approach.

A number of other studies focussed on the shipping sector with the aim of projecting GHG emissions (as well as pollutants) within the sector (rather than, for instance, transport policy), most notably the GHG studies sponsored by the International Maritime Organisation (IMO). The most recent iteration, Smith et al. (2014), used a scenario based approach that assumed an exogeneous transport demand. The transport supply was estimated using assumed capacity utilisation factors. Fuel consumption and emissions were then estimated using an assumed evolution of fuel mix, technology, fuel and carbon costs. The performance of the fleet (in terms of fuel consumption and emissions) was derived from these assumed drivers by estimating cost driven technology take up (Smith et al. 2014).

4.4 Research Focus

The exigencies of climate change have spawned large areas of research both on the science and its associated economic and social effects. In the context of shipping, most research has been focused on reducing emissions from the sector through technological advances and operational optimisation. However, a holistic understanding of these risks is hampered by the lack of quality data available to researchers. Indeed, attempts to quantify emissions have led to large ranges of estimates from the sector. Thus most research has focused on clarifying this area to determine some base line value from which emissions trajectories can evolve.

Unfortunately, impacts of climate change on shipping and trade have been somewhat overlooked (Tamiotti et al. 2009, Watson & Wright 2010). This is particularly concerning as according to a number of studies, not least Rogelj et al. (2011) and more recently Raftery et al. (2017), it is extremely likely we will exceed the 2 degree C above preindustrial levels target based on full implementation of current commitments.

The impacts of climate change on the sector coupled with other developments already outlined are not understood. This is largely due to the crude tools that are used to understand the maritime system and the alluded to 'data gap'. For example, marginal abatement cost curves (MAC curves) are often used to identify the technologies and changes that could be adopted to reduce emissions often at negative cost. However, MAC curves contain an inherent contradiction - negative cost technologies should already be implemented. Consequently, the use of these tools to identify barriers to uptake (only one of which is the direct monetary cost of implementation) can at best be complementary to a more sophisticated understanding of the system.

Some considerable work on predicting the transport demand in the sector in the long run and its expected emissions and technology uptake has been undertaken (for example Smith et al. (2016) and Eyring (2005)). However, in many respects this provides little understanding in how the system will evolve. In this thesis, research focuses on the DBSS system, particularly treating the DBSS as a complex adaptive system and using the approach, agent based modelling (ABM), in analysing it.

As Bergkvist et al. (2005) state, EBM contain an enforced structure whereas in ABM the structure is emergent from the interactions between the individuals. Further to this, Parunak et al. (1998) states that

> ABM is most appropriate for domains characterized by a high degree of localization and distribution and dominated by discrete decisions. EBM is most naturally applied to systems that can be modelled centrally, and in which the dynamics are dominated by physical laws rather than information processing.

4.5 Summary

Shipping dominates the transport of goods and commodities by volume, largely due to its economies of scale. Although the cost of transport is driven by distance and volume, the dynamics of geographic supply and demand, amongst other factors, result in large fluctuations in the price of transport in the short term with changing trade patterns and the long lifespan of vessels affecting it in the long term.

The modelling of the evolution of the shipping sector has predominantly followed the canonical transport modelling approach of the FSM and other equilibrium based approaches. These approaches are appropriate for systems that are, unlike the shipping industry, stable and not subject to constant supply-demand inequalities. This chapter introduced a more suitable approach: consideration of the system in terms of its interacting agents. In this situation, the aggregate supply-demand balance is an emergent property rather than an enforced boundary. Due to the distinction between the various sectors within the industry, each shipper sub-sector can be considered in isolation, with this thesis focussing on the DBSS. The main contribution of this thesis is to propose a complex adaptive systems approach for understanding the maritime shipping system to understand how it can be expected to respond under different future scenarios.

Chapter 5

The Emergence of Complexity

5.1 Introduction

This chapter provides a brief introduction to complex adaptive systems with a particular focus on the modelling of those systems using ABM. Following this it provides some examples of applications of ABM in relevant fields before focussing on its applicability to the research. Finally, it discusses limitations of the approach.

5.2 Emergence of Complexity

A system is complex if it is composed of interacting units which exhibit emergent properties, becoming a complex *adaptive* system (CAS) when these interacting units exhibit goal-directed behaviour (Tesfatsion 2006). Moreover, CAS are a subset where the agents within the system can adapt locally to maximise their utility or fitness.

The study of CAS investigates how the interactions of the parts of the system give rise to collective behaviours of the system. Key elements of these complex systems are that the interactions between agents are typically local and non-linear. These local, rich interactions lead to emergent behaviour at the macroscopic level. Together with this, complex systems have a historic dependency and most importantly operate far from equilibrium conditions. The assumption of equilibrium is a key to most EBM models that is relaxed in this framework. As discussed in **Chapter 4**, there remain knowledge gaps of the causal mechanisms in the shipping system; the investigation of causal mechanisms of this type is a fundamental goal of agent based modelling (Tesfatsion 2006).

Limits to growth (Forrester & Meadows 1972) was one of the first works to take a system approach and explicitly treat complexity within global systems and spawned the area of system dynamics. Specifically, it models the causal mechanisms and feedbacks of the system by treating the system as a series of rates and flows. The system is allowed to evolve, rather than producing point estimates at defined periods, without an enforced equilibrium or steady state. However, by not considering the individual agents interactions, it contains an enforced structure and is considered an EBM style approach.Notwithstanding this limitation, ABM, and other fields such as complexity science, are related to this approach and draw on this and other fields for their theoretical foundations.

ABM tends to be referred to in different areas: Multi-Agent Based Systems (MABS) in flow systems and Agent Based Computational Economics (ACE) in business based applications. Although they diverge in naming convention, their framework and model structure is fundamentally the same. For this thesis, the convention of agent based modelling (ABM) is used.

Bonabeau (2002) succinctly outlines the advantages of ABM over other modelling techniques:

- ABM captures emergent phenomena: The whole is more than the sum of its parts where emergent system properties may seem counterintuitive to the properties of the parts. Therefore, it is good for finding system regularities that the user is interested in altering or at the very least understanding their provenance.
- ABM provides a natural description of a system: Describing a system using a series of aggregate analytical models is conceptually considerably more abstract than defining how agents interact with each other whether physically (eg. in traffic flows) or in marketplaces (eg. through bids and asks).
- ABM is flexible: It can be trivial to adjust the number of agents and more importantly vary their strategies and their complexity. For an EBM, this can require changes to the system structure (Van Dam 2009).

Macal & North (2010) suggest that CAS was originally motivated by investigations into adaptation and emergence of biological systems and has been said to have its origins in the evolutionary theory of Darwin. Chen (2012) suggests that ABM as applied in market simulation has its origin in work of Leon Walras’ 1874 proposal for a competitive general equilibrium model. However, the major breakthrough which brought the approach into common use was in Thomas Schelling’s (Schelling 1969, 1971) models of segregation using a cellular automata framework. Schelling showed that system regularities emerge which are not necessarily coupled with the objectives of the agents (Macal & North 2010).However, it wasn’t until the appearance of the Sugarscape model in 1996 (Epstein & Axtell 1996) that ABM was applied to entire artificial societies (Crooks & Heppenstall 2012) and began to be applied more widely.

Although definitions vary of an agent, Tesfatsion (2006) describes it as "bundled data and behavioural methods representing an entity constituting part of a computationally constructed world". Examples range from individuals to firms and institutions as well as crops and livestock and physical entities such as geographical regions. Macal & North (2010) extends the agent definition to requiring certain characteristics:

- An agent is identifiable with decision-making ability.
- An agent is situated with the ability to recognise and distinguish the traits of other agents.
- An agent may be goal-directed, autonomous and self-directed. As Macal (2016) note, the approach takes "the agent persepective".

Agents were originally rule based but have since been embedded with the potential for learning and memory (Crooks & Heppenstall 2012). The development of learning in ABM, followed two paths: normative learning that described the optimal learning process and learning that causes behaviour to converge towards optimal behaviour in equilibrium (Brenner 2006). Different fields favoured different learning paradigms with macro-economists favouring normative approaches and evolutionary algorithms and genetic programming frequently used in ACE. Reinforcement learning in ACE models has been applied to a large extent through the three main models: Bush-Mosteller, the principle of melioration and the Roth-Erev model.

However, there remains strong links to the early modelling with agent depiction in many simulations remaining (near) zero-intelligence or indeed randomly behaving agents. For example, financial agents are often modelled as zero-intelligence agents because their strategic behaviours are poorly known and understood (Chen 2012). This work has grown alongside a paradigm shift in micro-economics, where traditional assumptions of rationality and homogeneity are being challenged (Macal & North 2010). This included developments in consumer theory on the concept of bounded rationality, where consumers cannot know the property of all goods due to capacity and information constraints (Faber & Frenken 2009) and in behavioural economics such as the concept of satisficing (Simon 1996). Possibly the most important contribution from ABM, is its ability to generate complex phenomena or system regularities from a set of relatively simple agent rules (Luke et al. 2003).

An advantage of ABM is that the agents that are modelled can range from those with primitive reactive decision rules to complex adaptive artificial intelligence (Macal & North 2010). ABM has also facilitated the modelling of heterogeneity within agents, where they not only differ in skills and knowledge but also in preferences (Faber & Frenken 2009, Abar et al. 2017).

The architectures on which ABM is developed have increased dramatically with a number of different software platforms available. Further to this Wooldridge & Jennings (1995), defined four agent types: logic based agents, reactive agents, belief-desire-intention (BDI) agents and layered architectures; which define these architectures. The design of the architectures is considered as important as the design of the ABM itself (Lang et al. 2008), with the framework creating the shared ontology through which the agents interact and the system evolves. These architectures or environments define the operational space of agents, meaning agents can be spatially explicit (a location in geometrical space) or implicit meaning their location is irrelevant (Crooks & Heppenstall 2012). For MABS, agent communication languages were developed as context-free grammars to allow complete flexibility within the architecture, facilitating agent communication (Lang et al. 2008). The move towards these concepts of mental agency occurred in the 1990s in the BDI architecture.

The early 2000s saw a significant increase in the number of publications adopting an evolutionary perspective (Faber & Frenken 2009), dominated by ABM approaches. This trend has continued with ABM approaches been deployed in many disciplines including economics, sociology, psychology, archaeology, language studies and management (Faber & Frenken 2009, Macal 2016, Moglia et al. 2017), and indeed, it continues to find new areas of deployment (Nicholls et al. 2017).

According to Macal & North (2010), ABM should be applied when long-run equilibrium states are not the only results of interest, and when the past is no predictor of the future. Furthermore, they suggest that the systems requiring understanding are becoming more complex if not always too complex for EBM approaches.

In **Chapter 4**, the future impacts on shipping were introduced. These would suggest that the environment and demands on shipping are going to dramatically change over the coming years. A key factor that has been highlighted by many authors is the market barriers that exist in shipping to uptake of energy efficient technologies. Another key reason for using ABM is that agents learn and engage in dynamic strategic behaviour (Macal & North 2010). To understand the effect of, and ultimately to be able to remove, market barriers is a key research point.

More concretely, ABM facilitates a greater understanding of the system at work. There is a good understanding of each of the factors at work and how these can cause macro effects, such as the vessel construction time as a feedback effect on freight rates, but little knowledge of how these can combine. ABM can provide the opportunity to test theory that is not easily described using mathematical formulae (Axelrod 1997). It is more natural to map the theory to an ABM than an abstract theory of an emergent property

(Parunak et al. 1998). This mapping of interactions is naturally defined over networks or geographies.

5.3 Applications of Agent Based Modelling

A key area where ABM has achieved significant success is the area of innovation diffusion modelling, a trend likely to continue Moglia et al. (2017). Until the application of ABM to this subject, most work in technological innovation focussed on the seminal contagion model by Bass (1969). Although still nascent, it has created interesting work by facilitating a transition from an aggregate-level to an individual-level perspective (Kiesling et al. 2012).

Geographic systems have seen a wide application of ABM to investigate geographical problems like urban sprawl (Crooks & Heppenstall 2012). For example, Heppenstall et al. (2006) modelled geographic retail markets.

The dominant work in ACE has been on auction systems or advances on Sugarscape (Epstein & Axtell 1996) in growing economies. Such work has also carried over to transportation marketplaces, for example Dai & Chen (2011) developed an ABM framework in a carrier collaboration problem. The profit allocation is determined following collaboration amongst carriers that is facilitated by an auction process. However within the transportation sector, ABM applications have focussed on optimisation approaches to traditional operational research problems and traffic problems. For example, Farhan (2015) developed a simulation model for capacity planning of a cross border facilty accounting for pedestrian flows.

MABS systems in particular have been deployed as decision support systems in the areas of vehicle routing and transportation firm engagement. These areas have typically seen the deployment of optimisation systems. As Lang et al. (2008) suggest, ABM has the ability to include negotiation and cooperation that optimisation based approaches do not. This has led Davidsson et al. (2005), amongst others, to conclude that ABM is the way forward for transport logistics, a prediction that has largely been borne out (El-Amine et al. 2017).

Bergkvist et al. (2005) developed an ABM that can simulate a transport chain to understand the consequences of control policies in an operational setting (buying and selling of vehicles is not considered). The work itself was in an early phase, but showed the potential of such approaches in transport logistics. Engelen et al. (2009) completed one of the few ABM applications in the shipping sector. This approach is on short run analysis of the DBSS freight markets to assess the Efficient Market Hypothesis (EMF), concluding that bounded rationality is a suitable paradigm for DBSS agents.

Furthermore, they suggest that shipping companies tend to use practical filter rules or rules of thumb when making tactical and strategic decisions. A conclusion of their work was that defining a market equilibrium as a result of interacting individual strategies is a powerful approach to describing market price patterns.

These are notable exceptions in the application of modelling paradigms within the shipping sector. Most focus has been on integration across agents with little work on representing the different planning stages that protagonists use within the DBSS. More concretely, the DBSS does not have the same challenges of integration that liner shipping in particular has. The focus, to date, has been on determining the validity of assumed economic conditions and market properties such as the efficient market hypothesis (Engelen et al. 2009).

As highlighted by Bonabeau (2002), a key reason to use ABM is when agent interactions are heterogeneous and can generate network effects. Kaluza et al. (2010) showed that each of the main shipping subsectors resemble small world networks (Watts & Strogatz 1998) as well as other key emergent properties. Another reason, is that averages will not work (Bonabeau 2002): the shipping sector is strongly cyclical, but is treated as linearly stable in most approaches when in fact fluctuations are amplified within the system causing the cyclical phenomenon. As Stopford (2009) states, the sector is driven by cycles not long term trends.

As will be discussed in **Chapter 11**, shipping stakeholder behaviour is complex and is difficult to capture through aggregate transition rates. Activities, such as the various planning levels, are a more natural way to describe these agents.

5.3.1 Limitations of Agent Based Modelling

As with all models, a general purpose model cannot work. This appears a greater issue with ABM, as there is the temptation to model all interactions and processes within the real system. As the focus is, typically, on emergent properties of the system, setting a system boundary before these have been identified is difficult. Hence, there is a focus on developing simple models and adding complexity. As reiterated by Bonabeau (2002), this process remains an art more than a science. Too much detail can lead to excessive constraints and become overly complicated. Too little and key feedbacks and regularities may be missed. A key factor of CAS is its sensitivity to initial conditions. Given the level of detail required for defining an ABM system, the initial state of the system may not be completely known. Indeed, small changes in rules of interactions can cause system bifurcations. This so-called path dependence, results in ABM being heavily criticised when used for prediction (Crooks & Heppenstall 2012).

Further to this, the more interactions and agents captured within the system the greater the computational demand. Parallelisation can be deployed, but only on systems where the agents can be separated into parallel processes - typically in a physical space based model such as the modelling of human civilisations. If a system requires that all agents are interacting, or at least it is non-trivial in decomposing the groups into sub-groups, such as through communication networks, then opportunities for parallelisation are limited. Although computational power is constantly increasing, it remains a strong limiting factor.

As visual and flexible tools, a typical benefit of ABM is that it is a tool that users can play with, what Crooks & Heppenstall (2012) refer to as a miniature laboratory. However, this is also cited as a limitation. As Bonabeau (2002) suggests, “a manager cannot claim to have saved $X million by playing with a simulation of her customers”. In this regard, it is is ideal to adopt different approaches to tackling the same problems. Therefore, the parallel use of an EBM with an ABM is not without merits.

The main limitation in ABM is the area of validation and verification (Crooks et al. 2008). This is discussed in greater detail in **Chapter 12** when applied to the model developed in this work. Faber & Frenken (2009) refer to this limitation euphemistically as a “problematic relationship”. The validation process is an assessment of the “extent to which the model is a good representation of the process that generated a set of observed data”. In simple terms, the actual data is a sample from the generating process that is the ABM. As discussed above, in ABM the agents and interactions are modelled, not the macroscopic behaviour. However, the validation likely occurs at the macroscopic level which makes identification of causation of deviations from the required macroscopic behaviour difficult to diagnose, as the correlation of individual interactions and behaviours and emergent properties is often not simple.

5.4 Summary

In this chapter, a brief introduction to the field of complex adaptive systems was provided along with the key developments in evolutionary modelling particularly with ABM approaches. Additionally, it provided some example applications of the approach with a focus on transport applications. There have been many applications but focussed on short run operations, and as such many research opportunities in this area are available. The field can largely be viewed as nascent, it is still considered a new approach (Macal & North 2010), but with many detractors particularly due to its limitations on validation. It is a new paradigm and as one author suggested “a new way of doing science”.

Chapter 6

Part B: Analysis

6.1 Section Introduction

Following the context laid out in the previous section this part of the thesis highlights the areas of interest in the form of hypotheses and research questions. The following four chapters then provide detail on the approach used in answering these questions, specifically introducing the ABM developed in this thesis, *GooFy*. Following model evaluation, the results from the various approaches are discussed and the hypotheses analysed. **Chapter 9** provides a more specific literature review for the area being modelled. This complements the more general review provided in **chapter 5**.

The development of the PHD, in chronological terms, followed the path outlined in **Figure 6.1**. An initial shipping sector vulnerability was conducted (detailed in **Chapter 8**). Following this, the PHD focussed on the DBSS and the selection of agent based modelling as a suitable approach. A more detailed DBSS analysis was then conducted (detailed in **Chapter 9**) that led to the definition of the agent strategies (detailed in **Chapter 11**) as well as the projection scenarios(detailed in **Chapter 13**). On development of the ABM, *GooFy*, hindcasting was undertaken to validate the model and the projection scenarios were run whose purpose was to investigate the hypotheses and research questions . The result of this is outlined in **Chapter 14**.

The development of the research questions and hypotheses (detailed in **Chapter 3**) took place following the decision to focus on the DBSS using ABM. These were maintained throughout the model development and further analysis of the DBSS.

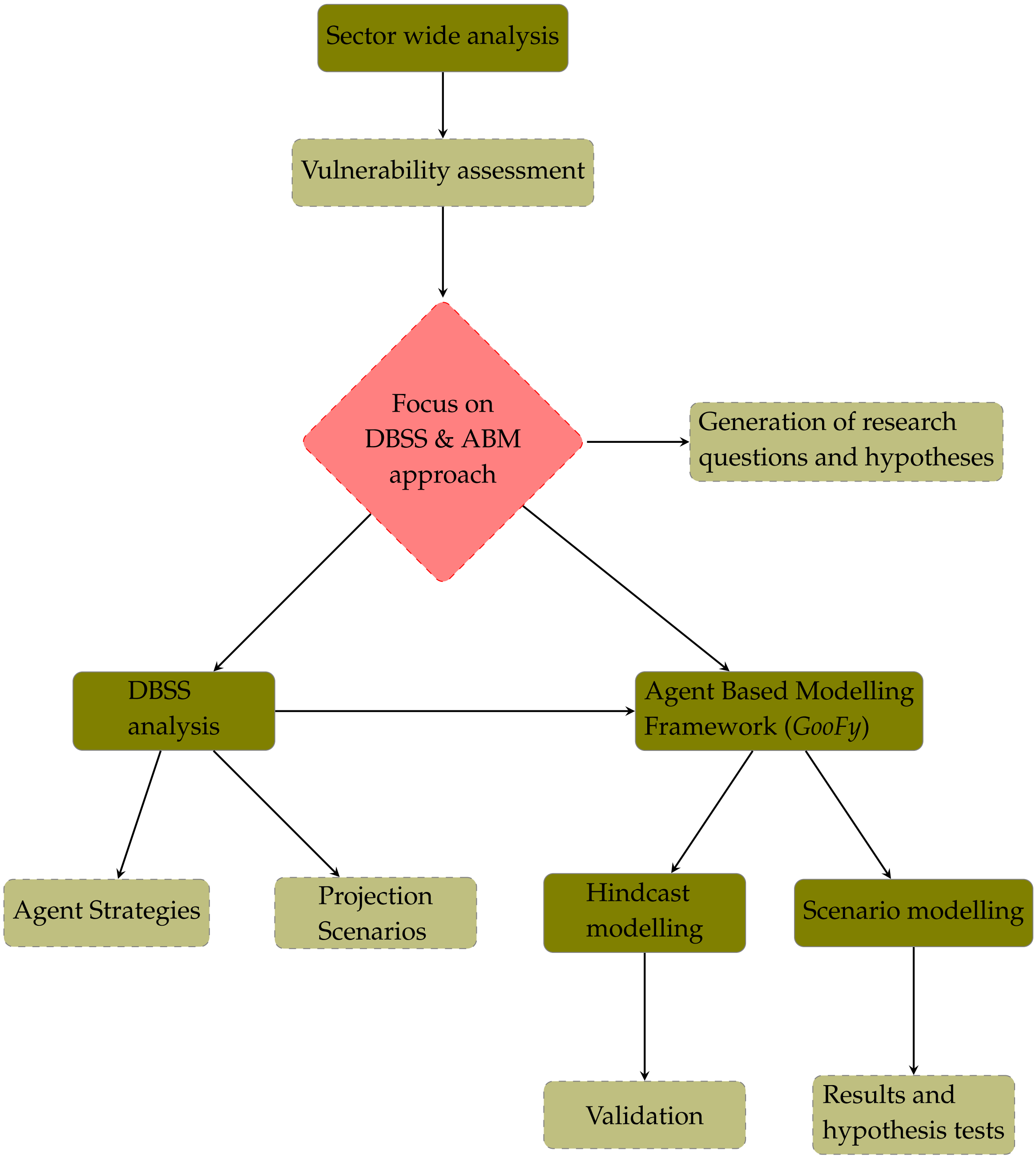


Figure 6.1. Analysis Approach: The light green boxes show outputs and dark green show analysis or development sections. The pink triangle indicates a decision node. The arrows mark the chronological path of work conducted.

6.2 Timeline of Thesis

The timeline of the evolution of the thesis is shown in **Figure 6.2**, conducted over a period of 8 years. In the initial phase, a vulnerability assessment was conducted to identify the scope of work for the thesis. The data and inputs for this assessment have not being updated as this work is considered a snapshot study that provided a starting point to the PHD research. This led to the identification of a coupled system dynamics trade model and a shipping model using agent based modelling as a suitable approach to ansewr the research questions. Following the development of the initial coupled model, the scope was narrowed to focus on the agent based transport model using the Repast library. The decision to exclude the trade model was taken to make the model computationally tractable.The agent based model was further scaled up from a theoretical network to represent the full DSSS from 2015 when it was deployed to AWS to allow parallel running of the simulations. Since that period, further development has focussed on reducing computation runtime and integration of unit testing for model verification. Hindcasting for validation and deployment of final projection scenarios was done from 2017.

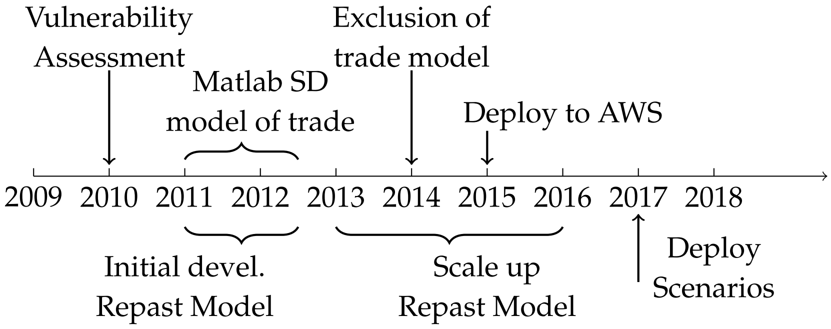


Figure 6.2. PHD Timeline: Evolution of work completed for thesis

Chapter 7

Overall Approach

7.1 Outline

Included for information is a vulnerability assessment that was undertaken at an early point in the thesis from which the main body of the thesis was developed. Following the vulnerability assessement is the description of the ABM that was developed in order to answer the research questions outlined in **Chapter 3**. The chronology of work is covered in **Chapter 6**, particularly **Figure 6.1**.

The purpose of the vulnerability assessment was to identify key areas for the research to focus on. **Chapter 8** provides the full report. It is also used to define system boundaries for the modelling in further chapters and key areas to focus on. The vulnerability analysis is completed for the whole maritime sector and provides a justification for focussing on the dry bulk shipping sector.

The thesis thereafter focusses on modelling the DBSS, specifically vulnerability to:

- Physical impacts of climate change through the opening of Arctic sea routes.
- Changing demand for commodities due to climate change and external projected evolution of the global economy
- Changing fuel prices due to external projected changes in the shipping sector
- Effects of mitigation of climate through carbon pricing and minimum standards on vessel efficiency

A description of the DBSS is provided in **Chapter 9**, identifying system regularities trade properties, markets and stakeholders.The description of the ABM is split between three chapters. **Chapter 10** outlines the modelling framework and provides agent descriptions and the rules. **Chapter 11** outlines the available agent strategies. **Chapter 12** uses the framework to hindcast over the first decade of this century to validate it.

At this point, the scenarios for future projection are introduced in **Chapter 13** before presenting key results in the final two chapters.

Chapter 8

Vulnerability Assessment

8.1 Introduction

Globalisation has transformed the globe in the last fifty years! Advances in technology and global capital flows have allowed greater interconnectedness of disparate societies and communities. Over this period as shown in **Figure 8.10**, the growth in trade has allowed greater and greater choice for many countries, often being responsible for improvements in health and welfare. This has been particularly felt in developed countries where growth in world GDP has correlated with growth in seaborne merchandise trade (UNCTAD 2008).

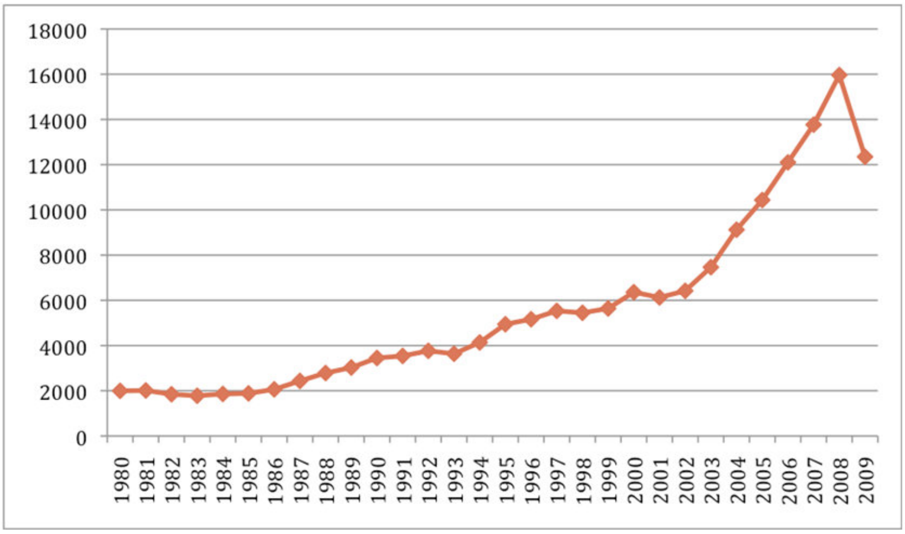


Figure 8.1. Global merchandise exports (billions US$ f.o.b.) of goods 1980 - 2009
Source: IMF (2016)

Trade is often perceived as the backbone of globalization, allowing goods to be produced and shipped in the most efficient manner to allow consumers access at their lowest price. Certainly, many cities could not exist and global trade could not occur without systems to transport people and goods cheaply and efficiently (Ribeiro et al. 2007). International trade involves countries specializing in the production and export of goods where they have a comparative advantage and importing other goods from their trade partners where they have no such advantage. Globalisation, viewed in terms of international economic connectivity and integration, has been facilitated by the growth of shipping and particularly the reduction in transport costs. The reduction in transport cost has been facilitated through technological innovations and has occurred at a time when there has been increased trade liberalization (Tamiotti et al. 2009). Indeed, transportation is considered one of the cornerstones of globalization along with communications, international standardization, and trade liberalization (Corbett & Winebrake 2008). Of this, shipping accounts for 89% of goods transported.

However, the realities of climate change mean that the increased global transportation, coupled as it is with fossil fuel use, conflicts with current attempts to reduce greenhouse gas emissions. Attempts to arrive at global agreements have ended in stalemate, with little to no discernible progress. Nevertheless, the exigencies of climate change have spawned large areas of research both on the science and its associated economic and social effects. In the context of shipping, most research has been focused on reducing emissions from the sector. Attempts to quantify emissions have led to large ranges of estimates from shipping, thus most research has focused on clarifying this area to determine some base line value from which emissions trajectories can evolve.

Unfortunately, impacts of climate change on shipping and trade have been somewhat overlooked (Tamiotti et al. 2009, Watson & Wright 2010). With an agreement to succeed Kyoto remaining elusive, the need for greater research into adaptation multiplies. Indeed, according to a recent study by Rogelj et al. (2009), it is virtually certain we will exceed the 2C above pre-industrial levels target based on full implementation of current commitments. As a result, the focus of this research is on the shipping industry and its relationship with trade when affected by the twin factors of climate change and emissions mitigation measures. The reason for a combined approach is simply that policy initiatives, although possibly effective at reducing emissions, may in fact lower the sectoral resilience to dealing with climate change impacts (for example, as this is likely to increase the cost base of companies thus making them less resilience to costly business interruptions). The following sections provide a background to the merchandise shipping industry with a particular focus on risk management within the industry before introducing the approach of the research followed by results. The discussion section provides an analysis of the results before offering some concluding remarks.

8.1.1 Shipping and the supply chain

Goods are traded internationally for many reasons, principal among these are differences in production costs and differences in natural resources (Stopford 2009). Labour cost differences have been the dominant reason for offshore production although other factors such as quality control, reliability and volatility and predictability of demand are also factors (Drewry 2007). Superimposed on this are time variations due to seasonal availability and demand, short-term cycles, economic cycles and long term trends.

The transport of goods, particularly long distance transport, is dominated by shipping as demonstrated by Figure 2. Indeed, the greatest contribution of shipping to global trade has been to make sea transport so cheap that the cost of freight for non time-dependent products is in many cases incidental when considering where to source goods. This is the major reason why it dominates the transport of goods and this cost performance has been achieved by a combination of economies of scale, new technology, better ports, more efficient cargo handling and the use of international flags to reduce overheads (Stopford 2009). It is the low transport cost and service reliability that has allowed production to shift to Asia (Golicic et al. 2010). Indeed, some authors predicted a death of distance as transport costs became lower and lower. However, Carrere & Schiff (2004) found the opposite to be the case with distance of trade declining for most countries with elements such as regional integration and counter-season trade and their relative evolution to be important.

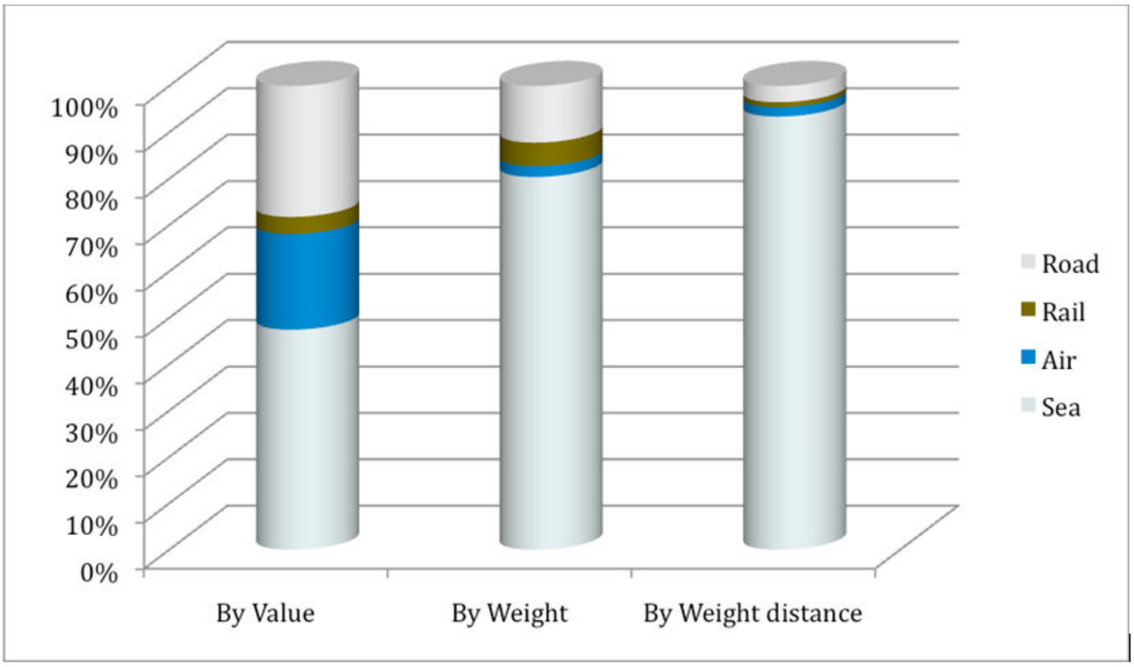


Figure 8.2. Modal split for world exports by value, weight and weight distance
Source: Hummels (2009)

Aside from transport costs, other factors are important when choosing how to transport your goods. Factors such as transport reliability, product time to market, product value, parcel size are also important. Where time is an important factor and the product is less sensitive to transport cost, transport by air is the mode of choice. Due to the low per unit transport costs, goods that travel by sea can be characterized as goods that are sensitive to these transport costs. On the other hand higher value, lower volume freight is better able to absorb this transport cost penalty imposed by transport by air (Mangan et al. 2010). Certainly in the bulk shipping sector, low value high volume goods are predominantly transported. Seaborne trade is expected to increase by 44% by 2020 and double by 2030 (UNCTAD 2008). To meet this demand, the supply of sea transport is affected by three major factors: ship operation and productivity; scrappage and delivery rates; and finally, freight rates (Stopford 2009). The availability of shipping capacity is affected by average haul and average speed of ships, port congestion and load capacity. Obviously, the ship stock availability is an important determinant as well as the revenue gained for ship owners. When considering transport and trade costs to determine where products will be sourced, its important to remember that often supply chains are competing and not individual transport modes. The interconnection of transport modes and storage and distribution centres is of greater importance than any single transporter. Certainly, the importance of ports and inter-modal connections becomes a paramount element of a value driven supply chain (Song & Carter 2009). Indeed shorter transport distances are often more sensitive to dwelling times and costs at port than shipping time and transport cost.

8.1.2 Shipping: Commodities and Markets

Traditionally, the shipping industry can be broken up into two major sectors: bulk transport and liner transport with other specialized cargo being dealt with by specialized vessels. The routes and industry make-up of these two areas are idiosyncratic and the following two sections will investigate each in turn, with a final section dealing with specialized cargo.

Bulk Transport

Shipping markets will be investigated in detail further in this chapter, but suffice it to say the bulk trade can be considered to take place in a perfectly competitive market, where hundreds of similar ships compete for homogeneous cargoes on an equal basis with little in the way of product differentiation. Bulk shipping uses large unsophisticated ships to transport goods in bulk on a contract basis. The industry is highly competitive with price fluctuating wildly even in the course of a single week (Haralambides 2007). What is a bulk commodity? Stopford (2009) defines its characteristics as enough to fill a ship, a consistent granular composition that can be easily handled with automated equipment, low value and requiring regularity of trade flow. To a first approximation, bulk transport can be divided into liquid bulk and dry bulk. Crude oil dominates both the bulk sector and shipping as can be seen in **Figure 8.3**. In this trade, most vessels are chartered from the spot market. This is largely in response to the oil crisis of 1973 and subsequent volatility in oil prices Stopford (2009) as oil shippers became more risk averse.

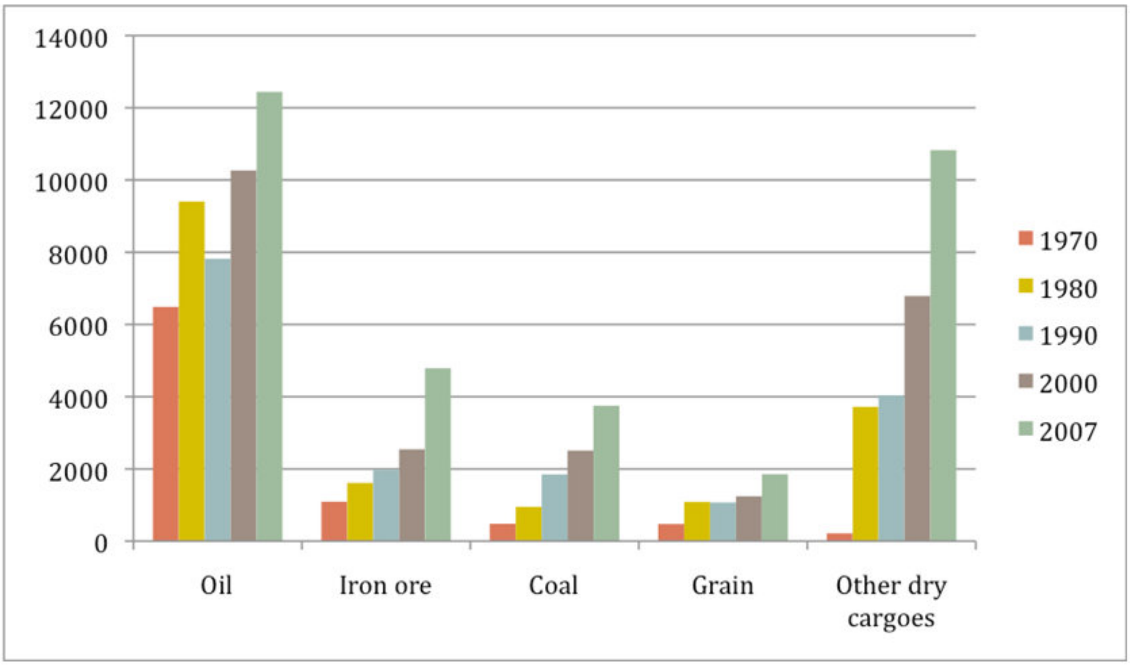


Figure 8.3. World seaborne trade in ton-miles for bulk commodities, selected years
Source: UNCTAD (2008)

Major crude oil exporters are shown geographically in **Figure 8.4**, with the largest source being the Middle East, which contains 60% of the world proven crude oil reserves (Stopford 2009). This region also acts as the swing oil supplier, thus acting as a ship demand multiplier (Stopford 2009). When demand for oil is high, marginal supply comes from this area. This demand tends to come from developed countries, i.e. North America and Europe, leading to large supply distances thus increasing the average haul compounding the ship supply pinch.

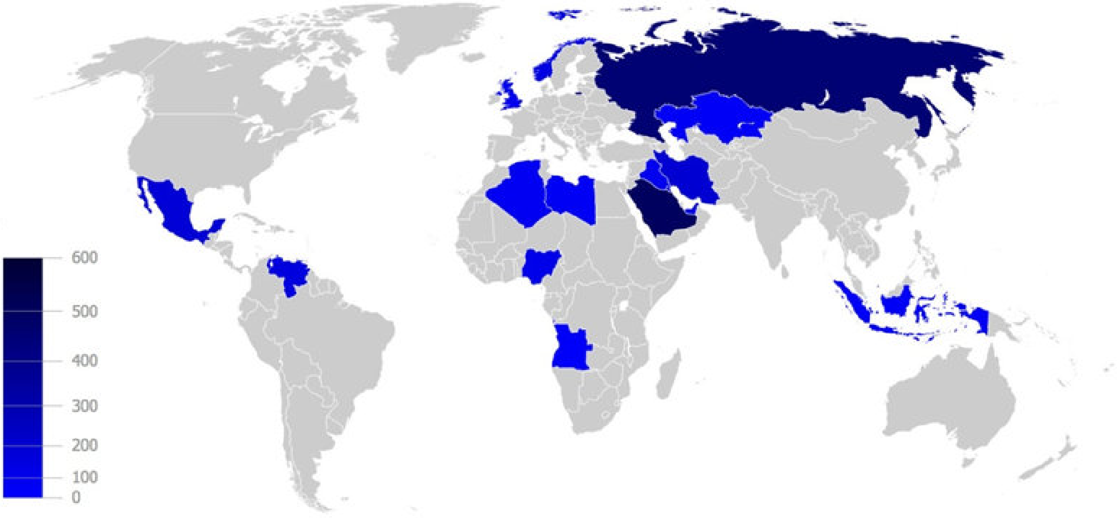


Figure 8.4. Major crude oil exporters, 2005, million tonnes of oil annually
Source: Data from BP Annual Review (cited Stopford (2009))

A selection of other bulk commodities are displayed in **Figure 8.5** with their associated source country. This figure highlights the dominance of one or two countries in each trade. Australia and Brazil dominate the export market occupying almost 70% while the United States market share is almost 40%.

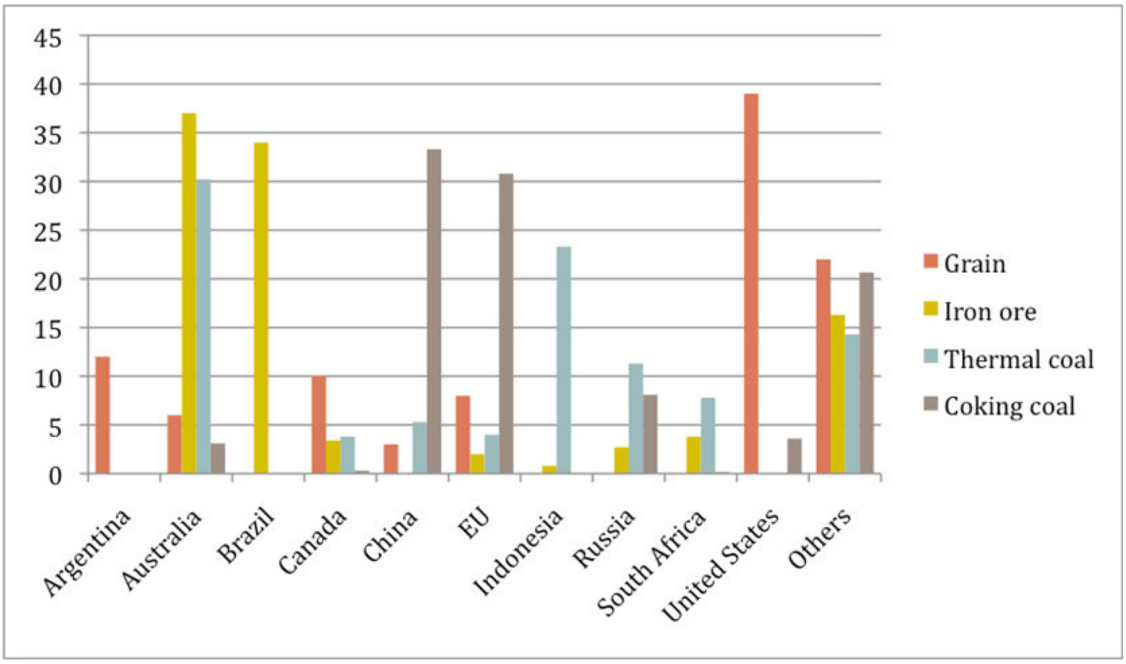


Figure 8.5. Selected world bulk commodity exporters for selected commodities as a % of total global weight of commodity exported in 2008
Source: COMTRADE (2018), UNCTAD (2008)

Bulk transport vessels are predictably large particularly for liquid bulk transport and economies of scale have been the major contributing factor behind the reduction in transport costs of shipping. However, restrictions still occur with many ports unable to cater for the larger vessels. Also, traditional way-points, for example the Suez and Panama canal, have draft restrictions.

General Cargo and the Liner Trade

General cargo accounts for about 60% of the value of goods shipped by sea (Stopford 2009), the majority of which is transported by containerized liner services. The main difference between the liner and the previously mentioned bulk sea trades is that the cargo that is shipped is predominantly less than truckload (LTL) size. Therefore, the importer would not charter a whole vessel for their cargo but would simply book space on a reliable, scheduled service as provided by the liner trade. Liner shipping is geared to the provision of regular services between specified ports, according to timetables and prices advertised well in advance (Haralambides 2007), always sailing whether filled or not. This highlights another feature of the liner trade: transport tariffs are fixed unlike the volatility of the spot market (Stopford 2009). As mentioned above, the liner trade differs from other sea transport trades in that it deals with parcels too small to fill a ship or hold including manufactures, minor bulks and reefer cargo. Liner companies operate scheduled routes using owned ships, supplemented by ships chartered in, especially during weaker market periods. Although predominantly cellular container vessels, the liner trades also include multi-purpose vessels (MPPs), tweendeckers, general cargo liners, roll-on roll off (Ro-ros) and barge carriers (Stopford 2009). However, the advantages that the containerized fleet maintains is that it allows bigger ships to be used, leading to the container-ship fleet capacity growing rapidly. This highlights again the advantage that shipping has over other modes: economies of scale lead to smaller and smaller transport costs. In recent years, the container trade has grown exponentially for several reasons. Principal among these is the move to containerization for a growing number of goods coupled with increased global trade. Indeed this is evidenced by the shift of minor bulks from the bulk trade to containerized transport (UNCTAD 2008). Secondly, the deployment of mega vessels reshaped the container shipping networks towards hub-and-spoke systems, which requires more transshipments in the hub ports (Song & Carter 2009). Each liner route can have a number of port calls thus maximizing load carried. However, this has to be offset against market demand. Competition in the liner market is severe (Stopford 2009) but is tempered by the various alliances and conferences, especially during market downturns, which insulate liner companies from some of the market risk. According to (Stopford 2009), the choice of container transport depends on a number of characteristics including reliability and frequency of service; flexibility of space available; transit time; and , of course, carrier cost. Although fixed, many factors affect the pricing of cargo carriage. Product differentiation in pricing occurs between high and low value commodities on the same route allowing product value to be expressed in the price. Customers looking to ship higher value products have a higher willingness to pay allowing low value products to travel for less, often below cost. Also, in recent times, liner companies have increased rates due to an unexpected shortage of containers (Cassidy 2010).

Specialised Cargoes and Other Trades

Each specialized trade has its own distinctive features arising from the character of the cargo and the way the transport providers have adapted to improve their performance in carrying it (Stopford 2009). Each product has specific loading/unloading requirements as well as unique storage requirements on board. Therefore, product differentiation occurs in the form of improved cargo handling, improved cargo stowage and also ability to adapt to integrate with the customers inland transport operation. Specialised vessels with their high capital costs offer economies of scale that containerships or bulkers couldnt offer for specialized cargoes (Stopford 2009). It includes transport of chemicals, LPG trade, LNG trade, refrigerated cargo and unit load cargo including roll-on/roll-off and pure car carriers. Finally, the tramp trade fills the gaps in the transport system not catered for by the bulk and liner trades. As a business model it is nearing obsolescence, although it does maintain a not insignificant portion of global trade. They depend on the spot market for voyage charters with no fixed itinerary, and as the name alludes, they work from port to port transporting whatever is available. However, they can supplement the liner trade and are often chartered to liner companies in need of extra capacity.

The Shipping Network

The overall route network is decided by the geography of trade. As indicated in **Figure 8.6**, world maritime trade is dominated by North America, Europe and Asia, being accountable for 88% of imported cargo transported by sea in 2005 (Stopford 2009). The route a shipper takes depends on relative freight rates, journey time, vessel size limitations, fuel costs, canal charges, port congesting and dwelling time and inland transport costs (Stopford 2009).

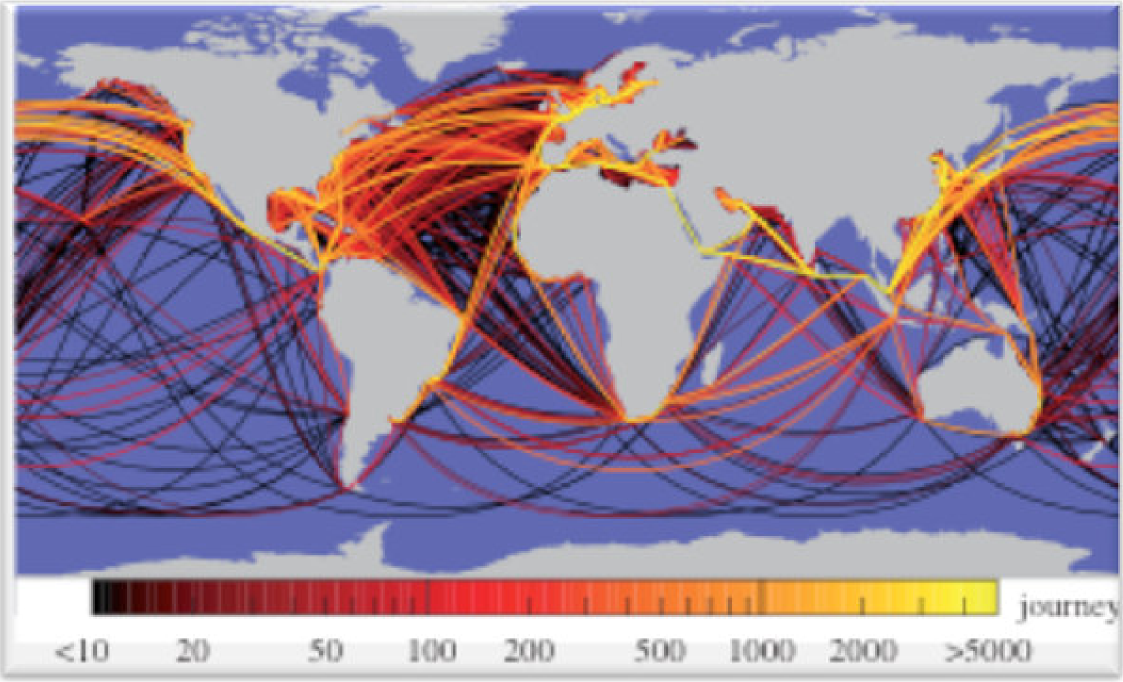


Figure 8.6. The trajectories of all cargo ships greater than 10 000 GT during 2007. The colour scale indicates the number of journeys along each route. Ships are assumed to travel along the shortest (geodesic) paths on water
Source: Kaluza et al. (2010)

The geography of liner trades can be broken into three types:

- East-West trades: The largest volume of trade occurs on east-west routes and dominate the liner business covering 39% of TEUs transported.

- North-South trades: Services cover the trade between the main industrial centres of Europe, Asia and North America and their southern counterparts covering 21% of TEUs transported.
- Intraregional trades providing feeder services for the distribution of containers brought into hubs such as Rotterdam. Liner shipping tends to follow complex networks such as hub-and-spoke, pendulum and butterfly designed to maximize capacity utilization. For the bulk trades however there tends to be a single pick up location, although there may be a multiple of drop off ports.

Economies of scale are the greatest way to reduce the price of sea transport although there are complexities. However, the economies of scale on short-haul routes are much smaller than on long-haul routes (Stopford 2009) and for short sea shipping, less time is spent at sea, so the importance of cargo handling becomes more significant. Problems exist with economies of scale on longer routes as delivery volumes decrease rapidly as the voyage length increases (Stopford 2009). There are also variations within the different categories of seaborne trade. The trading of natural resources is limited by the location of these sources. The pattern is also affected by demand: swing suppliers become more dominant in time times of high demand. Certainly it becomes more complex for derived products such as the oil products trade where trade patterns depend on refinery location, trade balancing and deficit trade.

The Shipping Markets

The provision of sea transport has developed through the interaction of four closely related markets: the freight market trades in sea transport, the sale and purchase market trades second-hand ships; the new-build market trades new ships; and the demolition market deals in ships for scrapping. Although all markets are interdependent, they are all fundamentally driven from exogeneous trade demands that act on the freight market. As alluded to in the previous section, the freight rate market, effectively the cost of transport, works differently for each of the different trades and main commodity classifications. These markets include tankers, bulk carriers, container-ships , gas tankers and chemical tankers. Their behaviour differs in the short-term but because the traders are all the in the same broad group, what happens in one sector eventually ripples through into the others (Stopford 2009). The freight market has basically two types of transaction to fix or charter a ship :

- In a freight contract, the shipper buys transport from the shipowner at a fixed price per ton of cargo. For a voyage charter, the shipowner is contracted to carry a specific cargo at a negotiated price. If the voyage is not completed within the terms of the contract (charter-party), the shipper is entitled to a claim, for example, if the voyage is delayed. A variant of the voyage charter is the contract of affreightment, where the shipowner contracts to carry regular tonnages of cargo for an agreed price per ton.

- In a time charter, the ship is hired by the day. In a traditional time charter, the ship is hired complete with crew whilst for a bare boat charter, the shipper hires the ship without crew so the shipowner requires no ship management expertise. The time charter can be over a single voyage (trip charter) or period of months whilst the bare boat charter is over a longer period, generally anything from 2 years. The biggest international charter market is in tanker and dry bulk , but there is also a significant and growing market for liner and specialist services with more than half the fleet of the top 20 service operators provided in this way by 2007 (Stopford 2009).

As discussed previously, in the liner trade, the customer does not charter the vessel as such but rents space on board for a particular journey on a scheduled service. The liner company itself may own its own vessels or may charter vessels through a time charter to service the route. Liner companies base their pricing policy on the dual principles of price stability and price discrimination (Stopford 2009). With so many customers, individual price negotiation is not an option thus once set, prices should only change for a valid reason. Product price discrimination involves charging higher rates for commodities which can bear the cost, and discount low value commodities to attract a wider range of cargoes than would be economic if there was a single standard freight charge. By increasing the volume, this permits larger ships and more regular savings. Price discrimination also occurs between customers, where larger or regular customers receive discounts through service agreements. Companies involved in the liner trade engage in alliances and conferences, although this is viewed as anti-competition and is thus being phased out. The bulk and tanker shipping markets most closely resemble a perfect competition structure where companies have little product differentiation and an individual companies pricing strategy has little effect on the market. The participants in the sale and purchase market are the same mix of shippers, shipping companies and speculators who trade in the freight market. A ship may be sold with or without the benefit of an ongoing time charter. A ship may be sold for a number of reasons: company policy of replacing ships at a certain age, shipowners may be changing their trade; the shipowner believes that prices are about to fall; or, finally, there is a distress sale in which the shipowner sells the ship to meet day-to-day commitments. Transactions are carried out through shipbrokers, often more than one. The sale and purchase market thrives on price volatility with asset play profits earned from well-timed buying and selling activity an important source of income for shipping investors. Freight rates are the primary influence on ship price. Ship price is also affected by age, with ships depreciating at an average rate of 5-6% per year (Stopford 2009). Similar to the sale and purchase market, demand for new ships is driven by freight rates, financial liquidity of buyers, availability of credit and expectations. It is also contingent on the price of modern second-hand ships. Sometimes, it is cheaper to buy a new ship than one on the second-hand market due to the shipbuilding time with the ship not available for 2-3 years from the contract date, by which time conditions may have changed. The supply of ships is limited by production costs, number of product slots available and the size of the orderbook. In the demolition market the customers are the scrap yards, with largest buyers form the Far East, which dismantle the ships and sells the materials. Prices are dependent on the availability of scrap and the demand for scrap metal. Prices also vary based on type of ship, which may have different suitability for scrapping.

8.1.3 Risk Management in the Shipping Industry

Risk management describes how uncertainty surrounding hazards are identified, assessed and dealt with. The following section outlines what these hazards are, and how they are managed within the industry by the different players.

The principal risk in shipping is derived from freight rates, in other words the financial loss arising from imbalances between the supply and demand for sea transport (Stopford 2009). All other hazards, be they physical, logistical, operational etc., eventually cascade through and are reflected in market changes. In shipping, the primary risk takers are the shipowners and the cargo owners or shippers and between these two risk is shared by adjusting supply to demand. The platform on which the risk sharing takes places is the shipping contract or charter party. The first case is where the cargo owner is both shipper and ship owner. In this instance the cargo owner is confident about the long term sustainability of their cargo and hence optimistic about adopting the risk. At the other extreme, there is the spot market where the ship owner, as a separate entity, assumes all the risk. In this case, the cargo owner, employs the shipowner to transport their goods as and when they need it. A shared risk situation occurs through the period market and freight forward agreements. The period market involves the cargo owner taking long term charters from independent owners. Shippers pay an agreed daily rate, regardless of whether the ship is needed, whilst leaving residual risk with shipowners.

A relatively new innovation in the freight market are the freight derivatives. This market emerged to allow hedging of risk by compensating for the cost of a large adverse movement in the variable being hedged. Freight derivatives, or freight forward agreements (FFAs), rely on indices which accurately reflect the risk being swapped, examples of which are the Baltic Freight Index (BFI) and the Baltic Dry Index (BDI). In freight forward agreements, the shipper or ship owner hedges against adverse future freight rates. Shipping markets are idiosyncratic. Different risk preferences exist within shipping and they price risk differently to financial institutions. Financial institutions approach risk by concentrating on the relationship between risk and return and require more volatile investments to pay higher returns. Stocks with a bigger standard deviation are expected to pay higher return and vice versa. In shipping, because of the high fixed costs, capital management dominates the business and therefore high risk and low returns distinguishes shipping from other investments. However, earnings before interest and depreciation for shipping companies are rarely negative. Capital investment in ship stock dominates the annuitized costing for a ship. Therefore, as long as investors have patience, returns are there to be made. Due to capacity variations which directly affect the rate of shipping investment it is difficult to determine what the normal profit should be.

For example, shipowners may demand a higher return when they charter their ship for 10 years to compensate for the loss of flexibility. Shipping entrepreneurs are attracted to the high risk options due to the volatility of the shipping cycles and its other characteristics, especially the liquid market for shippings assets which means that once in a while they can make fabulous profits (Stopford 2009).

However, it is the high fixed costs and long lead in times of ship building that makes it hard for companies to adjust their capacity to market downturns. Pompeo & Sapountzis (2002) found that the industry has been poor at managing risk: strong growth in trade has masked inefficient practices that havent maximized profitability. 2003 saw the beginning of a boom period for shipping with investors trebling their capital in five years. However, the recent global downturn has affected the industry as much as any other.

Market cycles are a key feature of the shipping industry and indeed their short period (typically seven years) encapsulates the volatility of the market. The framework of each cycle is set by economic fundamentals: economic conditions, the business cycle, trade growth and the ordering and scrapping of ships are the fundamental variables which can be analysed, modelled and extrapolated. In this sense, shipping market cycles are composed of three fundamental cycles: long-term cycles driven by technical, economic or regional change; short term cycles or crises that run at a period of seven years; and finally, seasonal cycles that capture variations in commodity demand and supply throughout the year (Stopford 2009).

In an evolving market cycle, shipping companies move their ships in and out of layup to cope with changes in demand. In the liner trade, companies form alliances to increase capacity utilization on routes and allows them to maintain market share. However, in the long run, the four shipping markets can work against each other. We can see how this happens when we consider that short term cycles have traditionally had a seven year period and the lifetime of a ship is around 25 years. If ships are ordered on the new build market towards the end of a peak period they will not be delivered until the market has collapsed as the delivery of time is in the order of two years.

There are also several contract anomalies that prevent shipping companies from hedging their risk. Although customers break their contracts without recompense for the shipowner, the shipowner cannot do the same this is mostly to do with the lack of a system for compensating customers with non-urgent cargoes that could comfortably sail on the next available ship (Pompeo & Sapountzis 2002).

A significant risk with the shipping industry is accorded to trade imbalances. This leads to capacity utilization problems with vessels on return journeys and as well as empty container repositioning issues. Song & Carter (2009) found that the cost of repositioning empty containers was 27% of the total world fleet running cost and that overcapacity continues to be a problem.

Ultimately, shipping has no inherent value as it is a derived demand from the need for transport of goods. Thus, changes in patterns of trade could have significant impacts as average hauls decrease or increase accordingly, thus affecting the shipping demand/supply ratio. Such a change occurred during the Suez canal crisis of the 1950s, when 46 ships were sunk by Egypt to block the Suez canal. This resulted in the need for ships to transport around the cape a considerable longer distance to European and North American markets and thus increased the average haul and freight rate considerably.

Iron ore: A Market in Transition

The recent increases, until the crash of 2008, in demand for iron ore, particularly from China has led to demands in contract changes by iron ore suppliers. For years, iron ore was plentiful leading to stable price and contracts were based on an annual benchmark system as a corollary. However, from 2000 to 2008, Chinas iron ore demand had grown to such an extent that the 40 year old system of annual contracts has been abandoned (Blas 2010) at the behest of the suppliers. Contracts are to be negotiated seasonally eventually leading to a spot price. However, since 2008 the market has changed significantly with the Baltic Dry Index, which measures the rates charged for chartering the bulk industry vessels, falling by almost 60% in its longest streak of consecutive declines for nine years (34 days as of July 14th).Again, this decline has mostly been driven by a lack of demand from the Chinese market.

Figure 8.7. Baltic Exchange Dry Index January 1995 July 2010
Source: Exchange (2010)

8.2 Framework and Methodology

8.2.1 Introduction and Approach: Dealing with Uncertainty

The current prevailing philosophy for tackling climate change is a parallel path approach: mitigation or adaptation. However, each of these approaches is treated virtually in isolation from the other. However, there may be cases where mitigation policies weaken resilience to climate change thus affecting the ability to adapt. As discussed in the introduction, the purpose of this research is to establish the vulnerability of the shipping industry to climate change impacts and mitigation measures through an understanding of the sectors scope and activity and the development of potential impact pathways. It does not attempt to determine the likelihood of any particular impact being realized but identifies where and how the sector may be vulnerable should such an impact arise or combination of impacts arise. The merits of this approach become apparent when considering the difficulty in associating changes in the shipping sector with a specified number of degrees of global warming or with a particular time horizon, when so many of the main drivers of changes in the shipping sector are not directly climate related but climate associated. Also, the nature of climate change is that it is a wicked problem with no solution as such but rather a condition that must be managed (Prins et al. 2010). It is believed that adaptation and mitigation in order to be effective must be complimentary. **Figure 8.8** outlines the general approach of this research. The following sections discuss each facet of the research.

Figure 8.8. Schematic view of methodology

The approach seeks to elucidate areas of weakness and resilience within the sector rather than determining probability of events of varying strength. This obviously overcomes the high levels of uncertainty related to this area of research. Uncertainty can be identified in a number of areas of this research:

- Climate change science: Non-linear and stochastic elements of the climate system and our own inadequacies in modelling it effectively result in an opaque image of future climate. Indeed, it is not just this initial layer of uncertainty but how it cascades through ecosystems and human systems and their co-evolution that prevents any accurate establishment of climate change impacts and their responses.
- Global development: Predicting how economies will develop through to 2050 is a highly uncertain task
- Shipping sector: It remains difficult assessing the current state of the shipping sector due its inherently global nature and the lack of data in many areas. Consequently, predicting how it will change in the future from an uncertain baseline makes the task rather difficult. However, it is a derived demand and therefore some assumptions can plausibly made in terms of how the route network would develop, the uptake of new technology to increase efficiency etc.

These barriers are dealt with, and to some extent overcome, through a number of ways. First of all, the research is necessarily qualitative, thus not necessitating high level data and its associated uncertainty. Secondly, climate change impacts and their associated impact vectors are assumed to have occurred in a range of what if scenarios. Again, this approach has been adopted for predictions of global development, where the IPCC SRES scenarios have been used. Also, trade and shipping patterns are assumed to have changed according to their respective development scenario. Technological innovations to improve resilience are not considered to have occurred in determining the vulnerability map but are taken in account, where suitable, in the discussion following the results section.

8.2.2 Establishing Impact Categories

The following sections outline the impact variables used in this chapter: climate change impacts, climate change impact vectors, climate change mitigation measures and global development scenarios.

Climate Change

Table 8.1 below gives a brief introduction to the climate change impacts considered in this chapter. Although projected impacts vary by SRES development scenario, the most adverse effects of climate change are considered in this chapter. Therefore a single worst case, albeit qualitative, is taken when developing the impact pathways.

Variable	Projection
Mean temperature	Increases in global mean surface air temperature (SAT) continuing over the 21st century. By late century (2090-2099), differences between scenarios are large, and only about 20% of that warming arises from climate change that is already committed. Geographical patterns of projected SAT warming show greatest temperature increases over land and at high northern latitudes, and less over the southern oceans and North Atlantic.
Temperature extremes	It is very likely that heat waves will be more intense, more frequent and longer lasting while cold episodes are projected to decrease significantly. Almost everywhere, daily minimum temperatures are projected to increase faster than daily maximum temperatures, leading to a decrease in diurnal temperature range. Decreases in frost days are projected to occur almost everywhere in the middle and high latitudes, with a comparable increase in growing season length.

Mean precipitation	Precipitation is projected to generally increase in the areas of regional tropical precipitation maxima (such as monsoon regimes) and over the tropical Pacific in particular, with general decreases in the subtropics, and increases at high latitudes as a consequence of a general intensification of the global hydrological cycle. Globally averaged mean water vapour, evaporation and precipitation are projected to increase. Precipitation extremes and drought Intensity of precipitation events is projected to increase, particularly in tropical and high latitude areas that experience increases in mean precipitation. Even in areas where mean precipitation decreases (most subtropical and mid-latitude regions), precipitation intensity is projected to increase but there would be longer periods between rainfall events. There is a tendency for drying of the mid-continental areas during summer, indicating a greater risk of droughts in those regions. Snow and ice Glaciers and ice caps lose mass owing to a dominance of summer melting over winter precipitation increases.
Sea level	Sea level is projected to rise between the period 1980-1999 and the end of this century for each scenario by up to 0.59m (A1T upper bound). Thermal expansion is the largest component contributing 70 - 75% of the central estimate. Glaciers and ice caps are also projected to contribute positively to sea level. Greenland Ice Sheet is not expected to contribute to sea level rise until after this century and the Antarctic Ice Sheet is projected to remain too cold for widespread surface melting.
El Nio	Continued El Nio-Southern Oscillation (ENSO) inter-annual variability in the future no matter what the change in background conditions. Monsoons An increase in precipitation is projected in the Asian monsoon. And the southern part of the west African monsoon with some decrease in the Sahel in northern summer, as well as an increase in the Australian monsoon in southern summer in a warmer climate. However, the uncertain role of aerosols in general, and carbon aerosols in particular, complicates the nature of future projections of monsoon precipitation, particularly in the Asian monsoon.
Sea Level Pressure	Poleward shift of the storm tracks of several degrees latitude with a consequent increase in cyclonic circulation patterns over the high-latitude Arctic and Antarctic regions. There is a likely increase of peak wind intensities for hurricanes and typhoons and notably, where analysed, increased near-storm precipitation in future tropical cyclones.
Mid-latitude storms	Model projections show fewer mid-latitude storms averaged over each hemisphere, associated with the poleward shift of the storm tracks that is particularly notable in the Southern Hemisphere. The increased wind speeds result in more extreme wave heights in those regions.

Atlantic Ocean Meridional Overturning circulation (MOC)	It is very likely that the MOC will slow down during the course of the 21st century. In spite of this slowdown, there is still warming of surface temperatures around the North Atlantic Ocean and Europe due to the much larger radiative effects of the increase in greenhouse gases.
Climate change commitment	If greenhouse gases were stabilized, then a further warming of 0.5 would occur. If greenhouse gas concentrations could be reduced, global temperatures would begin to decrease within a decade, although sea level would continue to rise due to thermal expansion for at least another century.

Table 8.1. Summary of climate change projections. Source: Adapted from Meehl et al. (2007)

In many cases, the effects of climate change may not be felt as a direct result of the projections outlined above, but in fact manifest through changes in other dependent systems. The following section outlines these, in what are termed ”climate change impact vectors” for the purpose of this chapter.

Climate Change Impact Vectors

Many climate change impacts will not be felt directly by the shipping sector but instead these impacts will cascade through other systems. These are considered in four broad categories:

- Agriculture, forestry and ecosystems;
- Water resources;
- Human health;
- Industry, settlement and society.

These have been derived from the IPCCs fourth assessment report (Meehl et al. 2007), and selected due their perceived link with the shipping sector. A brief outline of projected changes under these headlines is given below:

Agriculture, Forestry and Ecosystems Agriculture and forestry is expected to change dramatically as a result of climate change. Currently, about 40% of the Earths land surface is managed for crop-land and pasture (Foley 2005) and in developing countries nearly 70% of people live in rural areas where agriculture is the largest supporter of livelihoods (Easterling 2007). According to Easterling (2007) mid to high-latitude regions could expect moderate benefits to crop and pasture yields while lower latitudes and seasonally dry regions could expect to experience a reduction in yields as even a slight increase in warming has adverse effects. The International Food Policy Research Institute (Nelson et al. 2010) found especially pronounced reductions in crop production in Sub-Saharan Africa and South Asia. More significantly, is that increased frequency of heat stress, droughts and flooding events reduce crop yields and livestock productivity beyond the impacts due to changes in mean variables alone, creating the possibility for surprises (Easterling 2007). In summary, most developing countries are projected to become increasingly more reliant on food imports (Easterling 2007).

Water Resources The balance of water demand and water availability is likely to be a defining area in years to come. Currently, irrigation accounts for over 70% of global water withdrawals and indeed is expected to be the sector most affected. Increases of the order of 10% are projected for China and India, where most irrigated land is located, by 2020 (Kundzewicz Z.W. & Shiklomanov 2007). But water is also used for hydro-power production, industrial processes and indeed domestic use. It is in the domestic and industrial sectors where the largest demand increase is expected with estimates of up to 83% increase by 2050 (Kundzewicz Z.W. & Shiklomanov 2007). Most importantly, areas of the world dependent on snow melt for freshwater supply are projected to suffer from variations in availability. The corollary is that climate change is likely to affect river discharge, with low flow conditions affecting navigation along with other effects on in-stream and out of stream areas. Examples of this kind are already occurring with wells and tributary rivers of the Yangtze in China drying up (Cyranoski 2005), affecting both populations and industry that depend on uninterrupted flow. These reduced flow events cause sand and mud to be deposited in areas of rivers that can later lead to flooding events due to a reduction in the channel cross section.

Human Health According to Costello et al. (2009), human health may experience severe effects of climate. These effects are projected to be experienced unevenly throughout the globe with developing countries suffering more as illustrated through the effective image in **Figure 8.9** below.

Figure 8.9. Regional distribution of four climate-sensitive health consequences (malaria, malnutrition, diarrhoea and inland flood related fatalities). Source: Costello et al. (2009)

Indeed, the World Health Organisation estimates that the warming and precipitation trends due to anthropogenic climate change of the past 30 years already claim over 150,000 lives annually (Patz et al. 2005).Climate mediated infectious disease,along with heat-related mortality, is of particular concern for global communities as diseases vectors extend into northern latitudes. In fact, it is not just human health that is of concern for the shipping sector. It is the incidence of climate-mediated infectious diseases for livestock that is also of concern. An example of this is beef exports from Brazil. Historically, beef exports were the affected by the presence of foot and mouth disease (Kaimowitz, D, Mertens, B., Wunder, S. & Pacheco 2004); prior to 1998, no Brazilian state had been certified as being free of foot and mouth. However, a drive for certification of disease free areas led to a sharp upward trend of beef export.

Industry, Settlement and Society The association of this area with climate change is more complex than previously discussed vectors. Changes in climate can result changes in demand for energy services or public health services as well as changes in physical infrastructure (Wilbanks, T.J., P. Romero Lankao, M. Bao, F. Berkhout, S. Cairncross, J.-P. Ceron, M. Kapshe et al. 2007). Again, there are disparate effects between developed and developing regions where industrialized nations are projected to suffer greater monetary damages while developing regions are projected to suffer greater human damages (Wilbanks, T.J., P. Romero Lankao, M. Bao, F. Berkhout, S. Cairncross, J.-P. Ceron, M. Kapshe et al. 2007). The same report found that both actual climate change impacts and a perception of of future impacts or regulatory measures could affect trade and investment. Climate change could change trade through the reshaping of regional competition for climate-sensitive production as well as a lack of capacity to cope with extreme events.

Climate Change Measures

Current international efforts at determining a unified mitigation policy have been slow at best a characteristic of all international agreements particularly in a UN framework. Within the shipping industry, the IMO is seen as the only platform at which emissions from shipping should be addressed. However, there is a cognitive dissonance between IMO principles and those of the UNFCCC. The UNFCCC principle of common but differentiated responsibility is fundamentally at odds with the IMOs principle of no more favourable treatment. This is leading to slow progress at the Marine Environment Protection Committee (MEPC), the committee charged with establishing an agreement on emissions reductions for shipping (Meade 2010). However, some progress has been made in establishing an energy efficiency design index (EEDI) for new build vessels due to become mandatory in 2014. Also in effect at a voluntary level are an operational index (EEOI) and a ship energy efficiency management plan (SEEMP). Discussions on the merits of an emissions trading scheme (ETS) are also taking place at the MEPC. The inclusion of shipping in a global ETS or remaining a closed system, designation of the responsible entity, setting of the cap trajectory and the method of initial allocation of credits are all contentious elements of such a system and have profound consequences for the industry (Faber, Freund, Kopke & Nelissen 2010). An open emissions trading scheme, in which credits can be traded across different sectors is more likely to result in a more stable carbon price as it is less susceptible to sector specific market cycles (Faber, Markowska, Eyring, Cionni & Selstad 2010). In such an open system, there would be a greater credit transfer to shipping as shipping would require a high carbon price to drive significant change. According to recent research, it would require a carbon price of $1000 to reduce emissions by 50% in shipping (Anger, A., Barker, T., Pollitt, T., Lindstand, H., Eyring, V. Lee 2010). For the purpose of this research, what is considered is how an emissions reduction initiative would manifest itself. There a number of ways through which this would occur:

- Increased transport costs resulting from either an emission trading scheme or through a carbon tax on fuel. In both cases, it is assumed that the carbon price or tax would increase over time.
- Geographically specific escalating transport costs resulting from geographically disparate mitigation policies. For example, the inclusion of shipping within the EU ETS.
- Higher fuel price and higher carbon price/tax will have different effects on different vessel types (Faber, Freund, Kopke & Nelissen 2010).

Development Scenarios

As discussed above, these scenarios do not serve as predictions or even best guesses of how the future might unfold, but simply alternative images (IPCC 2000). Additional climate initiatives are not included, meaning no scenario is included that explicitly assumes implementation of the United Nations Framework Convention on Climate Change (UNFCCC). Adopted story-lines are A1, A2 and B2 as these serve as competing, alternative development images.

A1 Storyline The A1 storyline is a case of rapid and successful economic development, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Regional average income per capita converges with current distinctions between ″poor″ and ″rich″ countries eventually dissolve. Other major themes include convergence amongst regions, capacity building, and increased cultural and social interactions, with substantial reduction in regional differences in per capita income.

A2 Storyline This storyline describes a very heterogeneous world where the underlying theme is self-reliance and preservation of local identities against a backdrop of increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than other story-lines.

B1 Storyline The central elements of the B1 future are a high level of environmental and social consciousness combined with a globally coherent approach to a more sustainable development. Heightened environmental consciousness might be brought about by clear evidence that impacts of natural resource use, such as deforestation, soil depletion, over-fishing, and global and regional pollution, pose a serious threat to the continuation of human life on Earth. In the B1 storyline, governments, businesses, the media, and the public pay increased attention to the environmental and social aspects of development. Technological change plays an important role.

8.2.3 Shipping Receptor Categories

The effects of the cumulative impacts described above are considered under a number of shipping receptor categories.These are outlined below along with examples of how these categories may be affected:

- Shipping network and supply chain
  - Forced alterations to network
  - Effects on reliability of supply chain
- Port and inter-modal connections
  - Loading and unloading of cargo
  - Storage of cargo
  - Transfer and location of inland transport network
- Ships and ship operation
  - Running of auxiliary services on board (for example refrigeration on reefers)
- Demand for shipping
  - Reduced demand for tankers
- Shipping supply
  - Reduced scrappage and delivery rates
- Shipping players and market structure
  - Unequal attribution of market risk between players
  - Distorted market competition

8.2.4 Impact Pathways: Interlinking Categories

Figure 10 illustrates how the elements highlighted in the previous sections are combined to create impact pathways. Climate change impacts can affect shipping both through direct effects and through systems that societies depend on. These, coupled with global development scenarios and various climate mitigation measures combine to create compound impacts on the shipping system. Coupled with this, impacts vary in terms of time horizon by appearing as shocks or long running trends and indeed the effects can be short term or long term and can vary geographically. How these impacts manifest themselves on the shipping sector are investigated under the titles shown in **Figure 8.10**, firstly through direct impacts. However, there are also issues of contagion, where impacts felt in one sector of shipping can cascade through to other areas. On consideration of impacts, the sector exposure is scored according to the following section. Where particular pathways have additional information not contained in their table. In determining resilience, each development scenario is considered separately as it is considered that each scenario may have a different resilience to establish a resilience score for each scenario. It is only the resilience that can vary by score, while the exposure looks at a single discrete set of impacts and not impacts specific to each development scenario. The following section outlines how the scores of the resilience and exposure are combined to determine vulnerability.

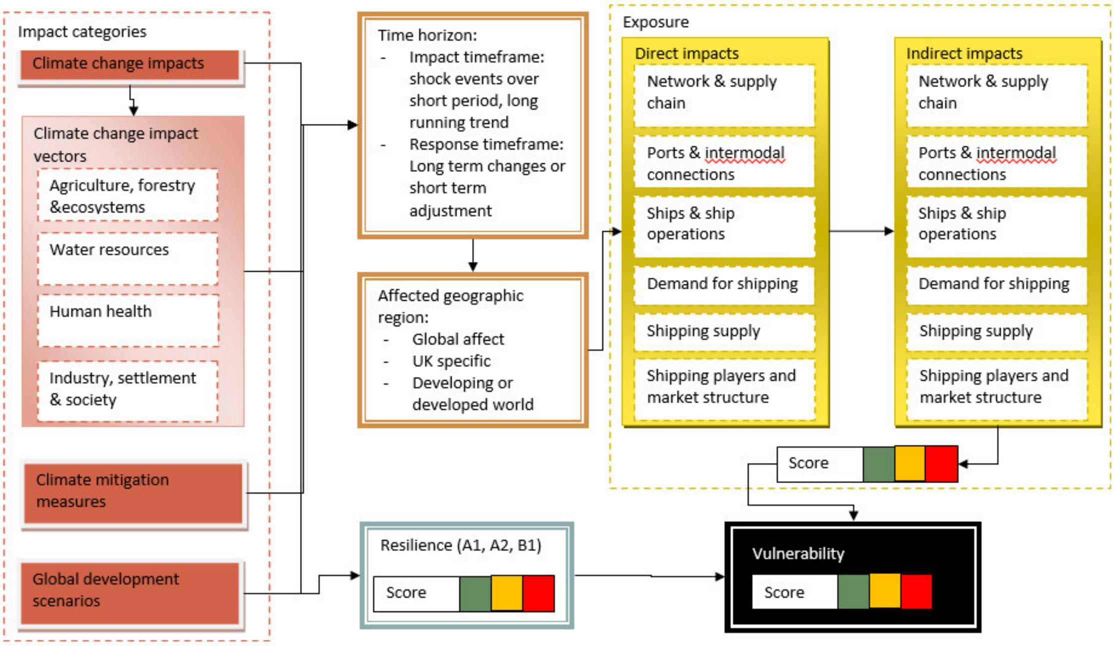


Figure 8.10. Interlinking Pathways

8.2.5 Establishing and Mapping Vulnerability

Resilience and vulnerability are considered in a number of contexts

- Shipping as product: In this case, the service that shipping provides, i.e. transport of goods, is adversely affected. In other words, the services becomes interrupted by delays, inflexibility of service, reliability reduces etc.
- Market structure: Any impacts that affect market structure or typical market functioning such as increased volatility or company consolidation is considered adverse and scored accordingly.
- Interlinking shipping, trade and global resilience: In the case where shipping itself is not affected negatively but facilitates adverse changes on countries such as disproportionate benefits to developed economies.

Resilience and exposure are scored as indicated in **Figure 8.11** and vulnerability is thus calculated as per the vulnerability map. These are then combined according to the traffic light mapping system shown below in **Figure 8.11**.

Exposure	Resilience: High	Resilience: Medium	Resilience: Low
Low	🟩	🟧	🟧
Medium	🟧	🟧	🟥
High	🟧	🟥	🟥

Figure 8.11. Mapping Vulnerability

A final element that requires outlining is the treatment of the UK within the global context. Shipping, by nature, is a global sector, therefore disentangling the UK from the global sector is difficult. Accordingly, vulnerability and resilience are considered in the global context, but where impacts or vulnerabilities are specific to the UK then they are explicitly dealt with as UK specific. With any changes in a sector there are opportunities as well as constraints. These will be discussed in the opportunities section following the analysis.

8.2.6 Limitations and Assumptions of the Approach

The approach taken in this chapter is necessarily qualitative and thus lacks in depth quantitative analysis. As alluded to previously, the reason for this is to highlight areas of further research without being hindered by data availability and time constraints. It allows conceptual consideration of the issues to serve as a basis for further work. As discussed, the development scenarios do not take into consideration any climate mitigation measures. However, mitigation measures are included in the analysis. Therefore, internal feedback from mitigation policies that affect development are not considered although in reality they would be expected to be significant. Some of these internal feedback are highlighted in the analysis, the feedbacks are not exhaustive. Commodity demands for the UK are assumed to remain in the same ratio as they are now, however for developing regions who 's GDP converges with the developed world, it is assumed that their consumption preferences would echo the current developed world, exemplified by a shift towards a meat based diet.

8.3 Results

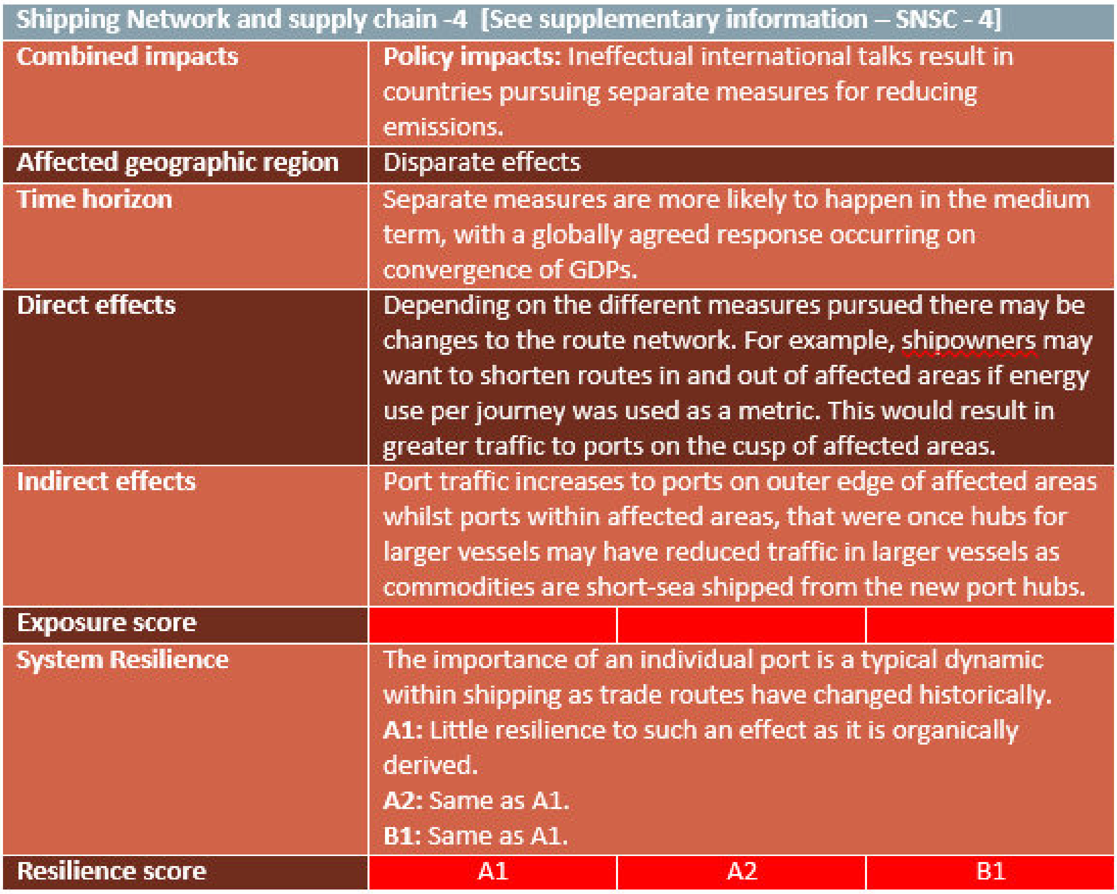
8.3.1 Core Analysis: Establishing Vulnerability

Each impact pathway is described in the following tables (where each table is assigned a unique id in the title for referencing):

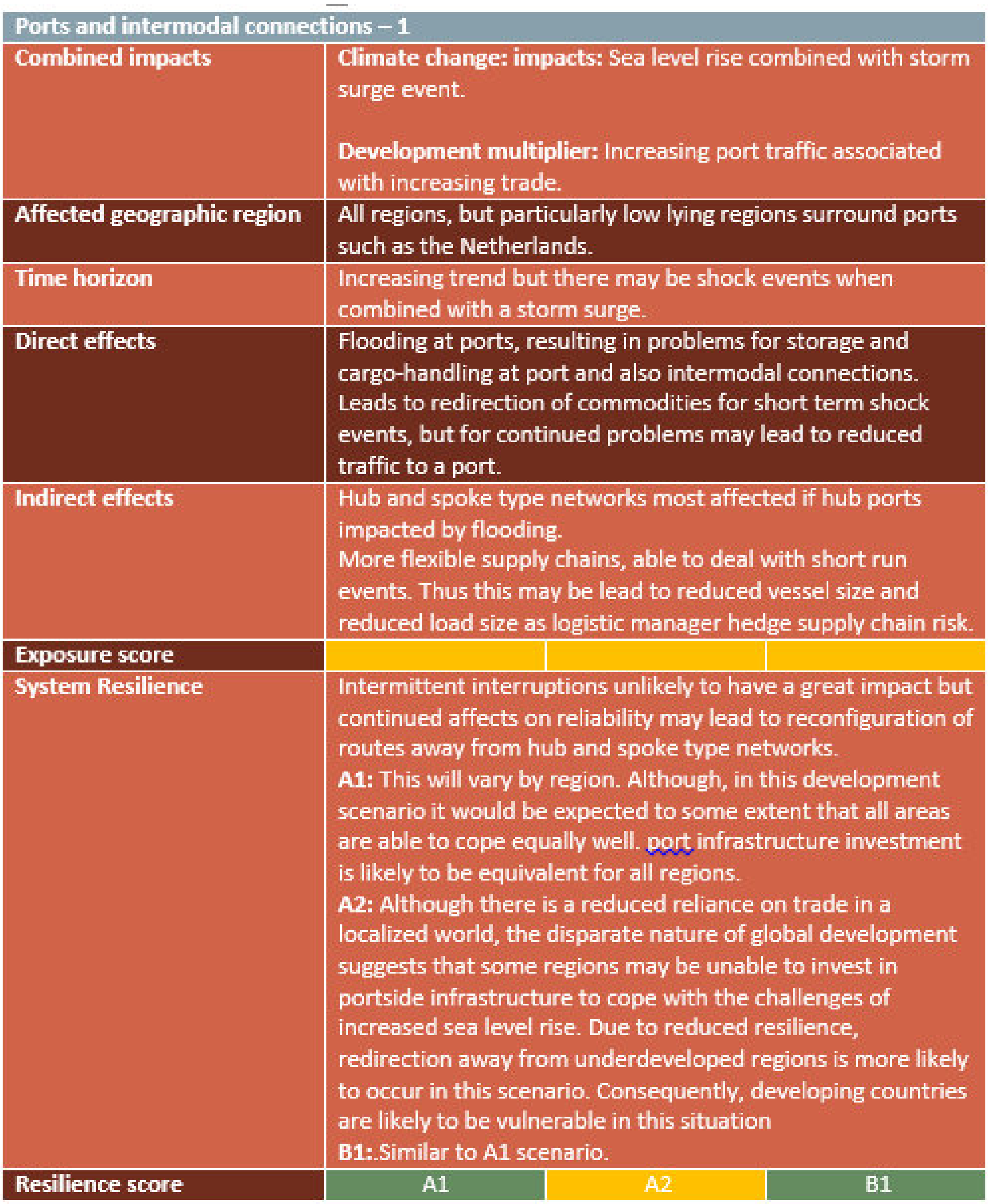
Shipping Network and supply chain – 1 [See supplementary information [SNSC - 1]]			
Combined impacts	**Climate change: impacts:** Changes in storm tracks and tropical cyclone activity. **Development multiplier:** Increased North-South traffic due to increased trade involving developing countries, particularly latin American countries.		
Affected geographic region	Vessels affected are those pass between 10° and 30° of the equator.		
Time horizon	Hurricanes are short term events, thus response will be short term. Although they are also seasonal, continued interruptions from increased intensity could lead to long changes in the route network.		
Direct effects	What routes pass by there? How do they currently deal with it. May result in seasonal route changes in the long term.		
Indirect effects	Rerouting causing an increase in the average haul, thus creating a squeeze on available shipping capacity.		
Exposure score	🟥	🟥	🟥
System Resilience	North South routes are likely to be mostly effected. Other areas affected are likely to be east west trade that traverse straits in South East Asia. Interruptions to trade and thus shipping capacity and reliability may result in modal shifts for some commodities during hurricane seasons. **A1:** Increased trade results in less resilience to continued interruptions. **A2:** As areas are less reliant on global trade, and there is a slower convergence of GDP, it is unlikely to be as affected as A1, but susceptible none the less. **B1:** Similar to A1 scenario.		
Resilience score	A1	A2	B1

Shipping Network and supply chain -2			
Combined impacts	**Impact vectors:** Increasing temperatures in northern latitudes, requires greater energy use for summer periods for residential and commercial air conditioning. However, this would be offset during the winter months by reduced heating needs. **Development multiplier:** Increasing global population and convergence of GDP results in increased demand for energy resources		
Affected geographic region	All regions.		
Time horizon	Long run trend		
Direct effects	Increased demand for shipping transport for crude oil and coal. Unclear as to whether Middle East being the marginal supplier has an increase on average haul as increasing demand from Asian countries offsets the demand from Europe and the US.		
Indirect effects	Marginal suppliers of primary energy fuels, such as the Middle East for oil, increasingly dominate the network increasing the average haul and thus squeezing shipping capacity.		
Exposure score	🟩	🟩	🟩
System Resilience	Transport costs would be expected to increase, particularly as supply pinches. **A1:** Less sustainable world requires greater amounts of fossil fuel based energy commodities. **A2:** As areas are less reliant on global trade, and there is a slower convergence of GDP, it is unlikely to be affected. Less affected than A1, but likely to see route changes, though this is not considered adverse. **B1:** Similar to A1 scenario. Less effected than A1 as sustainable sources of energy supply are projected to have being pursued.		
Resilience score	A1	A2	B1

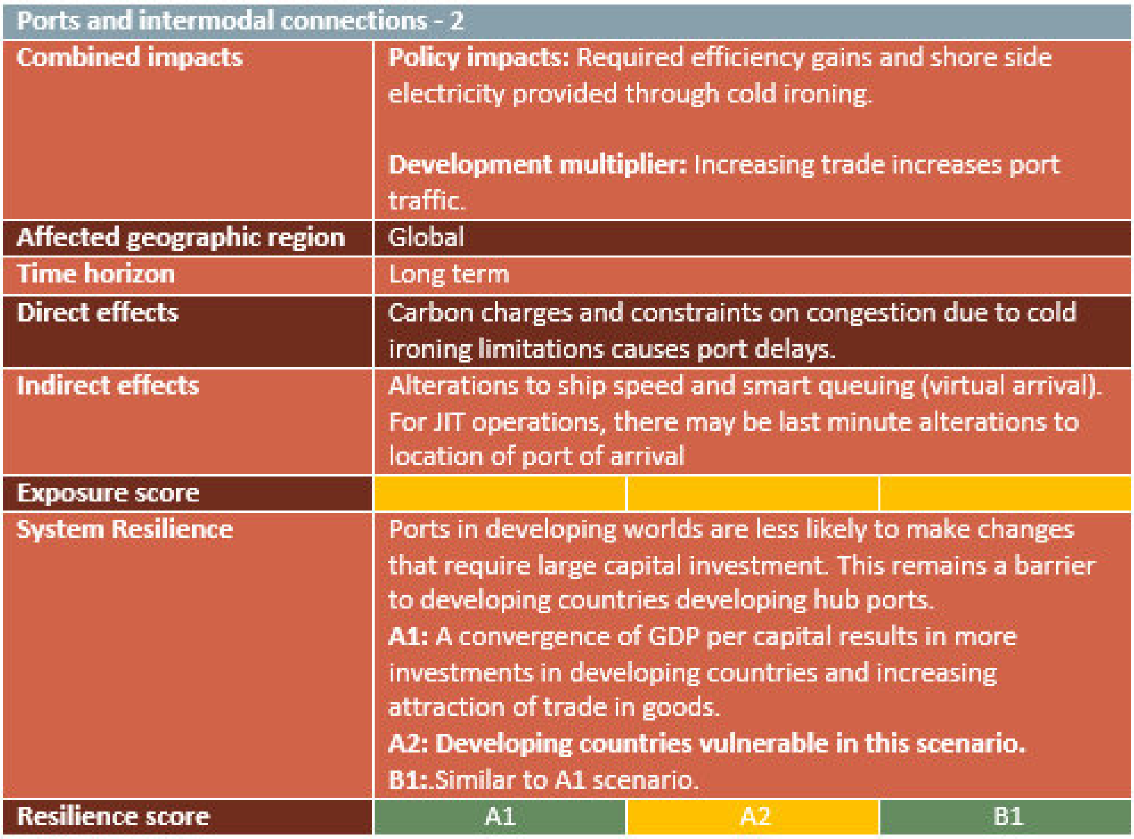
Shipping Network and supply chain -3			
Combined impacts	**Policy impacts:** Global emissions trading scheme resulting in an increasing carbon (particularly in a closed system) price manifesting as greater transport costs.		
Affected geographic region	All regions.		
Time horizon	Long run trend		
Direct effects	As transport costs increase, shipping distance becomes more significant in the prices of commodities. This results is less demand for goods shipped over a greater distance. More goods are shipped intraregionally. Routes where the pricing is based on marginal demand would become less profitable. Cost pass through would occur on routes where pricing is based on marginal costs.		
Indirect effects	Some consolidation within the industry would occur as larger companies would swallow costs in the short term to maintain market share. It would also restrict access to the market for new entrants.		
Exposure score	🟥	🟥	🟥
System Resilience	High value goods would be less affected as transport cost would remain a small fraction of overall costs. Some substitution or reduced demand would occur for transport cost sensitive goods. **A1:** Most affected by the increased transport costs. **A2:** Less affected than A1 because of local focus. However, for goods such as fruit and veg where substitution is not possible, it would be as vulnerable as A1. **B1:** Most resilient due to sustainable living.		
Resilience score	A1	A2	B1



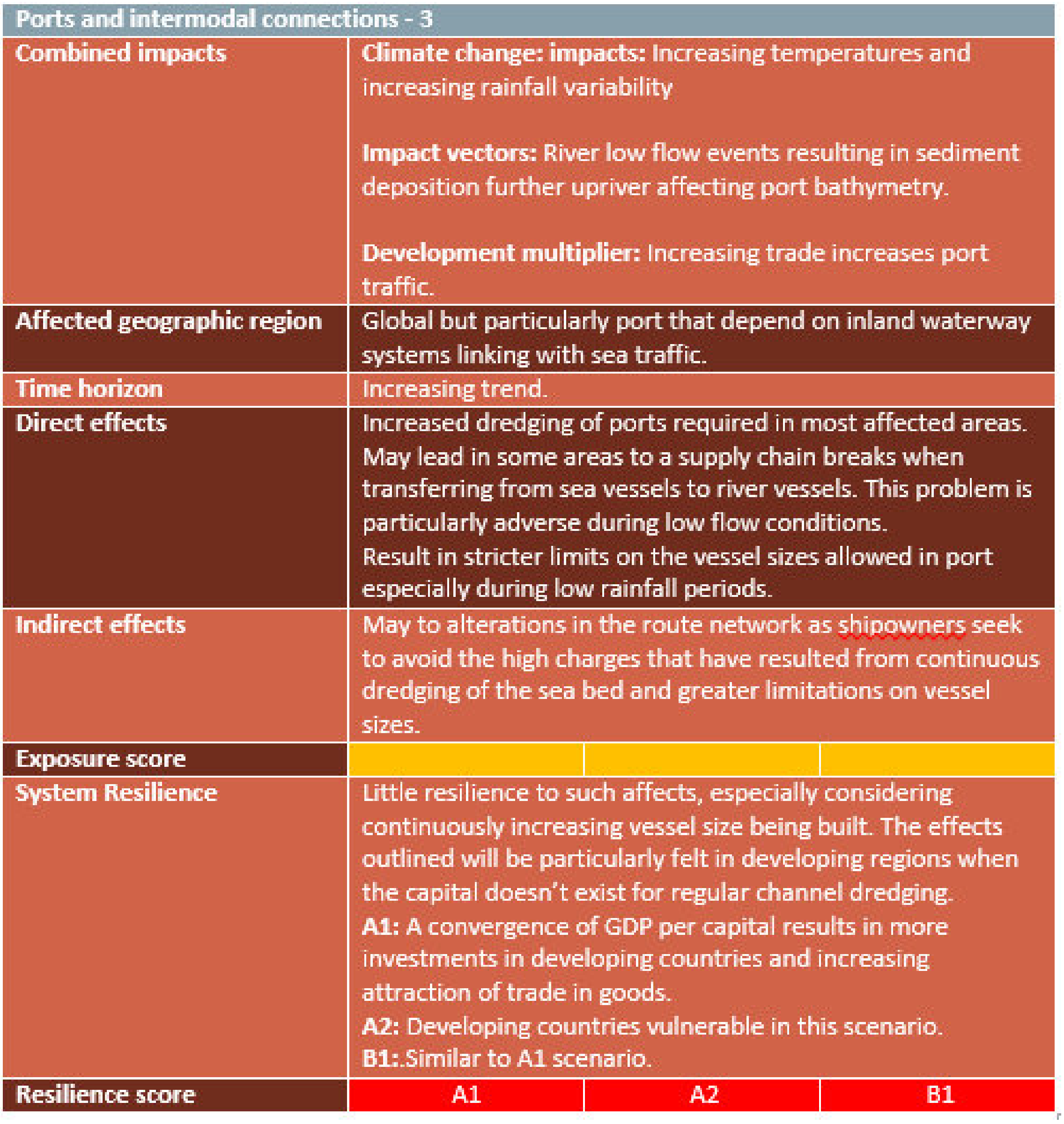
Shipping Network and supply chain -4 [See supplementary information – SNSC - 4]			
Combined impacts	**Policy impacts:** Ineffectual international talks result in countries pursuing separate measures for reducing emissions.		
Affected geographic region	Disparate effects		
Time horizon	Separate measures are more likely to happen in the medium term, with a globally agreed response occurring on convergence of GDPs.		
Direct effects	Depending on the different measures pursued there may be changes to the route network. For example, shipowners may want to shorten routes in and out of affected areas if energy use per journey was used as a metric. This would result in greater traffic to ports on the cusp of affected areas.		
Indirect effects	Port traffic increases to ports on outer edge of affected areas whilst ports within affected areas, that were once hubs for larger vessels may have reduced traffic in larger vessels as commodities are short-sea shipped from the new port hubs.		
Exposure score	🟥	🟥	🟥
System Resilience	The importance of an individual port is a typical dynamic within shipping as trade routes have changed historically. **A1:** Little resilience to such an effect as it is organically derived. **A2:** Same as A1. **B1:** Same as A1.		
Resilience score	🟥 A1	🟥 A2	🟥 B1



Ports and intermodal connections – 1			
Combined impacts	**Climate change: impacts:** Sea level rise combined with storm surge event. **Development multiplier:** Increasing port traffic associated with increasing trade.		
Affected geographic region	All regions, but particularly low lying regions surround ports such as the Netherlands.		
Time horizon	Increasing trend but there may be shock events when combined with a storm surge.		
Direct effects	Flooding at ports, resulting in problems for storage and cargo-handling at port and also intermodal connections. Leads to redirection of commodities for short term shock events, but for continued problems may lead to reduced traffic to a port.		
Indirect effects	Hub and spoke type networks most affected if hub ports impacted by flooding. More flexible supply chains, able to deal with short run events. Thus this may be lead to reduced vessel size and reduced load size as logistic manager hedge supply chain risk.		
Exposure score	🟨	🟨	🟨
System Resilience	Intermittent interruptions unlikely to have a great impact but continued affects on reliability may lead to reconfiguration of routes away from hub and spoke type networks. **A1:** This will vary by region. Although, in this development scenario it would be expected to some extent that all areas are able to cope equally well. port infrastructure investment is likely to be equivalent for all regions. **A2:** Although there is a reduced reliance on trade in a localized world, the disparate nature of global development suggests that some regions may be unable to invest in portside infrastructure to cope with the challenges of increased sea level rise. Due to reduced resilience, redirection away from underdeveloped regions is more likely to occur in this scenario. Consequently, developing countries are likely to be vulnerable in this situation **B1:**.Similar to A1 scenario.		
Resilience score	🟩 A1	🟨 A2	🟩 B1



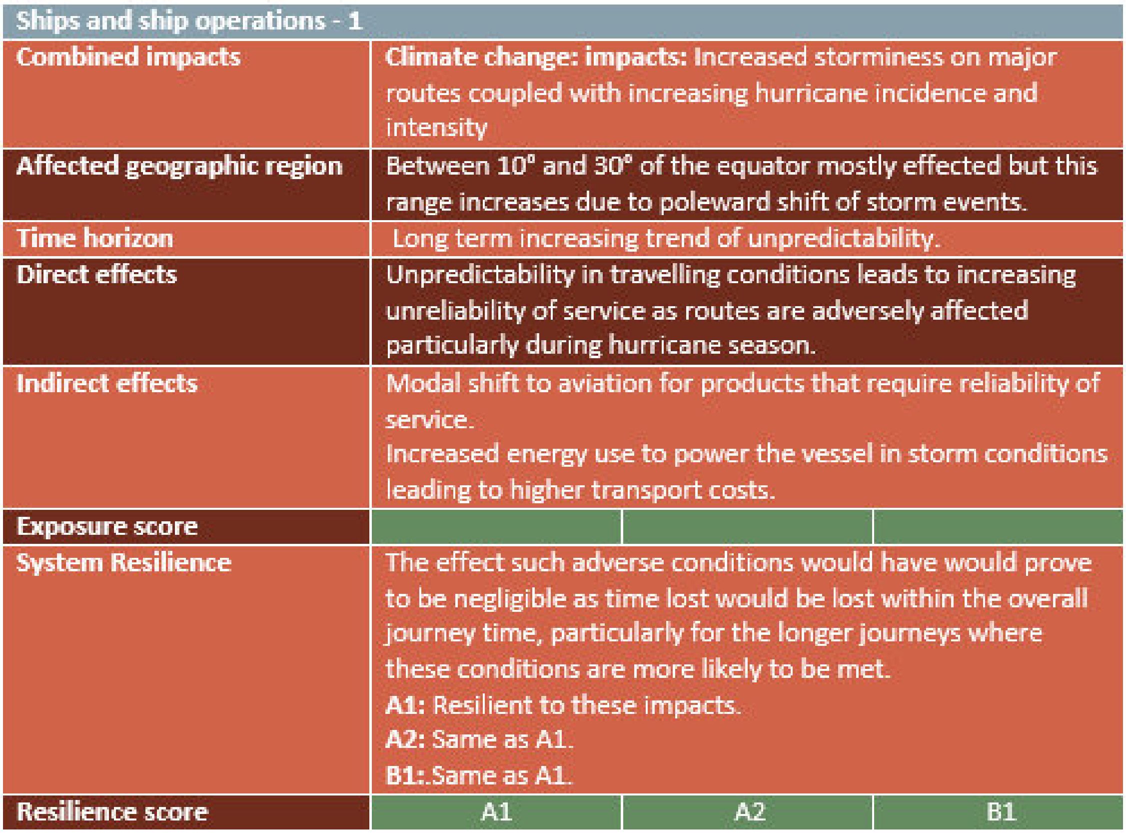
Ports and intermodal connections - 2			
Combined impacts	**Policy impacts:** Required efficiency gains and shore side electricity provided through cold ironing. **Development multiplier:** Increasing trade increases port traffic.		
Affected geographic region	Global		
Time horizon	Long term		
Direct effects	Carbon charges and constraints on congestion due to cold ironing limitations causes port delays.		
Indirect effects	Alterations to ship speed and smart queuing (virtual arrival). For JIT operations, there may be last minute alterations to location of port of arrival		
Exposure score	🟨	🟨	🟨
System Resilience	Ports in developing worlds are less likely to make changes that require large capital investment. This remains a barrier to developing countries developing hub ports. **A1:** A convergence of GDP per capital results in more investments in developing countries and increasing attraction of trade in goods. **A2: Developing countries vulnerable in this scenario.** **B1:**.Similar to A1 scenario.		
Resilience score	🟩 A1	🟨 A2	🟩 B1



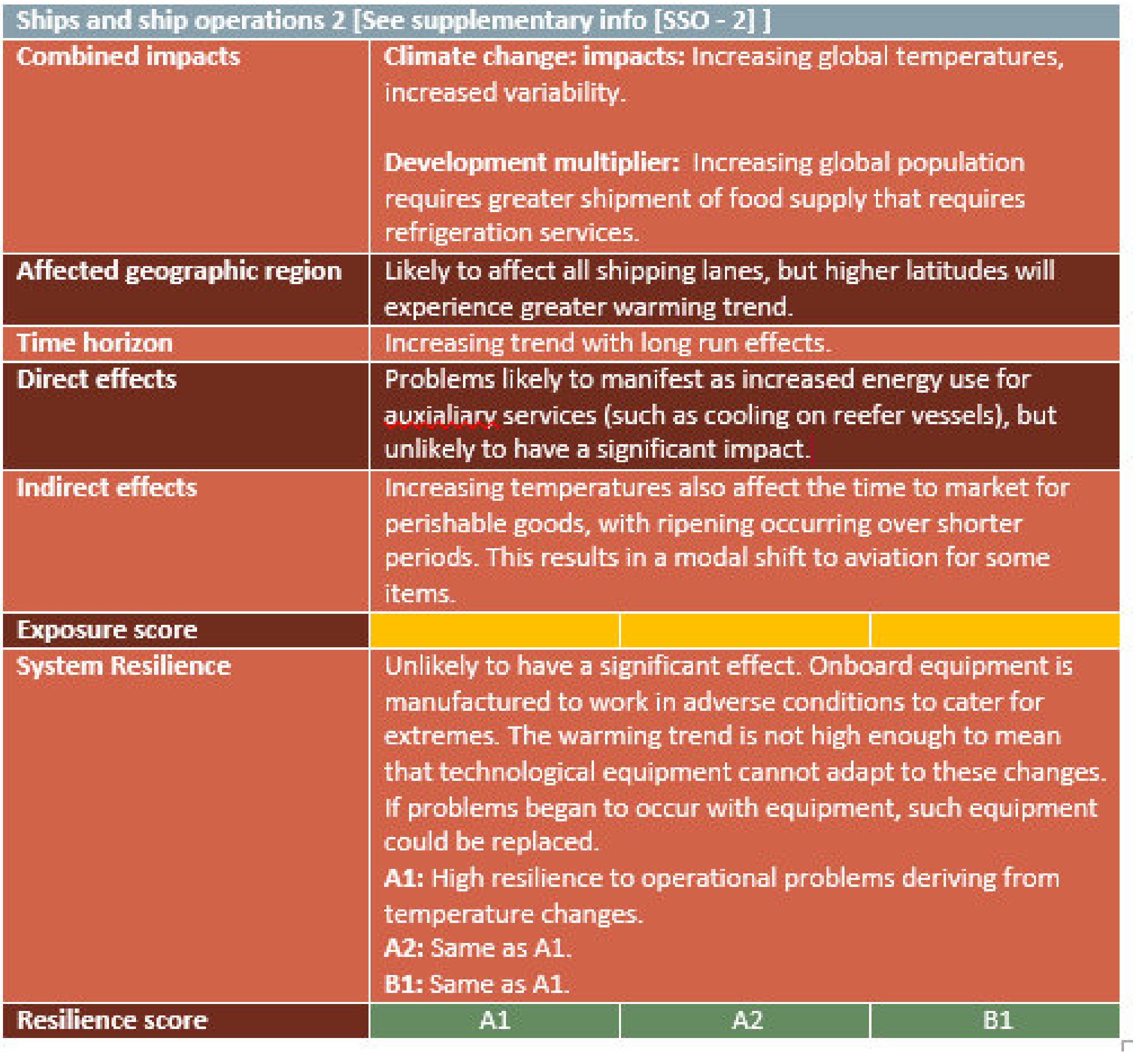
<table>
<tr><th colspan="4">Ports and intermodal connections - 3</th></tr>
<tr><td>Combined impacts</td><td colspan="3">Climate change: impacts: Increasing temperatures and increasing rainfall variability

Impact vectors: River low flow events resulting in sediment deposition further upriver affecting port bathymetry.

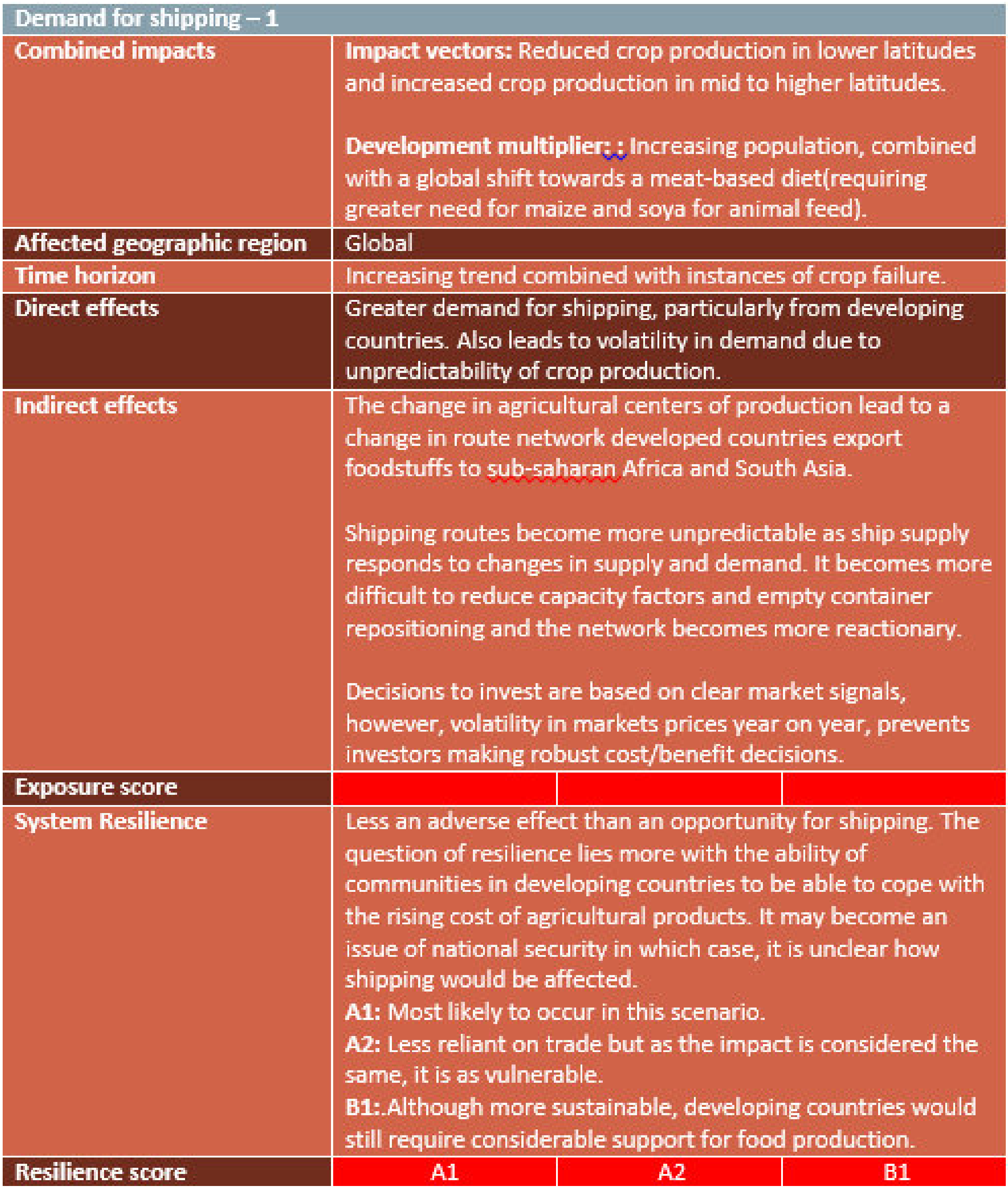
Development multiplier: Increasing trade increases port traffic.</td></tr>
<tr><td>Affected geographic region</td><td colspan="3">Global but particularly port that depend on inland waterway systems linking with sea traffic.</td></tr>
<tr><td>Time horizon</td><td colspan="3">Increasing trend.</td></tr>
<tr><td>Direct effects</td><td colspan="3">Increased dredging of ports required in most affected areas. May lead in some areas to a supply chain breaks when transferring from sea vessels to river vessels. This problem is particularly adverse during low flow conditions.
Result in stricter limits on the vessel sizes allowed in port especially during low rainfall periods.</td></tr>
<tr><td>Indirect effects</td><td colspan="3">May to alterations in the route network as shipowners seek to avoid the high charges that have resulted from continuous dredging of the sea bed and greater limitations on vessel sizes.</td></tr>
<tr><td>Exposure score</td><td></td><td></td><td></td></tr>
<tr><td>System Resilience</td><td colspan="3">Little resilience to such affects, especially considering continuously increasing vessel size being built. The effects outlined will be particularly felt in developing regions when the capital doesn’t exist for regular channel dredging.
A1: A convergence of GDP per capital results in more investments in developing countries and increasing attraction of trade in goods.
A2: Developing countries vulnerable in this scenario.
B1:.Similar to A1 scenario.</td></tr>
<tr><td>Resilience score</td><td>A1</td><td>A2</td><td>B1</td></tr>
</table>



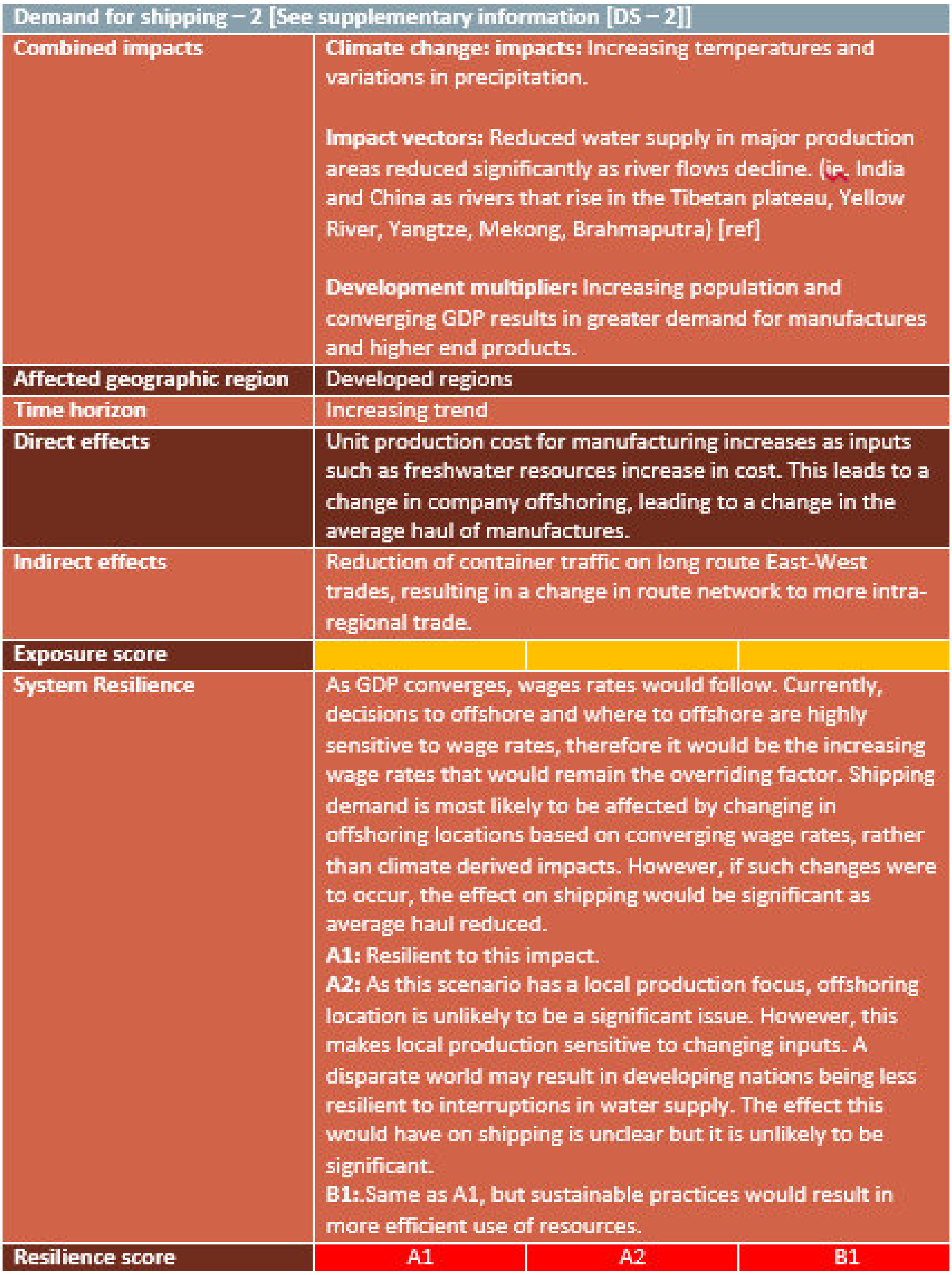
Ships and ship operations - 1			
Combined impacts	**Climate change: impacts:** Increased storminess on major routes coupled with increasing hurricane incidence and intensity		
Affected geographic region	Between 10° and 30° of the equator mostly effected but this range increases due to poleward shift of storm events.		
Time horizon	Long term increasing trend of unpredictability.		
Direct effects	Unpredictability in travelling conditions leads to increasing unreliability of service as routes are adversely affected particularly during hurricane season.		
Indirect effects	Modal shift to aviation for products that require reliability of service. Increased energy use to power the vessel in storm conditions leading to higher transport costs.		
Exposure score			
System Resilience	The effect such adverse conditions would have would prove to be negligible as time lost would be lost within the overall journey time, particularly for the longer journeys where these conditions are more likely to be met. **A1:** Resilient to these impacts. **A2:** Same as A1. **B1:**.Same as A1.		
Resilience score	A1	A2	B1



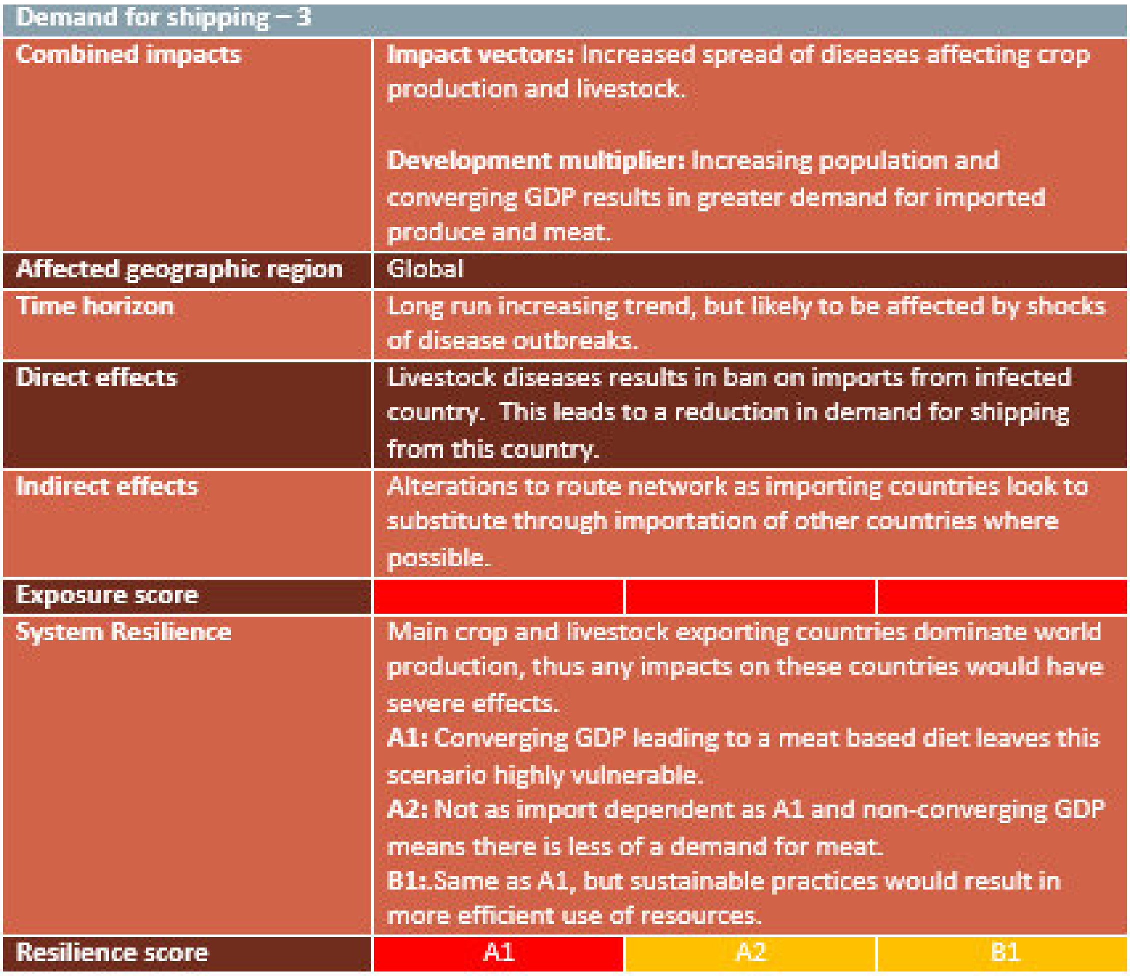
Ships and ship operations 2 [See supplementary info [SSO - 2]]			
Combined impacts	**Climate change: impacts:** Increasing global temperatures, increased variability. **Development multiplier:** Increasing global population requires greater shipment of food supply that requires refrigeration services.		
Affected geographic region	Likely to affect all shipping lanes, but higher latitudes will experience greater warming trend.		
Time horizon	Increasing trend with long run effects.		
Direct effects	Problems likely to manifest as increased energy use for auxialiary services (such as cooling on reefer vessels), but unlikely to have a significant impact.		
Indirect effects	Increasing temperatures also affect the time to market for perishable goods, with ripening occurring over shorter periods. This results in a modal shift to aviation for some items.		
Exposure score	🟨	🟨	🟨
System Resilience	Unlikely to have a significant effect. Onboard equipment is manufactured to work in adverse conditions to cater for extremes. The warming trend is not high enough to mean that technological equipment cannot adapt to these changes. If problems began to occur with equipment, such equipment could be replaced. **A1:** High resilience to operational problems deriving from temperature changes. **A2:** Same as A1. **B1:** Same as A1.		
Resilience score	A1	A2	B1



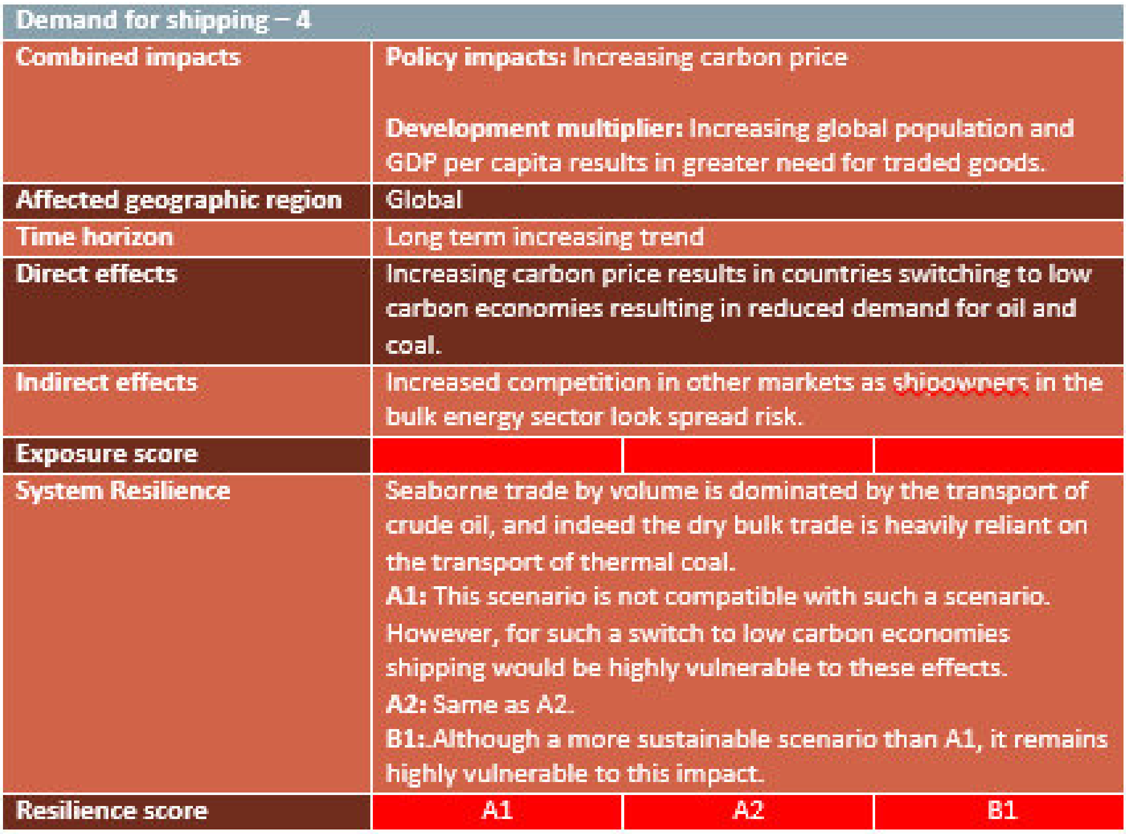
Demand for shipping – 1			
Combined impacts	**Impact vectors:** Reduced crop production in lower latitudes and increased crop production in mid to higher latitudes. **Development multiplier: :** Increasing population, combined with a global shift towards a meat-based diet(requiring greater need for maize and soya for animal feed).		
Affected geographic region	Global		
Time horizon	Increasing trend combined with instances of crop failure.		
Direct effects	Greater demand for shipping, particularly from developing countries. Also leads to volatility in demand due to unpredictability of crop production.		
Indirect effects	The change in agricultural centers of production lead to a change in route network developed countries export foodstuffs to sub-saharan Africa and South Asia. Shipping routes become more unpredictable as ship supply responds to changes in supply and demand. It becomes more difficult to reduce capacity factors and empty container repositioning and the network becomes more reactionary. Decisions to invest are based on clear market signals, however, volatility in markets prices year on year, prevents investors making robust cost/benefit decisions.		
Exposure score	🟥	🟥	🟥
System Resilience	Less an adverse effect than an opportunity for shipping. The question of resilience lies more with the ability of communities in developing countries to be able to cope with the rising cost of agricultural products. It may become an issue of national security in which case, it is unclear how shipping would be affected. **A1:** Most likely to occur in this scenario. **A2:** Less reliant on trade but as the impact is considered the same, it is as vulnerable. **B1:**.Although more sustainable, developing countries would still require considerable support for food production.		
Resilience score	A1	A2	B1



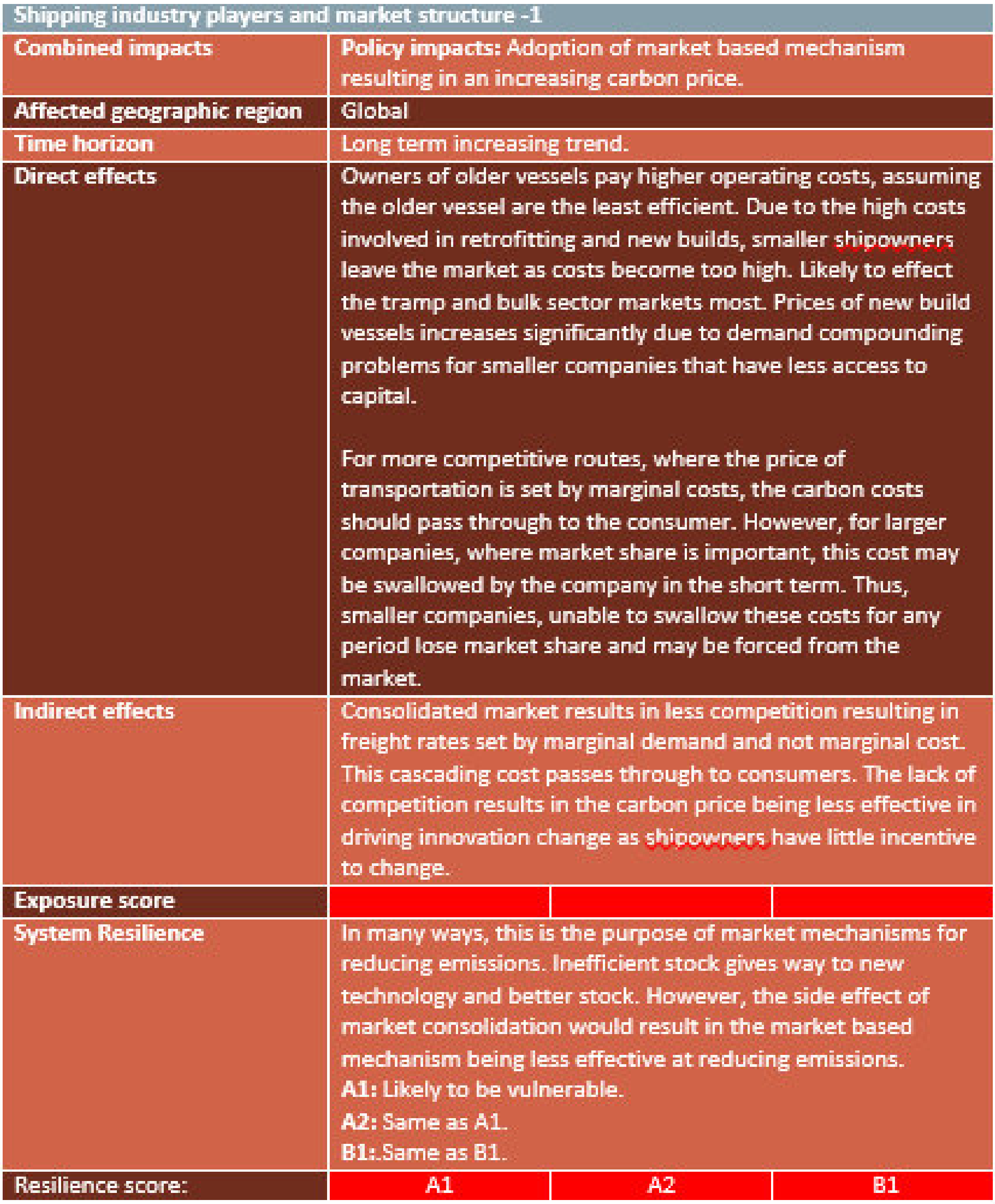
Demand for shipping – 2 [See supplementary information [DS – 2]]			
Combined impacts	**Climate change: impacts:** Increasing temperatures and variations in precipitation. **Impact vectors:** Reduced water supply in major production areas reduced significantly as river flows decline. (ie. India and China as rivers that rise in the Tibetan plateau, Yellow River, Yangtze, Mekong, Brahmaputra) [ref] **Development multiplier:** Increasing population and converging GDP results in greater demand for manufactures and higher end products.		
Affected geographic region	Developed regions		
Time horizon	Increasing trend		
Direct effects	Unit production cost for manufacturing increases as inputs such as freshwater resources increase in cost. This leads to a change in company offshoring, leading to a change in the average haul of manufactures.		
Indirect effects	Reduction of container traffic on long route East-West trades, resulting in a change in route network to more intra-regional trade.		
Exposure score	🟨	🟨	🟨
System Resilience	As GDP converges, wages rates would follow. Currently, decisions to offshore and where to offshore are highly sensitive to wage rates, therefore it would be the increasing wage rates that would remain the overriding factor. Shipping demand is most likely to be affected by changing in offshoring locations based on converging wage rates, rather than climate derived impacts. However, if such changes were to occur, the effect on shipping would be significant as average haul reduced. **A1:** Resilient to this impact. **A2:** As this scenario has a local production focus, offshoring location is unlikely to be a significant issue. However, this makes local production sensitive to changing inputs. A disparate world may result in developing nations being less resilient to interruptions in water supply. The effect this would have on shipping is unclear but it is unlikely to be significant. **B1:**.Same as A1, but sustainable practices would result in more efficient use of resources.		
Resilience score	🟥 A1	🟥 A2	🟥 B1



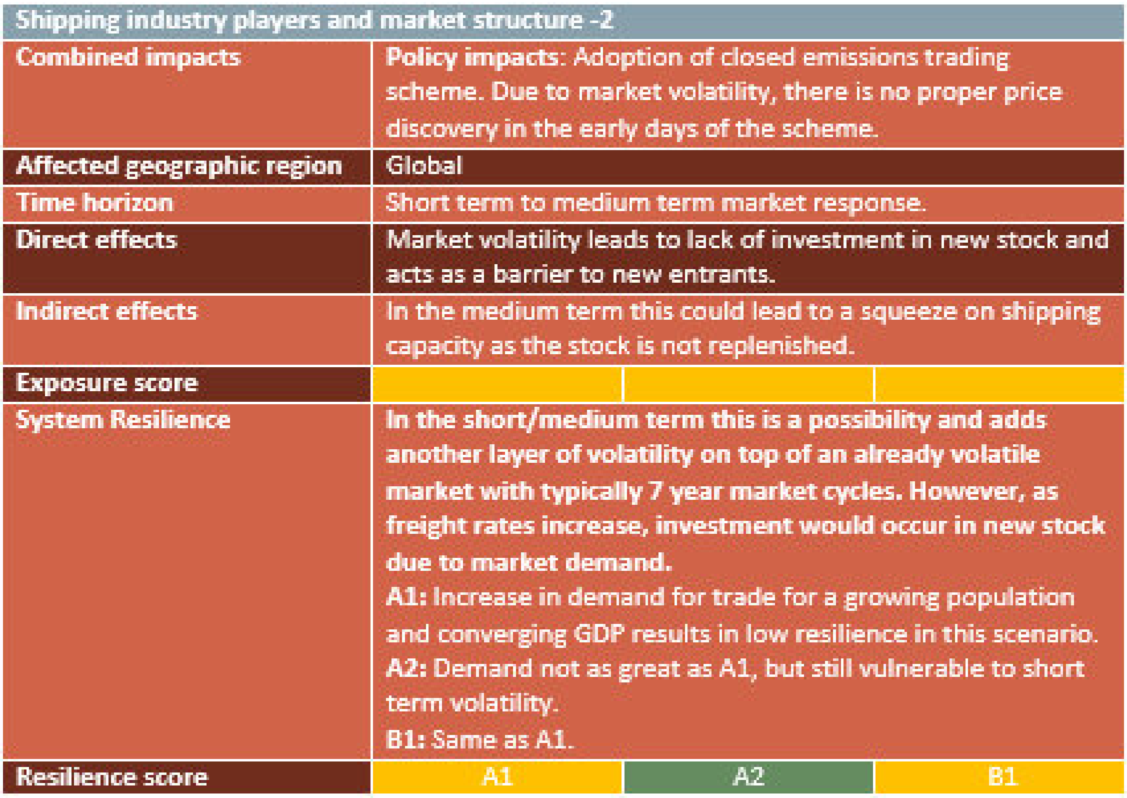
Demand for shipping – 3			
Combined impacts	**Impact vectors:** Increased spread of diseases affecting crop production and livestock. **Development multiplier:** Increasing population and converging GDP results in greater demand for imported produce and meat.		
Affected geographic region	Global		
Time horizon	Long run increasing trend, but likely to be affected by shocks of disease outbreaks.		
Direct effects	Livestock diseases results in ban on imports from infected country. This leads to a reduction in demand for shipping from this country.		
Indirect effects	Alterations to route network as importing countries look to substitute through importation of other countries where possible.		
Exposure score	🟥	🟥	🟥
System Resilience	Main crop and livestock exporting countries dominate world production, thus any impacts on these countries would have severe effects. **A1:** Converging GDP leading to a meat based diet leaves this scenario highly vulnerable. **A2:** Not as import dependent as A1 and non-converging GDP means there is less of a demand for meat. **B1:**.Same as A1, but sustainable practices would result in more efficient use of resources.		
Resilience score	🟥 A1	🟨 A2	🟨 B1



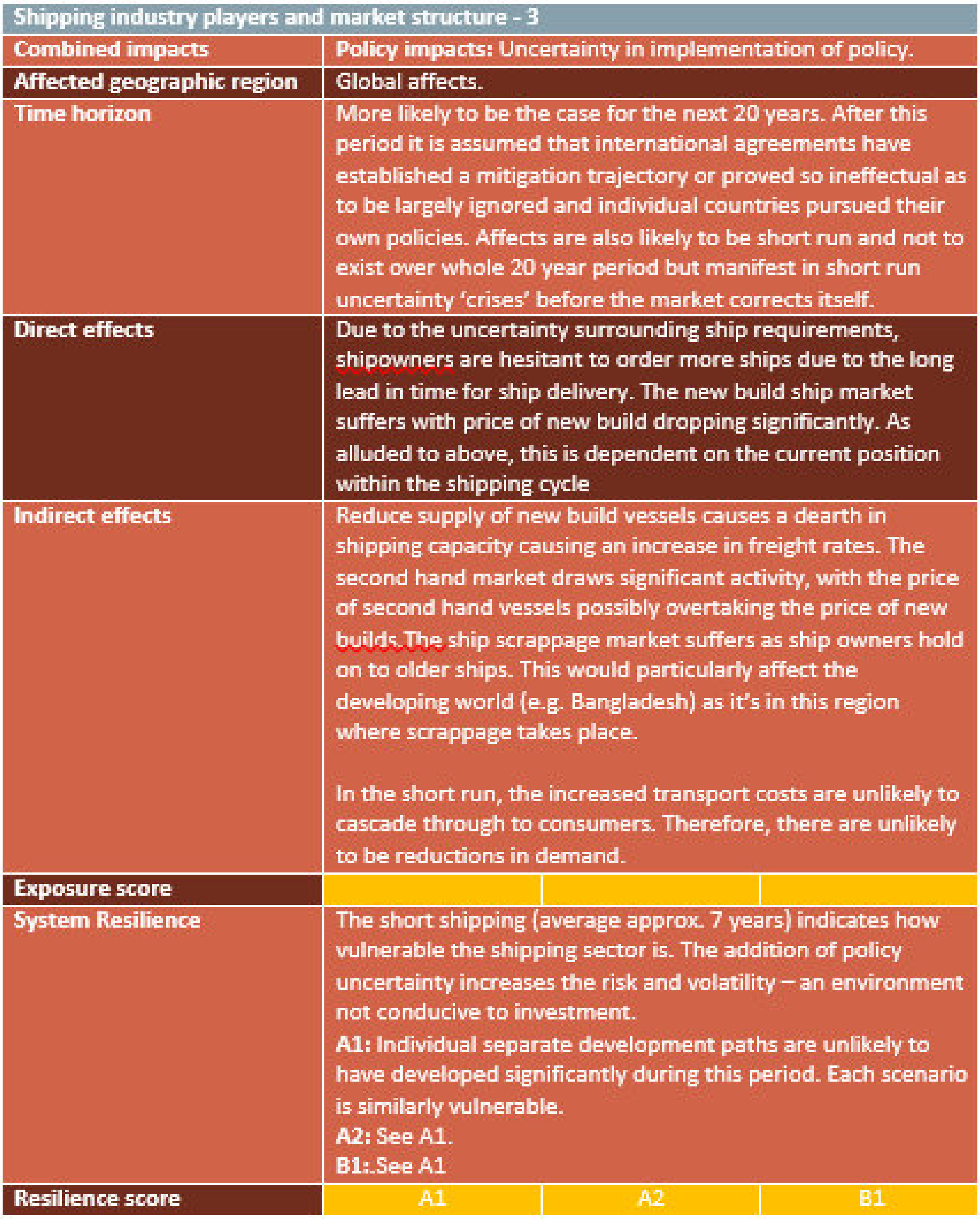
Demand for shipping – 4			
Combined impacts	**Policy impacts:** Increasing carbon price **Development multiplier:** Increasing global population and GDP per capita results in greater need for traded goods.		
Affected geographic region	Global		
Time horizon	Long term increasing trend		
Direct effects	Increasing carbon price results in countries switching to low carbon economies resulting in reduced demand for oil and coal.		
Indirect effects	Increased competition in other markets as shipowners in the bulk energy sector look spread risk.		
Exposure score	🟥	🟥	🟥
System Resilience	Seaborne trade by volume is dominated by the transport of crude oil, and indeed the dry bulk trade is heavily reliant on the transport of thermal coal. **A1:** This scenario is not compatible with such a scenario. However, for such a switch to low carbon economies shipping would be highly vulnerable to these effects. **A2:** Same as A2. **B1:** Although a more sustainable scenario than A1, it remains highly vulnerable to this impact.		
Resilience score	A1	A2	B1



Shipping industry players and market structure -1			
Combined impacts	**Policy impacts:** Adoption of market based mechanism resulting in an increasing carbon price.		
Affected geographic region	Global		
Time horizon	Long term increasing trend.		
Direct effects	Owners of older vessels pay higher operating costs, assuming the older vessel are the least efficient. Due to the high costs involved in retrofitting and new builds, smaller shipowners leave the market as costs become too high. Likely to effect the tramp and bulk sector markets most. Prices of new build vessels increases significantly due to demand compounding problems for smaller companies that have less access to capital. For more competitive routes, where the price of transportation is set by marginal costs, the carbon costs should pass through to the consumer. However, for larger companies, where market share is important, this cost may be swallowed by the company in the short term. Thus, smaller companies, unable to swallow these costs for any period lose market share and may be forced from the market.		
Indirect effects	Consolidated market results in less competition resulting in freight rates set by marginal demand and not marginal cost. This cascading cost passes through to consumers. The lack of competition results in the carbon price being less effective in driving innovation change as shipowners have little incentive to change.		
Exposure score	🟥	🟥	🟥
System Resilience	In many ways, this is the purpose of market mechanisms for reducing emissions. Inefficient stock gives way to new technology and better stock. However, the side effect of market consolidation would result in the market based mechanism being less effective at reducing emissions. **A1:** Likely to be vulnerable. **A2:** Same as A1. **B1:** Same as B1.		
Resilience score:	A1	A2	B1



Shipping industry players and market structure -2			
Combined impacts	**Policy impacts**: Adoption of closed emissions trading scheme. Due to market volatility, there is no proper price discovery in the early days of the scheme.		
Affected geographic region	Global		
Time horizon	Short term to medium term market response.		
Direct effects	Market volatility leads to lack of investment in new stock and acts as a barrier to new entrants.		
Indirect effects	In the medium term this could lead to a squeeze on shipping capacity as the stock is not replenished.		
Exposure score	🟨	🟨	🟨
System Resilience	**In the short/medium term this is a possibility and adds another layer of volatility on top of an already volatile market with typically 7 year market cycles. However, as freight rates increase, investment would occur in new stock due to market demand.** **A1:** Increase in demand for trade for a growing population and converging GDP results in low resilience in this scenario. **A2:** Demand not as great as A1, but still vulnerable to short term volatility. **B1:** Same as A1.		
Resilience score	A1	A2	B1

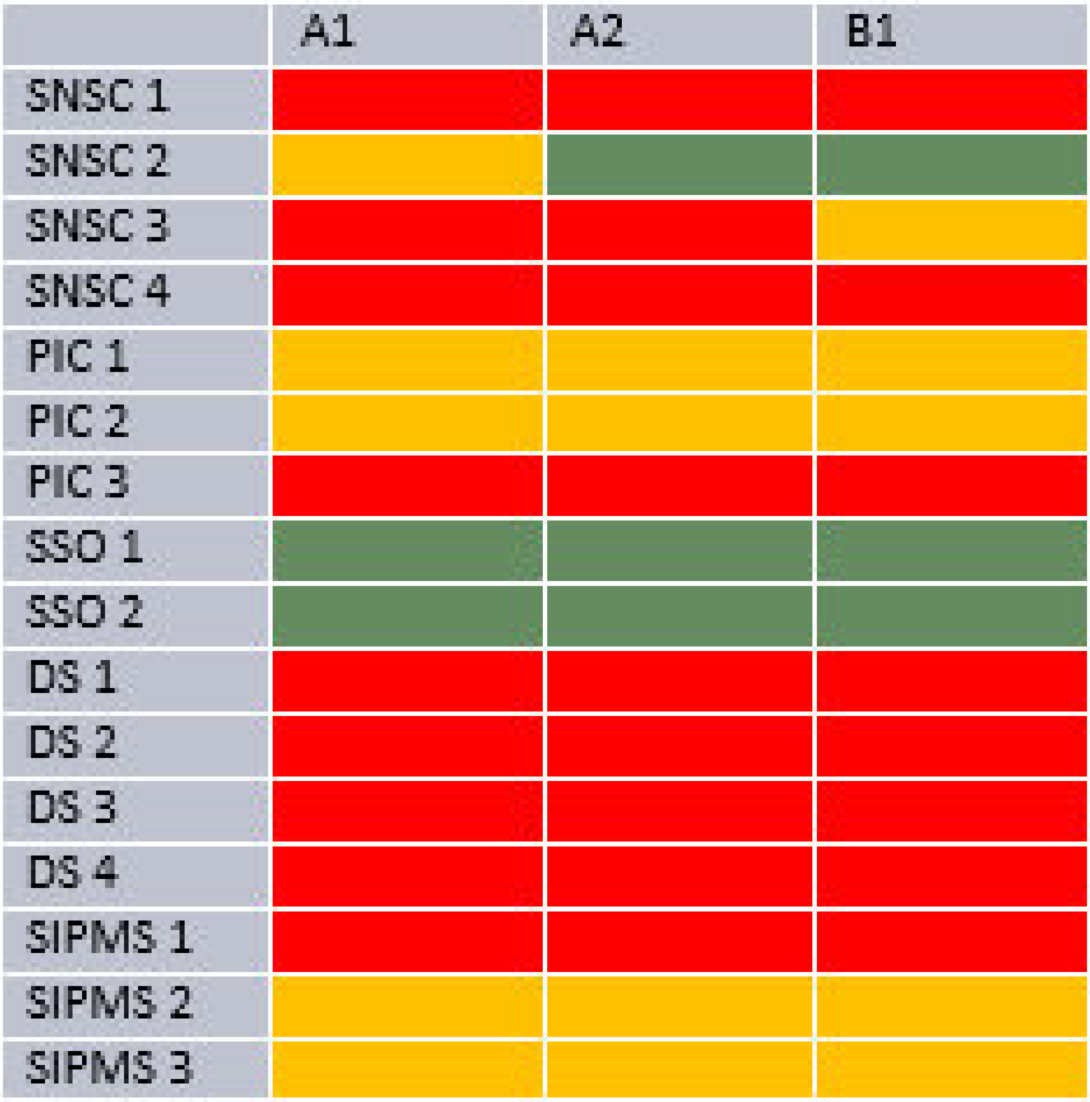


Shipping industry players and market structure - 3			
Combined impacts	**Policy impacts:** Uncertainty in implementation of policy.		
Affected geographic region	Global affects.		
Time horizon	More likely to be the case for the next 20 years. After this period it is assumed that international agreements have established a mitigation trajectory or proved so ineffectual as to be largely ignored and individual countries pursued their own policies. Affects are also likely to be short run and not to exist over whole 20 year period but manifest in short run uncertainty 'crises' before the market corrects itself.		
Direct effects	Due to the uncertainty surrounding ship requirements, shipowners are hesitant to order more ships due to the long lead in time for ship delivery. The new build ship market suffers with price of new build dropping significantly. As alluded to above, this is dependent on the current position within the shipping cycle		
Indirect effects	Reduce supply of new build vessels causes a dearth in shipping capacity causing an increase in freight rates. The second hand market draws significant activity, with the price of second hand vessels possibly overtaking the price of new builds.The ship scrappage market suffers as ship owners hold on to older ships. This would particularly affect the developing world (e.g. Bangladesh) as it's in this region where scrappage takes place. In the short run, the increased transport costs are unlikely to cascade through to consumers. Therefore, there are unlikely to be reductions in demand.		
Exposure score			
System Resilience	The short shipping (average approx. 7 years) indicates how vulnerable the shipping sector is. The addition of policy uncertainty increases the risk and volatility – an environment not conducive to investment. **A1:** Individual separate development paths are unlikely to have developed significantly during this period. Each scenario is similarly vulnerable. **A2:** See A1. **B1:**.See A1		
Resilience score	A1	A2	B1

Vulnerability Map

On combining the exposure and resilience score from the above impact pathways, the results in **Figure 8.12** below are derived according to the scoring system outlined in

Figure 8.11.



	A1	A2	B1
SNSC 1	🟥	🟥	🟥
SNSC 2	🟨	🟩	🟩
SNSC 3	🟥	🟥	🟨
SNSC 4	🟥	🟥	🟥
PIC 1	🟨	🟨	🟨
PIC 2	🟨	🟨	🟨
PIC 3	🟥	🟥	🟥
SSO 1	🟩	🟩	🟩
SSO 2	🟩	🟩	🟩
DS 1	🟥	🟥	🟥
DS 2	🟥	🟥	🟥
DS 3	🟥	🟥	🟥
DS 4	🟥	🟥	🟥
SIPMS 1	🟥	🟥	🟥
SIPMS 2	🟨	🟨	🟨
SIPMS 3	🟨	🟨	🟨

Figure 8.12. Vulnerability Scores

Composite Analysis

Overall combined results are shown in Figure 12 below. Results for all scenarios are generally the same with,for the most part, similar vulnerability for each of the impact pathways. This is largely due to the fact that shipping will most likely only differ in each scenario by scale. For the A1 and B1 scenarios, there would be an increase in trade, particularly South-South trade, although the commodities transported may vary. While in the A2 scenario, there is reduced trade but the network would be similar to its current configuration. Also to note is the high vulnerability of the shipping sector to impacts particularly in regards effects on the network and supply chain and the demand for shipping.

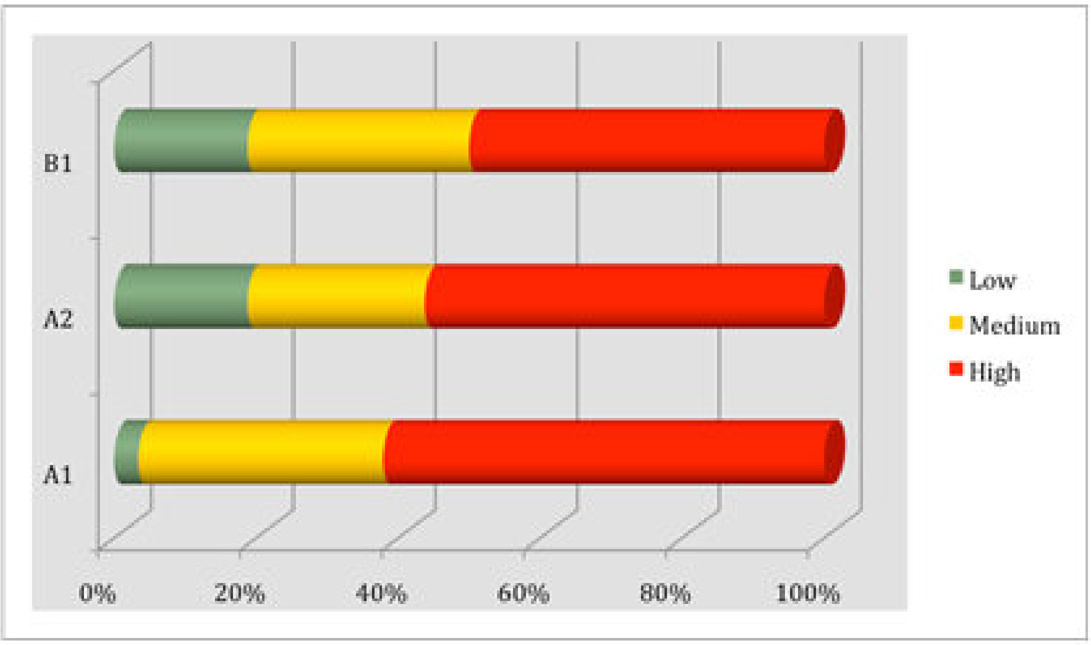


Figure 8.13. Overall Results

Figure 8.14 and **Figure 8.15** show the the results disaggregated into those resulting from climate change impacts and those from mitigation measures.

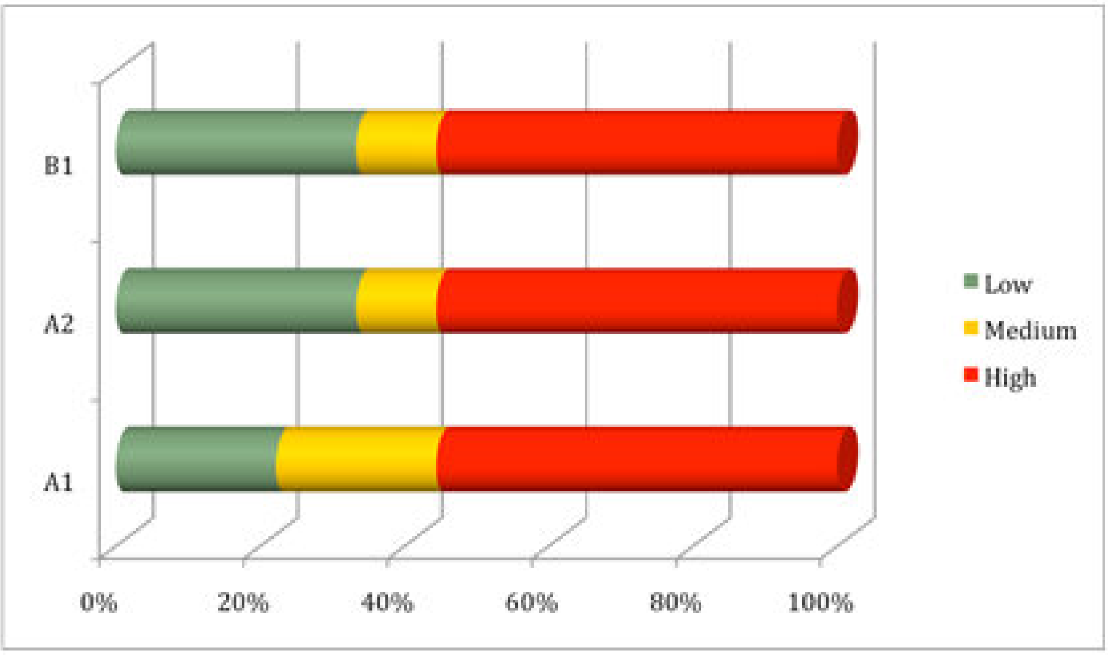


Figure 8.14. Combined results of vulnerability to climate change impacts.

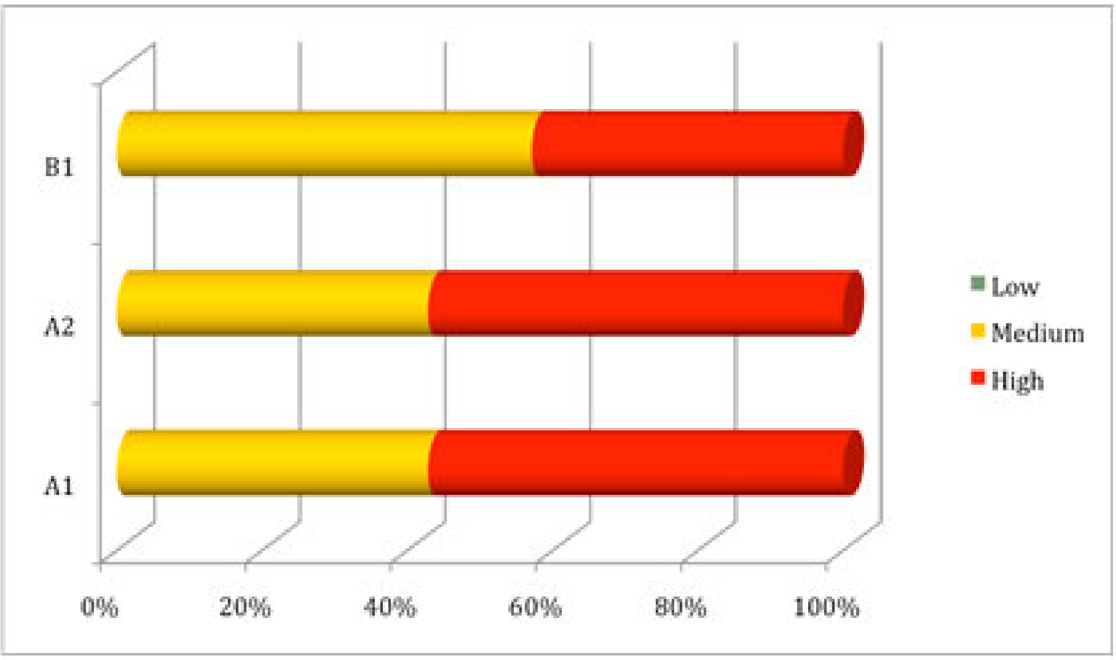


Figure 8.15. Combined results of vulnerability to climate change mitigation.

Finally, **Figure 8.16** displays the impacts pathways according to receptor category. According to the analysis, mitigation measures mostly affect shipping markets while climate change impacts affect the demand for and supply of shipping as well as ships and shipping operations.

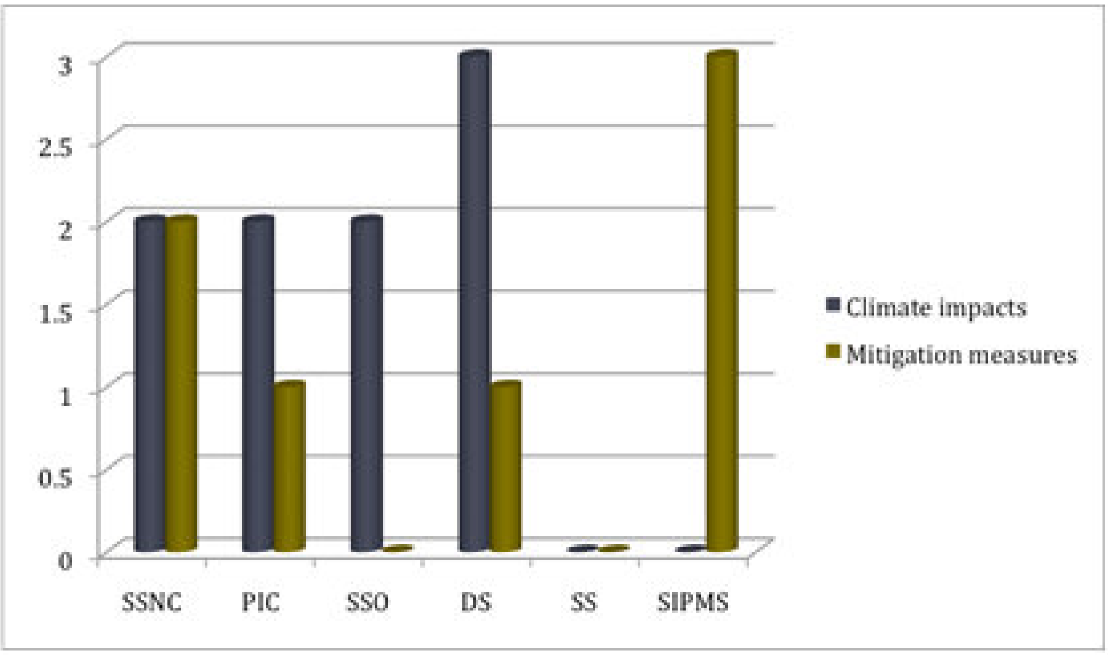


Figure 8.16. Spread of receptor categories according to impact type

8.3.2 Opportunities

A major opportunity for shipping is the opening up of new trade routes most obviously the North-West and North-East Passage providing a new route to Asia from Europe. Efforts to reduce emissions and early impacts of climate change have opened up an unexpected markets for shipping. Carbon capture is increasingly been seen as a major tool in tackling emissions, especially considering the huge spike in coal demand over the last ten years. In theory, coal-fired power plants would seek to remove carbon dioxide from emissions. The transportation of carbon dioxide is then, in many cases, envisioned to take place by sea to facilitate below sea storage (Stephens 2010). Indeed, it has recently being estimated that there as 750 mtCO2 located near the coast in the North Sea that could be transported via ship (Maersk 2010). Other opportunities include the transportation of freshwater. Many countries are currently experiencing severe water shortages (MDBA 2009, Hayhoe et al. 2004, Kundzewicz Z.W. & Shiklomanov 2007)and many climate climate change projections indicate that such shortages will only continue in the future. Consequently the opportunity for transporting water as a commodity will only increase. Policy initiatives to reduce emissions, in many cases, are an effort to increase the efficiency of ships through forced innovation within the industry. There are great opportunities for technological advances and improvements to supply chains. Also, through policy mechanisms, there is the opportunity to create large amounts of capital that can be reinvested back into the industry particularly to deal with issues of equity such as port improvements in developing countries. As well as technological innovation, there is also the possibility of improvements in how business is conducted and contracts developed. For example in the charter party contract, where typically the exporter provides the goods free on board (FOB), and the importer would pay cost,insurance and freight (CIF). Therefore, the importers responsibility only begins on taking the goods on board ship. They have no incentive to be punctual in collection, leading to delays in ports and extra storage costs for exporter.

8.3.3 Discussion

The analysis above has shown that climate change impacts and mitigation measures may affect the industry in different areas. Although not an exhaustive list, it does show a comprehensive set of impact pathways. As expected, mitigation measures are most likely to affect how the market behaves as this is the fundamental principle behind schemes such as the emissions trading scheme. Their principle is to drive innovation and change through the market. However, as outlined above there are some unwanted feedbacks. The issue of market consolidation resulted from a number of pathways. Increased market volatility overlaid on an already volatile market may bankrupt smaller companies unable to absorb short term losses and serve as a barrier to entrance for new players. Thus the shipping markets, particularly for shipowners becomes the preserve of a few major companies allowing them control over freight rates. Indeed, based on current trends, Hingorani et al. (2005) projected that by 2015 80% of the shipping container market will be controlled by the top 10 players. This research has highlighted that climate change impacts are likely to manifest in changes to demand and the route network particularly. This may come through changes in average haul, port congestion and interruptions, operational problems due to the adverse weather conditions and route changes. This suggests that shipping must become more flexible and responsive. We already see how the shipping industry is adapting to this through the adoption of virtual arrival in some ports. This system allows port operations to run more smoothly through efficient stacking of arriving vessels. However, flexibility is not a typical trait of shipping particularly for larger vessels. The ability to be more responsive to evolving conditions is not conducive with economies of scale. Interruptions to supply chains and routes are particularly concerning for the bulk transport sector. As shown in Figure 5, resources are concentrated in a small number of exporting countries. Therefore, vulnerability would be particularly high for these commodities. This point leads on to supply chains as a whole and their response to the impacts outlined above. The advent of JIT has allowed companies in many cases dispense with the need for storage with supplies arriving at the factory gate just in time. However, how will such inflexibility in the demands of the assembly marry with a shipping system that may be vulnerable to an unpredictable climate system? It is the volatility and the lack of predictability that will most affect supply chains. Such problems are only likely to affect the liner industry as the bulk industry carry less time dependent commodities. A concern for world trade is that in the future, it becomes a matter of national security. We currently see a number of commodities that are paramount to the functioning of economies that are in decline or their sourcing is limited to only a few regions around the world. As was discussed in Box 1, the escalation in price of iron ore is a major concern to China. The formation of new trade blocs will also impact significantly on trade. Indeed, the increase in South-South trade (UNCTAD 2008) may be an indicator of things to come. As the perceived intransigence of the developed nations in refusing to agree on a climate deal, exemplified by the recent Copenhagen talks as well as their refusal to satisfy the Monterrey Accords. In fact, in terms of predicting future trade patterns and flows, climate mitigation and policies could prove significant in their development. The UNFCCC Conference of Parties platform is possibly the most effective stage that developing nations have in influencing global development. Policy related impacts for shipping, such as rising transport cost, can be avoided through early acceptance of a triple bottom line. For example, if shipping were not included in an ETS, but other areas, such as aviation were, and this led to fuel efficiencies in these other areas, there may be shift away from shipping in the modally competitive areas (i.e. short sea shipping). Or if shipping was included at a later date but it hadnt made the technology gains that other modes had achieved, it would be difficult to catch up.

8.3.4 Conclusion

This research has provided preliminary steps in elucidating the interactions of shipping, climate change and climate policy initiatives. As has been discussed, the issue of uncertainty is a strong limiting factor on detailed analysis. Therefore, an approach such as this allows pathways of impacts to be investigated providing a platform for further focused research. The analysis has shown that combinations of impacts may prove to be significant. Indeed, an objective of this analysis was an holistic approach to understanding impacts on the shipping sector, rather than looking at just the effects of policy measures or an increasing population, it is in fact the combination of such changes that could result in significant change. A contentious issue with the climate change debate has been how we must modify our lifestyles to create a balance between our resource demand and resource availability. Indeed, carbon dioxide emissions can be considered in this context where our demand for emitting is not in balance with the supply of available storage. As was outlined in the introduction, our lives, particularly in the developed world, are hinged on product choice facilitated by international trade. Therefore, imaginings of a sustainable future are highly contingent on how the shipping sector and trade will evolve.

8.4 Supplementary Information

[SNSC -1] Typically, between 10 and 30 of the equator is the ideal location for the development of tropical cyclones (Henson 2008) as illustrated in the shaded sections in Figure 16 below.

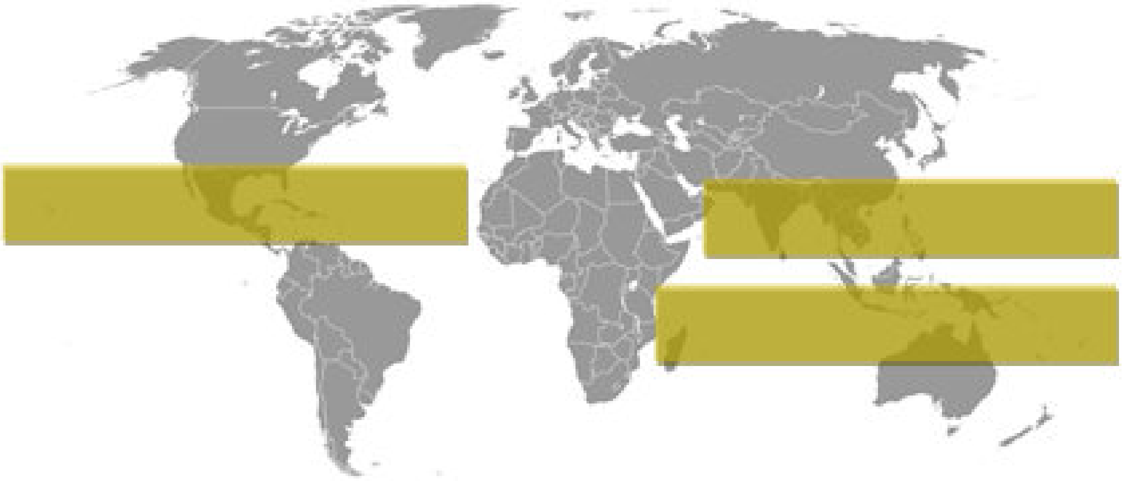


Figure 8.17. Hurricane locations indicated by shaded areas over ocean basins. Source: Henson (2008)

Large uncertainty remains over how if at all tropical cyclones will change. Indeed, there is quite a lot of dispute regarding how they have changed over the past 100 years as proxy evidence is hotly debated (Henson 2008). However, there is potential for poleward shift of storms, increases in intensity, increases in storm and tropical cyclone count as well as hurricane season variations. As shown in Figure 16, hurricane bands bisect the globe, making it difficult for major shipping routes to avoid.

[SNSC - 4] The EU has threatened the IMO with inclusion of shipping within the EU ETS. Coupled with this, the COP15 at Copenhagen resulting in an agreement that largely suggests countries adopt their own means at tackling emissions rather than a single binding global emissions reduction mechanism.

[DS - 2] **Figure 8.18** below shows a global map of current water security risk based on access to improved drinking water and sanitation; the availability of renewable water and the reliance on external supplies; the relationship between available water and supply demands; and the water dependency of each country's economy.

Figure 8.18. Water security risk index. Countries are rated from extreme risk (dark blue) to light blue (low risk). Countries with no data are in grey. Source: Maplecroft (2010)

[SSO - 2] The multi model mean for surface temperature increases is shown in Figure 18 below, take from the IPCC fourth assessment report.

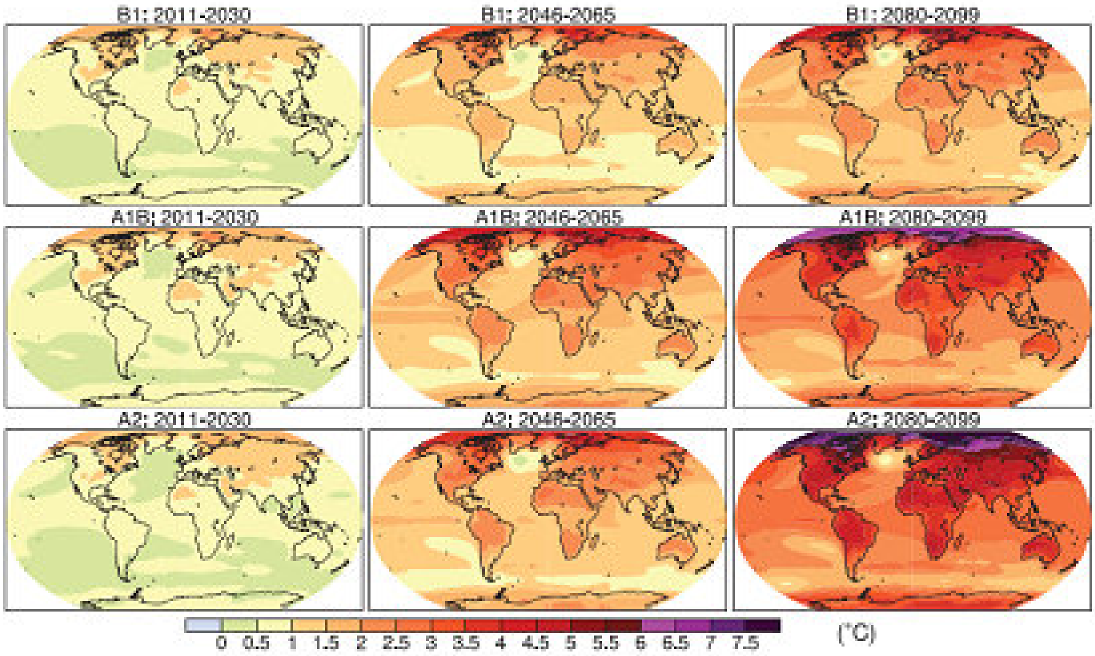


Figure 8.19. Multi-model mean of annual mean surface warming (surface air temperature change, C) for the scenarios B1 (top), A1B (middle) and A2 (bottom), and three time periods, 2011 to 2030 (left), 2046 to 2065 (middle) and 2080 to 2099 (right). Source: Meehl et al. (2007)

As discussed previously, the greatest amount of trade occurs on East-West routes, particularly between North America and Europe. **Figure 8.19** above shows that most warming will occur in northern hemisphere higher latitudes with ocean basins not experiencing as much warming as inland continental areas. Model averages show an increase in temperature in the order of 2.5 from the 1980-1999 average for the 2046 2065 period. However, systems are currently designed to work effectively in ambient temperatures of up to 50 (ThermoKing 2010). Therefore, the projected temperature change is not great enough to significantly affect refrigeration units although there would be associated energy use increases required by the unit.

Chapter 9

Characterising the Shipping Industry

9.1 Introduction

This section outlines the key characteristics of the DBSS as used in this research. Although the chapter is largely descriptive, it sets the context for generating the scenarios that are discussed in **Chapter 13**.

9.2 Emergent Properties

It was highlighted in **Chapter 5**, that ABM is a standard, albeit nascent, modelling approach for modelling systems that show regularities. The following regularities or emergent properties have been identified in the DBSS:

Shipping cycles Stopford (2009) suggests that "market cycles pervade the shipping industry". Short business cycles typically last 5-10 years. These are overlaid with external global economic cycles as well as seasonal trade cycles.

Network effects Due to tactical choices by shippers and shipowners, emergent network properties such as low repetition of routes. Kaluza et al. (2010) modelled each of the main shipping sectors as networks, with each link representing the journey between subsequent port stops (represented as vertices). They found evidence of the small world topology of the shipping system, including the DBSS. The small world topology, identified by Watts & Strogatz (1998), is a random perturbation of a sparse regular lattice network that is commonly found in many biological, technological and social networks. Kaluza et al. (2010) found the DBSS was less clustered , has a higher mean degree (connections per port) and fewer journeys per link than the liner trade and the wet bulk trade.

Mean reverting nature of freight rates Tvedt (2003*a*) and Tvedt (2003*b*) suggest that there is a general consensus on the mean-reverting nature of freight rates and prices. As Engelen et al. (2007) points out, if the market price deviates too much from the fundamental price, the probability that it will return to its mean will increase. There is an equilibrium price that the market moves towards, without necessarily reaching.

9.3 Trade

The DBSS is responsible for over one third of total international trade by volume (t), and in turn is dominated by 5 key commodities, referred to as the main bulks. This is shown for all dry trade in 2016 in **Figure 9.1** along with the list of these commodities. Due to the high volume nature of the DBSS in a few commodities, economies of scale are gained both in the vessel sizes used to transport the cargo but also in the dominance of several key exporters.

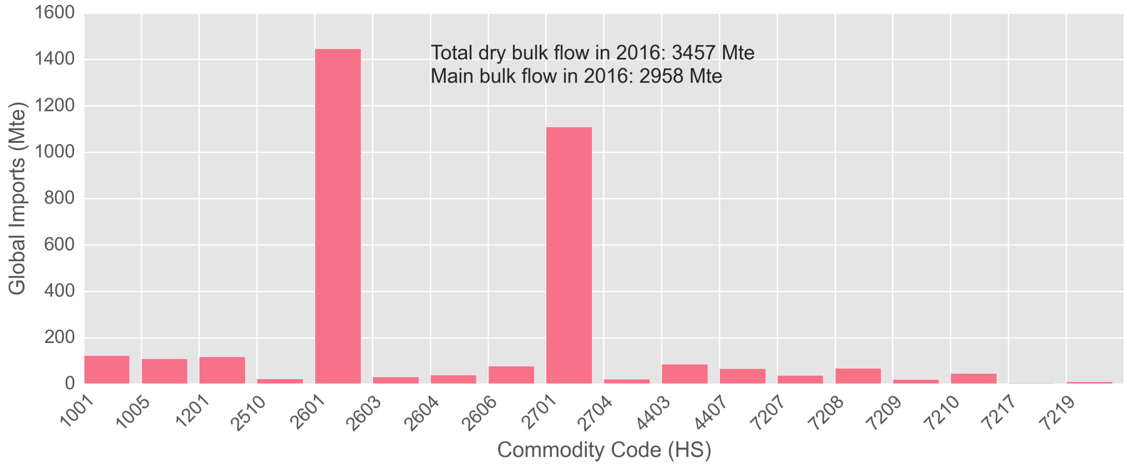


Figure 9.1. Global imports of dry bulk commodities in 2016 dominated by the main bulks which are Iron ore, thermal coal, coking coal, phosphates and grains. Source: COMTRADE (2018)

The main dry bulk commodities are usually shipped in full shiploads direct from load to destination ports, whereas the minor ones can require multi-stop routes (Christiansen et al. 2004). **Figure 9.2** shows this trade since 2010 as reported in COMTRADE (2018) with associated prices. The trade in commodities has had a continuous upward trend

HS Code	Descriptions
1001	Wheat and meslin
1005	Maize (corn)
1201	Soya beans
2510	Natural calcium phosphates
2601	Iron ores and concentrates
2603	Copper ores and concentrates
2604	Nickel ores and concentrates
2606	Aluminium ores and concentrates
2701	Coal, briquettes, ovoids etc, made from coal
2704	Coke and semi-coke of coal, of lignite or of peat
4403	Wood in the rough or roughly squared
4407	Wood sawn or chipped lengthwise, sliced or peeled
7207	Semi-finished products of iron or non-alloy steel
7208	Flat-rolled products of iron or non-alloy steel
7209	Flat-rolled products of iron or non-alloy steel
7210	Flat-rolled products of iron or non-alloy steel
7217	Wire of iron or non-alloy steel
7219	Rolled stainless steel sheet, width $>$ 600mm

Table 9.1. HS commodity codes and associated commodity names

since 2000, notwithstanding a minor decrease in 2009 following the global financial crash of 2008. Although much has been discussed since 2008 on how badly the shipping industry (particularly the DBSS) has suffered through low freight rates, this is largely due to the oversupply of vessels rather than a decrease in demand.

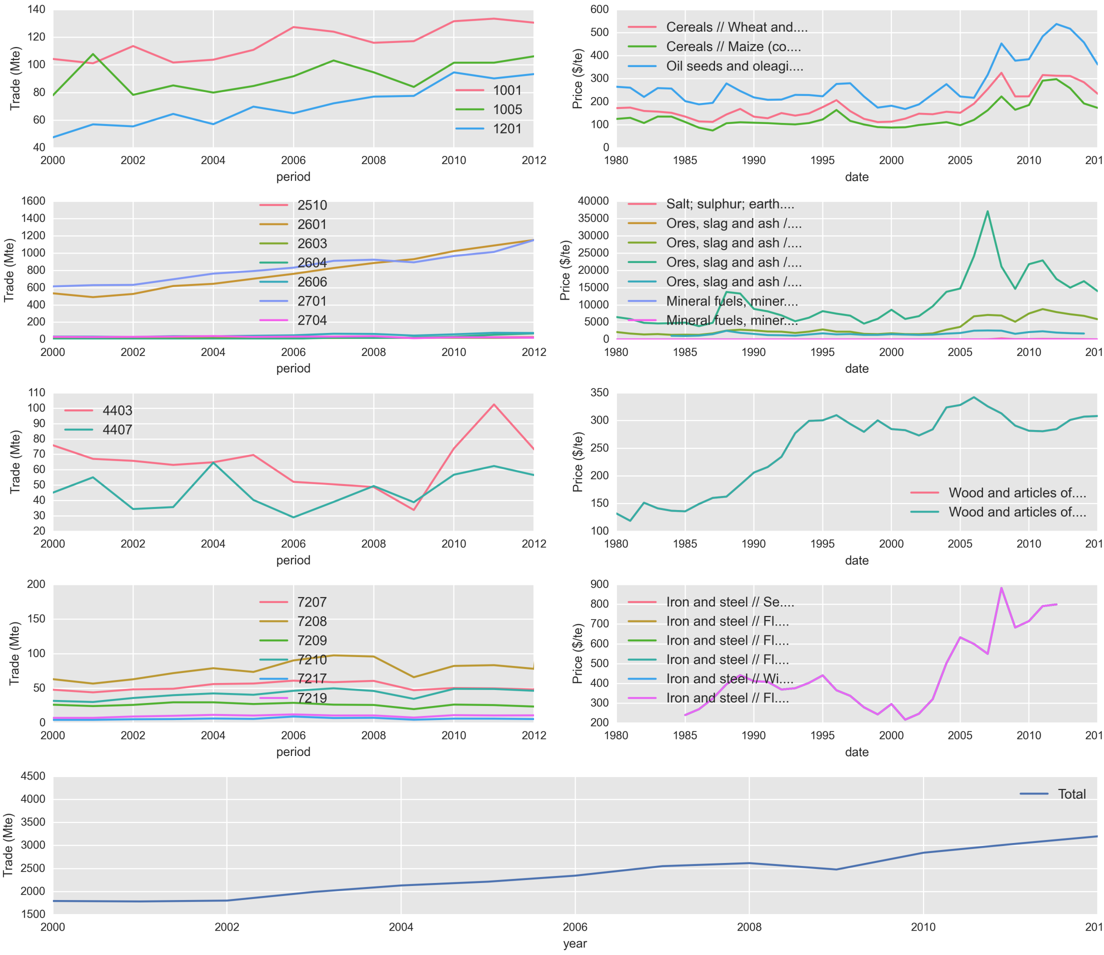


Figure 9.2. Time series (annual) of grouped commodities as trade demand (left column) and prices (right column) with the total trade in the last row. Each commodity from the left column is colour matched to an equivalent price. Where these prices coincide, it means there are multiple commodities mapped to a single representative price. The trade is limited to 2012 for clarity and consistency as there exists significant spurious datapoints in 2014 and 2015. Source: (COMTRADE 2018, IMF 2016)

As mentioned above, there is a tendency, particularly within the main bulks, for the trade to be concentrated within a small group of exporters, and as **Figure 9.3** shows, within trade flow pairs (where a trade flow pair in the context of this data is a country to country trade rather than port to port). Nickel, ores and concentrates (commodity code 2604) has over 80% of trade concentrade between two trade flow pairs.To a lesser extent, but no less significantly, 60% of iron ore (commodity code 2601) trade is concentrated within 5 trade flows. Derived steel products (commodity codes beginning with 7) can be manufactured in any country (notwithstanding economic considerations), unlike resource dependent commodities, have more of a distributed flow resulting in less concentration in trade flow pairs. As noted for the main bulks, the concentration of resources and the concentration of those industries that process these resources (particularly China) results in a dominance of small number of trade flow pairs. However, the demand for derived products and those products that require less processing for end use have a wider demand as is the case for wheat (commodity code 1001) and maize (commodity code 1005).

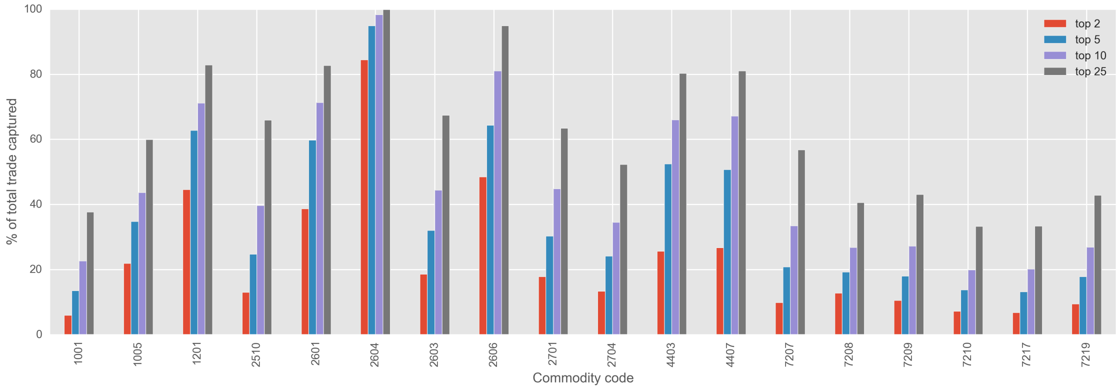


Figure 9.3. Percentage of total trade in each commodity captured by top 2,5,10 and 25 trade pairs in 2010. For reference, the main bulks are iron ore (2601), coal (2701 and 2704), phosphates (2510) and grains (1001, 1005, 1201). Source: (COMTRADE 2018)

In addition to the approximation to the process above, some commodities have a cyclical nature to them, particularly agribulks. **Figure 9.4** shows the time series fit to monthly data to identify trends and seasonality. Outliers have been identified and removed where possible, but some data remains that is spurious (see 2016 for commodity code 1001). Notwithstanding these limitations, the data shows seasonality of varying degrees on an aggregate level. This is particularly the case for soybeans (commodity code 1201) which is dominated by a few trade pairs and as an agribulk is seasonal by nature.

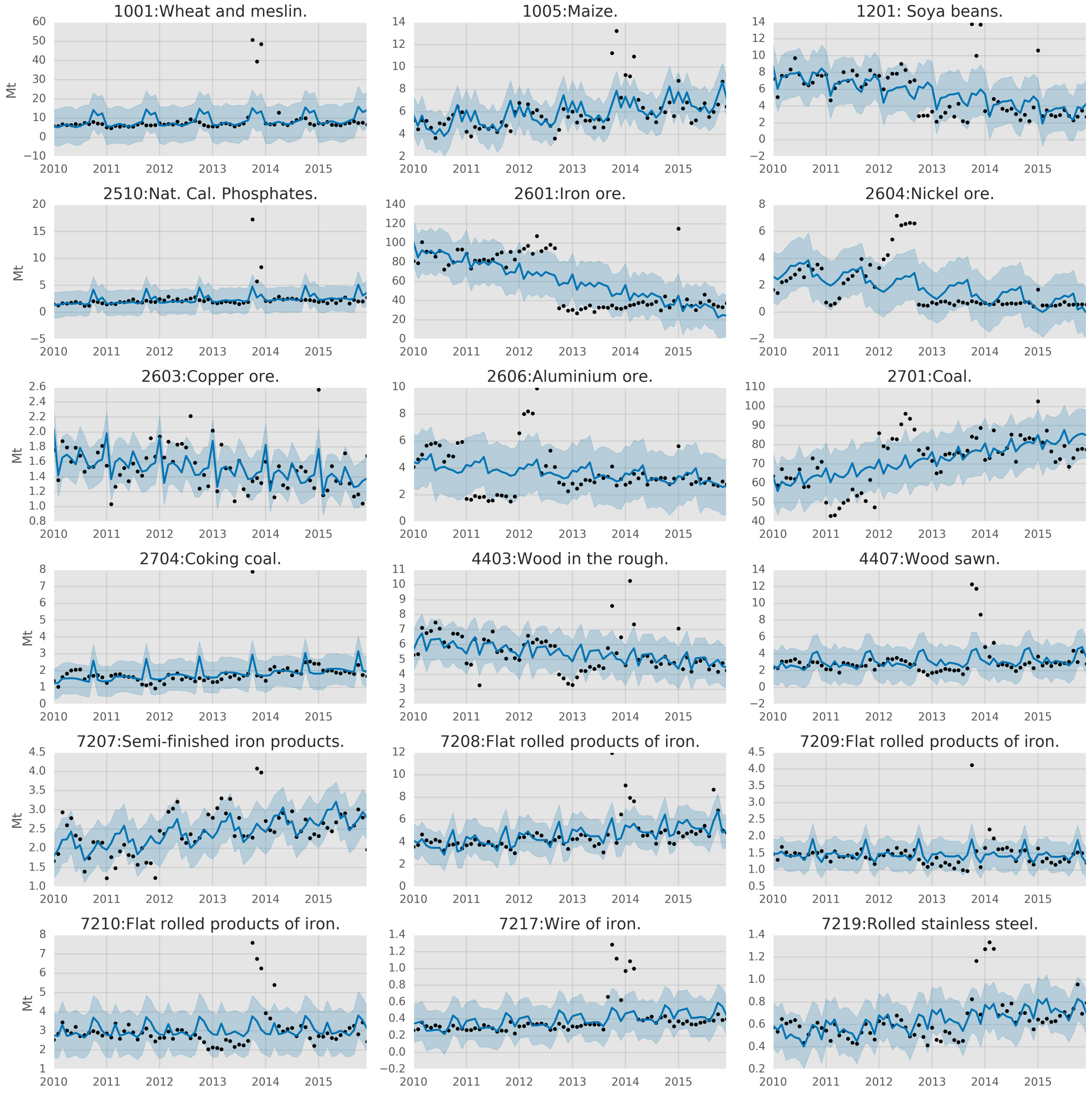


Figure 9.4. Time series of all commodity flows with some outliers removed and analysed using Facebook Prophet. The time series are decomposed in trend, cycle and seasonal elements. It can be seen that the data suffers from reporting errors with some potential outliers still existing. Source: COMTRADE (2018) and Taylor & Letham (2017)

The modelling of trade is generally restricted to the well known gravity model (Anderson & Van Wincoop 2004, Anderson & WIncoop 2003) and the GTAP project and in recent years there have been expansions to dynamic efforts to model trade using system dynamics (Osorio & Aramburo 2009). However, it has been claimed that the prices of primary commodities remains poorly understood (Deaton & Laroque 2003).

9.4 Infrastructure

We can consider the DBSS to be represented as a network of port nodes with edges representing the ships that connect these ports. This is the more disagregated view of international trade, with country to country trade decomposed into a series of port to port flows. For most non-agribulk commodities in the DBSS, there are few inland links with most facilities, for example steel mills and iron ore mines, located close to ports. Therefore, the transport system in the DBSS can largely be considered a pure shipping system with little consideration of inland flows.

9.4.1 Port selection

For the purposes of this thesis, a ports database has been generated for each of the vessel size categories. As no free comprehensive database exists for the dry bulk sector, one is generated combining a number of sources. The source databases for this are:

- Locode database containing all ports of the world. Locodes provides a list of all ports in the world. This is comprehensive in listing, containing 18,127 ports, however, entries are often incomplete with many ports missing location data.
- Eurostat database, which contains all European port and the number of port calls per year for each vessel size grouping. This database contains 521 ports (in contrast locode contains 8656 ports for the European area). It can be assumed that Eurostat contains a comprehensive database of European Union ports as all ports are required to report nationally and then national governments report this data to the EU.
- World port source (WPS), which is an online free source for ports of the world.
- World shipping register. An incomplete download of the ports in this database. Similar to WPS, it is not clear how complete this dataset is. This database has 750 ports.
- Fixture Database: The list of port used in the cargo fixtures listings from Clarksons (2013). Although it is not a complete list, it does provide insight into the most widely used ports in the DBSS.

The approach taken was to combine the above databases leveraging off dry freight specific information in the Eurostat database. **Figure 9.5** shows a comparison across the databases for the European ports, which has the most comprehensive data for vessel calls. WPS (with a size designation of larger than small) and the fixtures databases provides a good representation of the major ports in the European Zone and therefore, their coverage worldwide was assumed to be representative also. The combined dry bulk database was 1011 ports and is shown in **Figure 9.6**. Kaluza et al. (2010) found 616 dry bulk ports in their network analysis of AIS data.

Figure 9.5. Port database comparisions. The top figure shows the comparison across all European Ports. The second is the same figure excluding the locode database. The third panel shows in Europe where there were more than 50 port calls recorded in Eurostat. The final panel shows ports for which the port calls were greater than 50 but also WPS records the port as greater than small.

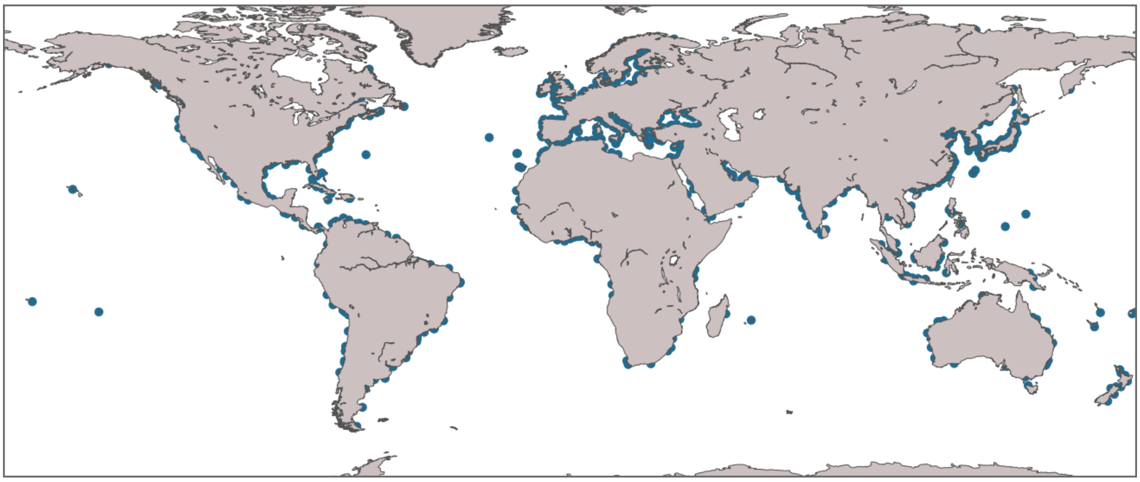


Figure 9.6. Location of ports in selected ports database.

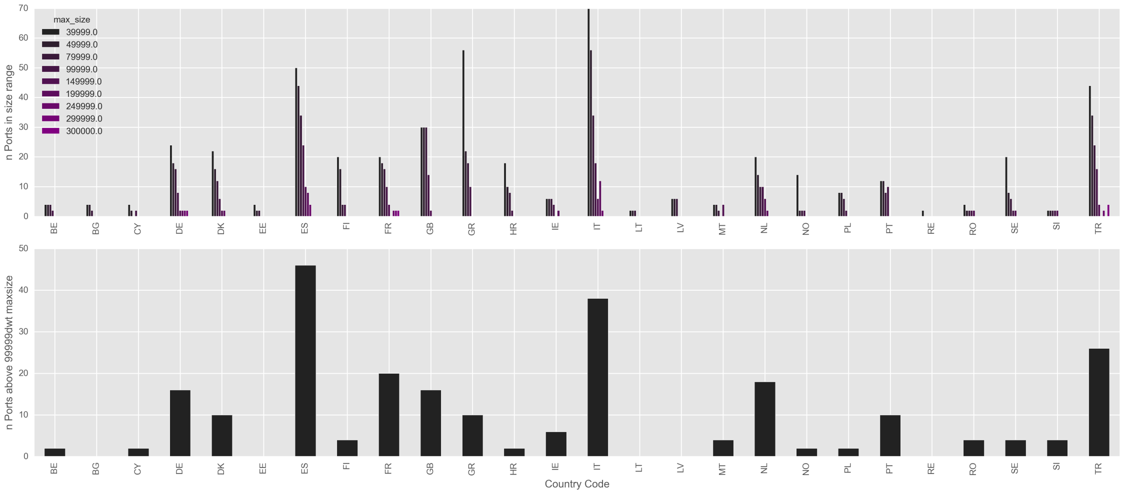


Figure 9.7. The number of ports in each country in Europe with a designated maxsize. The top plot shows the number of ports with a max as shown in the legend. The lower plot shows the number of ports with a maxsize of 99,999dwt or above

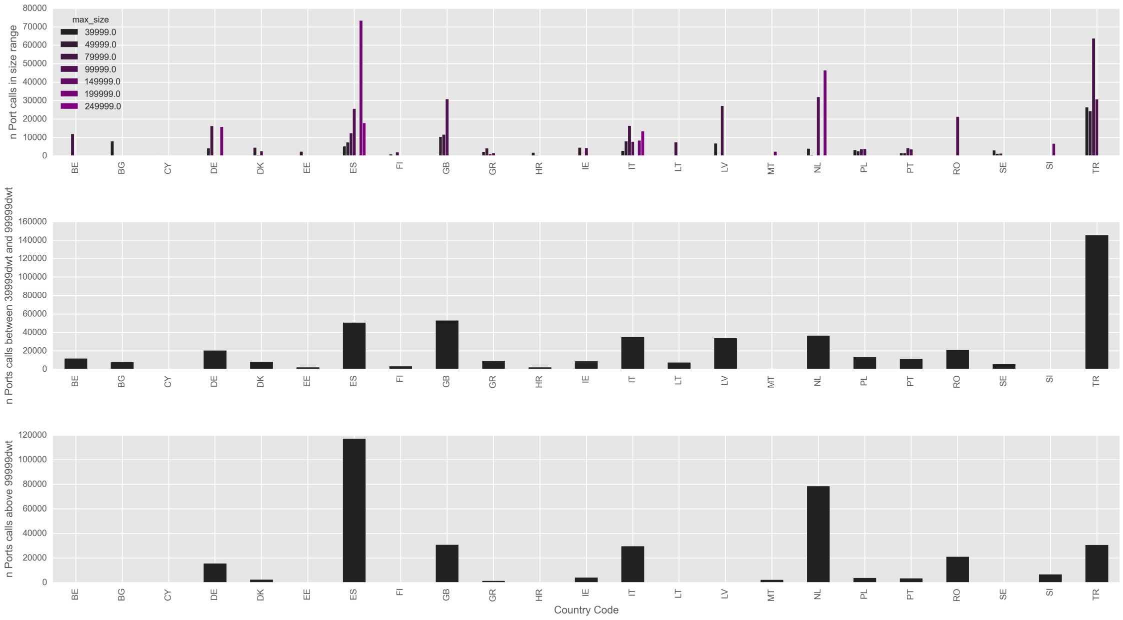


Figure 9.8. Similar to ***Figure 9.7*** *the plot shows the European ports split by max size. In this case, the plots show the traffic in each size category Source EU (2017)*

9.5 Shipping Transport System

9.5.1 Fleet Specification

The DBSS fleet are considered the least sophisticated of the shipping fleets. Cargo neither requires specific temperature conditions nor are there any specific hold safety requirements. There is also little sharing of commodities across different fleet types, although there is anecdotal evidence of some smaller grain flows being transported in containerised vessels. The fleet size distribution is shown in **Figure 9.9**. There is noticeable clustering around panamax size (up to 80,000t) and around 165,000t for capesize cargoes of iron ore and coal.

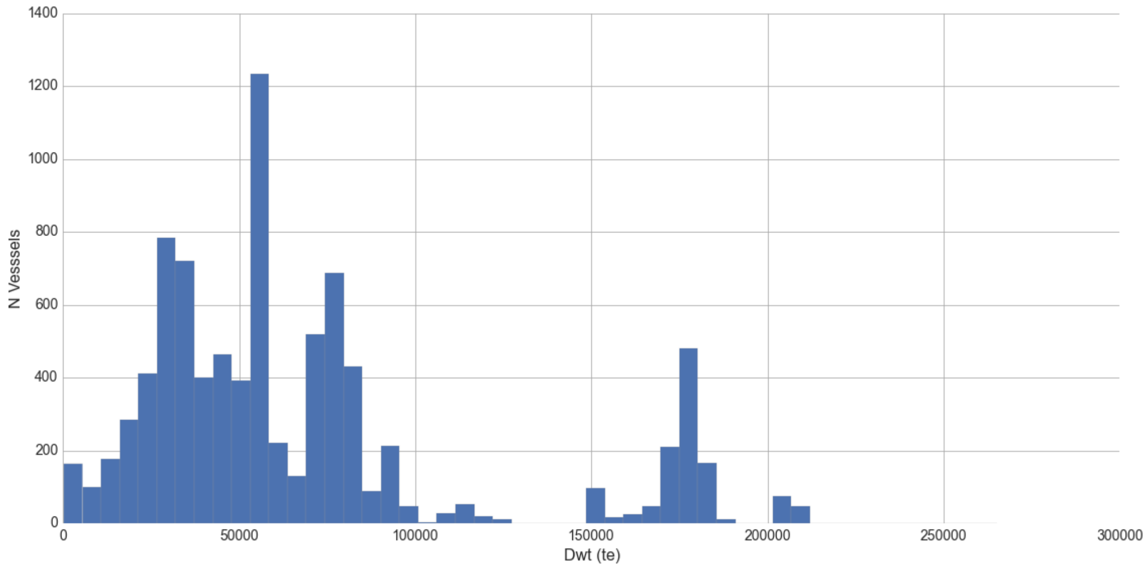


Figure 9.9. DBSS Fleet size distribution in 2011 Source: Clarksons (2011)

There are number of vessel efficiency related technologies available on the market that are at varying levels of maturity. Understanding the fleet in operation and being able to understand an individual vessels fuel consumption is a major factor in determination of transport costs. Increasing transport cost can significantly impact the working capital of ship operators, and may have an impact on market structure. Indeed, in the DBSS, there has been a significant move from voyage charters (where the ship operator pays for the fuel consumption and voyage costs) to trip charters, where these voyage costs are paid by the shipper.

Understanding the future transport costs requires knowledge of the uptake of technology and new build and scrappage. As highlighted above, these decisions are made at the company level, and strongly market dependent. For example, freight rates on the capesize market in 2010 were very low due to a glut of vessel delivery where vessels were purchased during a bull market.

9.6 Human factors

The transport of trade in the DBSS requires the interaction of a number of key stakeholders, not least of whom are port authorities, freight forwarders, shippers, ship builders and shipowners. In simple terms, the transport of cargoes is fundamentally based on the interactions of the shipper, the entity looking to transport the cargo, and the vessel operators. These two key actors will be discussed in greater detail, but first, we will investigate the key markets through which these entities interact.

9.7 Market Structure

The main markets that manage the provision of ocean transport are: the freight market, the sale and purchase market in second-hand ships; the newbuild market; and the demolition market. Although all markets are interdependent, they are all fundamentally driven from exogeneous trade demands that act on the freight market. As alluded to in the previous section, the freight rate market, effectively the cost of transport, works differently for each of the different trades and main commodity classifications. These markets include tankers, bulk carriers, container-ships , gas tankers and chemical tankers. Their behaviour differs in the short-term but because the traders are all in the same broad group, what happens in one sector eventually ripples through into the others (Stopford 2009).

The bulk and tanker shipping markets are believed to most closely resemble a perfect competition structure where companies have little product differentiation and an individual companies pricing strategy has little effect on the market.

Transactions are carried out through shipbrokers, often representing more than one stakeholder. Within each of these individual fleets, there are submarkets by vessel size. In the long run these markets are somewhat independent but in the short run there is some arbitrage between sizes, but typically only in neighbouring sizes. For this reason, we see the different networks in different size categories. Smaller vessels call at more ports throughout the year with short journey times while the larger sizes are deployed on intercontinental trades.

The principal risk in shipping is derived from freight rates, in other words "the financial loss arising from imbalances between the supply and demand for sea transport" (Stopford 2009), which can result in extreme fluctuations in rates (see **Figure 9.10**).

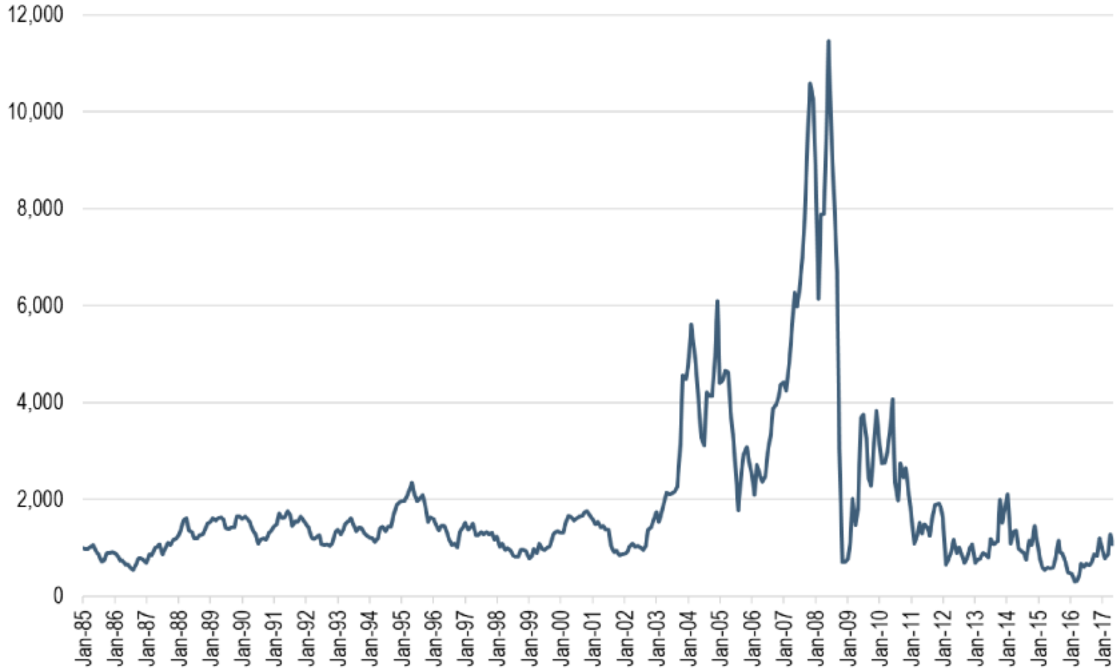


Figure 9.10. The Baltic Dry Index from 1985 to 2017. Source: Rodrigue et al. (2017)

9.7.1 Spot Market

The spot market has effectively three purposes: to enable transport of short term cargoes globally; to ensure efficient allocation of vessels, and; to provide a price signal to shippers and shipowners to allow them to provide enough supply for future decision making. Studies by Beenstock & Vergottis (1989, 1993) suggest that the freight rate is determined by the supply demand relationship. However, work by Alizadeh & Talley (2011) suggests that it is also due to laycan period (the time period between the fixture date and the layday). Indeed, the authors found laycan periods of freight contracts vary directly with freight (charter) rates as higher freight rates generally reflect a lower availability of dry bulk tonnage. In anticipation of low availability, vessel charterers will seek to enter the charter market earlier. Several studies have checked the effect of vessel age in the rates (Alizadeh & Talley 2011, Tamvakis & Thanopoulou 2000), but there was little to suggest this was a significant factor.

The term structure is another driver of changes in freight rates. Short run cargoes are priced based on current conditions while long term freight contracts in reality may include future expectations of the spot but including a risk premium. Adland & Cullinane (2005) conclude the risk premium must be time-varying and depend on current market conditions and the period of the charter.

The freight rate mechanism consists of bargaining between shippers and shipowners as represented by brokers. Due to the sparsity of the market at any time, prices can largely be a result of the bargaining skills of the protagonists. Although it does not share the anonymity of an auction, the freight rate mechanism results in a transport supply being sold at a price determined by competition among the buyers according to the rules set out by the seller (Krishna 2009). In recent years, web portals have emerged that are used for information exchange between shippers and shipowners and also for spot cargo marketplaces (Christiansen et al. 2004). This would be expected to lead to a reduction in price arbitrage and movement towards full allocative efficiency of the market.

The freight derivatives market emerged to allow hedging of risk by compensating for the cost of a large adverse movement in the variable being hedged. Freight derivatives, the most common being freight forward agreements (FFAs), rely on indices which accurately reflect the risk being swapped, examples of which are the Baltic Freight Index (BFI) and the Baltic Dry Index (BDI). In freight forward agreements, the shipper or ship owner hedges against adverse future freight rates.

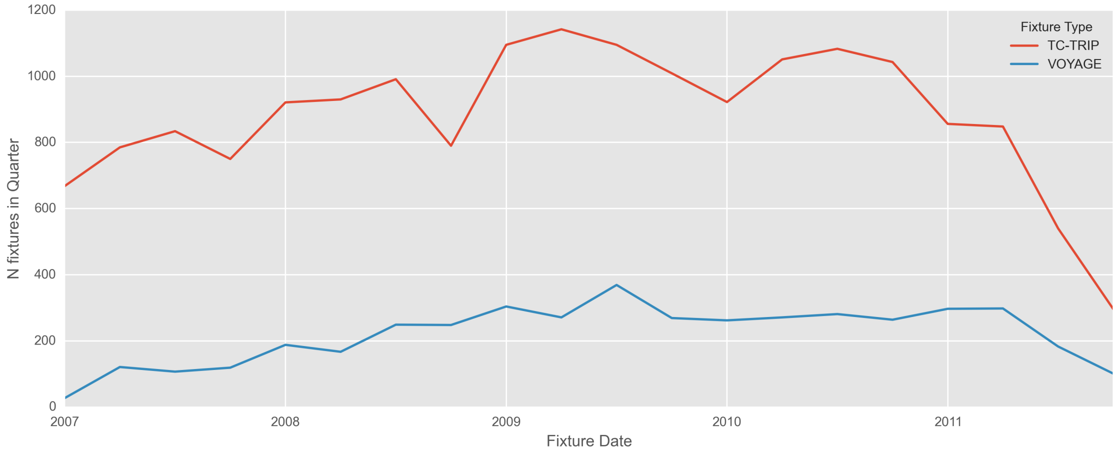


Figure 9.11. The plot shows the number of trip charters versus voyage charters. Source: Clarksons (2013)

9.7.2 Time charter Market

In shipping, the primary risk takers are the shipowners and the cargo owners or shippers and between these two risk is shared by adjusting supply to demand. The platform on which the risk sharing takes places is the shipping contract or charter party. The first case is where the cargo owner is both shipper and ship owner. In this instance the cargo owner is confident about the long term sustainability of their cargo and hence optimistic about adopting the risk. At the other extreme, there is the spot market where the ship owner, as a separate entity, assumes all the risk. In this case, the cargo owner employs the shipowner to transport their goods as and when they need it. A shared risk situation occurs through the period market and freight forward agreements. The period market involves the cargo owner taking long term charters from independent owners. Shippers pay an agreed daily rate, regardless of whether the ship is needed, whilst leaving residual risk with shipowners. Vessels are contracted out for the period through the time charter market. This risk sharing can have unwanted impacts on the fleet turnover and uptake of technology with vessels remaining inefficient despite a clear economic incentive to install technology to improve fuel efficiency, in a mechanism known as the split incentive (Rehmatulla & Smith 2013).

Figure 9.12 shows a preference for a longer time charter period (2 years plus) when the spot rate was high. Most time charters are up to 1 year. For this model, it is assumed that all time charters are for 1 year only.

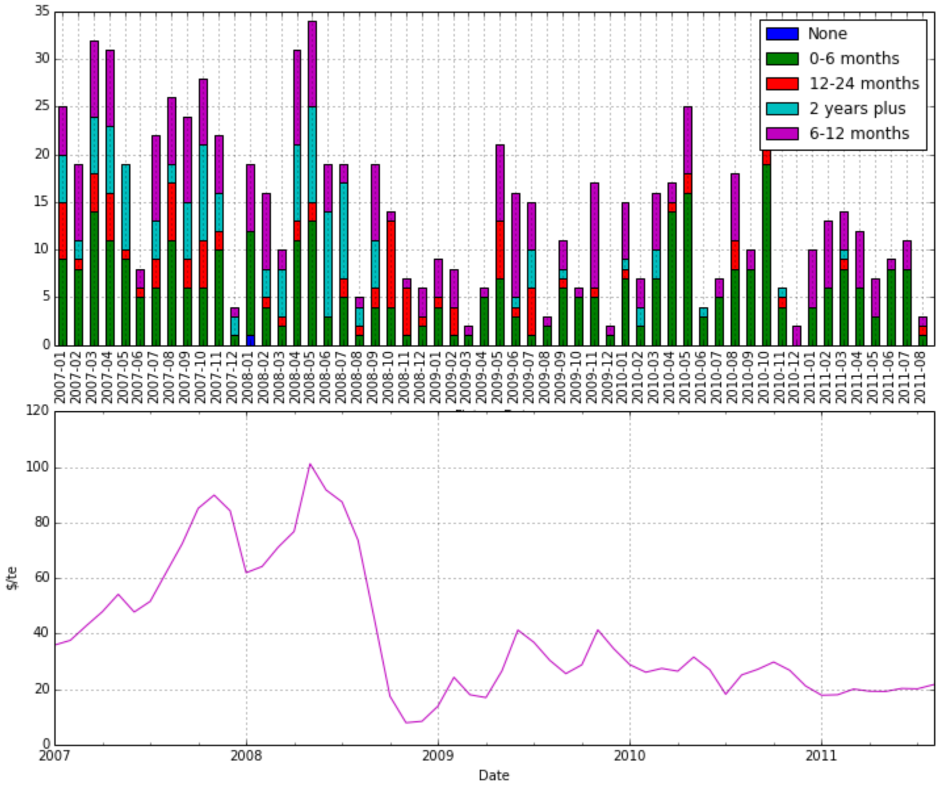


Figure 9.12. The top plot shows the period of time that capesize vessels were chartered within that month. The lower plots shows the spot rate for Tubarao to Beilun for the same period for a 165,000te dry bulk vessel. Source: Clarksons (2013)

9.7.3 Contracts of affreightment

For predictable commodity flows, shippers can arrange regular shipment of the cargo, either internally through industrial shipping or engaging ship operators to provide regular transport of the cargo through contracts of affreightment (CoA). Although it is known that these contracts take place, they are arranged over the counter, possibly through tender processes. In some cases, ship operators form alliances to share the transport risk if the flows are particularly large. Unfortunately, little is known about the price of these contracts or what percentage of flows are on industrial or CoA contracts.

9.7.4 Fleet turnover markets

Scrappage market In the demolition market the customers are the scrap yards, largely based in Asia, which dismantle the ships and sell the materials. Prices are dependent on the availability of scrap and the demand for scrap metal. Prices also vary based on type of ship, which may have different suitability for scrapping.

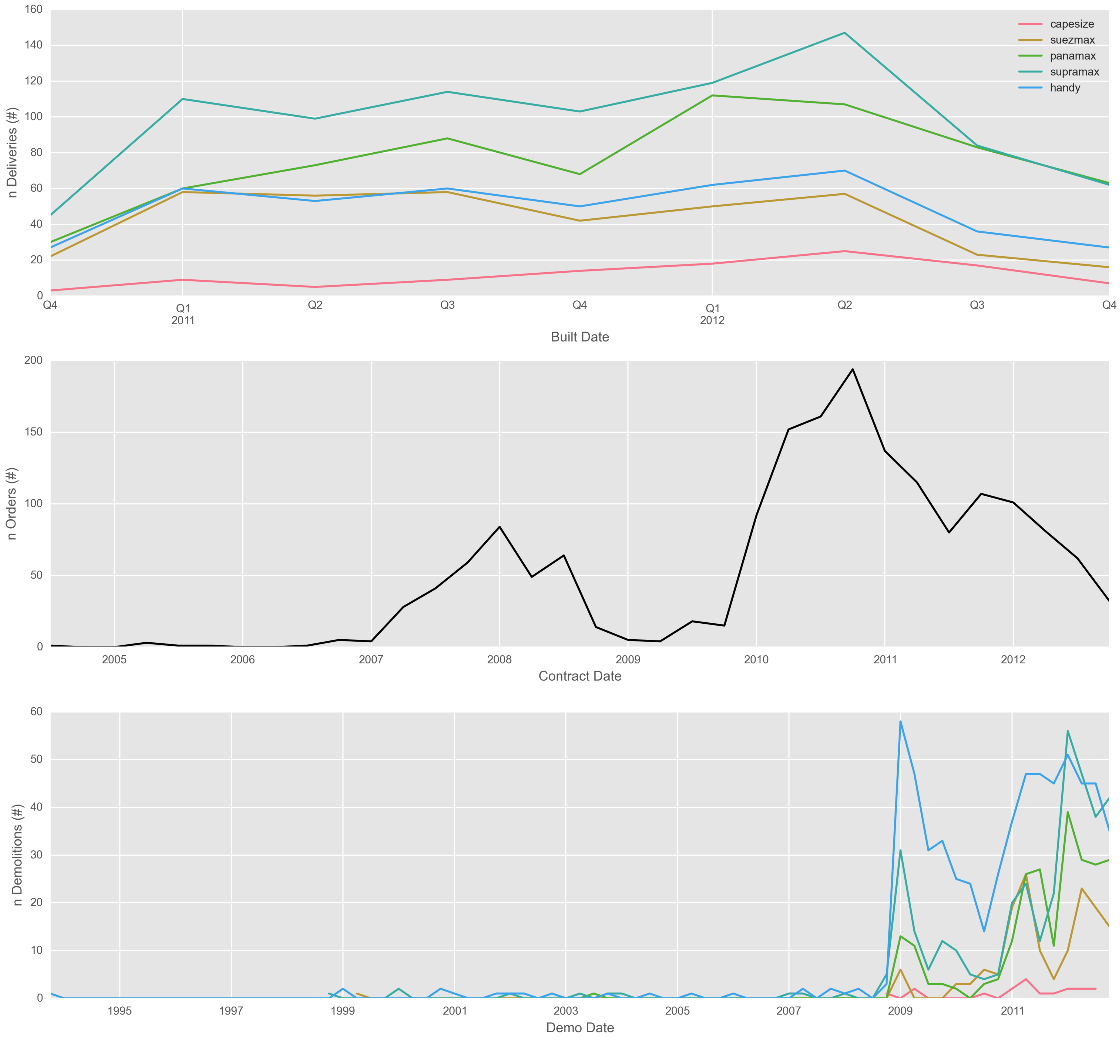


Figure 9.13. The top plot shows the number of vessels delivered in each quarter of 2011 and 2012 in each size category. The middle plot shows the number of vessels on order in total in each quarter. The lower plot shows the number of vessels scrapped in each quarter from 1993 to 2012. It should be noted that these figures are subject to reporting omissions. Source: Clarksons (2013)

New build market Similar to the sale and purchase market, demand for new ships is driven by freight rates, financial liquidity of buyers, availability of credit and expectations. It is also contingent on the price of modern second-hand ships. Sometimes, it is cheaper to buy a new ship than one on the second-hand market due to the shipbuilding time with the ship not available for 2-3 years from the contract date, by which time conditions may have changed. The supply of ships is limited by production costs, number of berths available and the size of the orderbook.

The movement towards a new era of shipbuilding dominated by China is evident in

Figure 9.14 with a significant number of new yards being created and constructing dry bulk vessels. Japan also retains a significant market proportion but there are few drybulk vessels being constructed in Europe. There are several reasons for this, the most important being the lower cost of construction in China and Asia in general but also the move in Europe to construction of more sophisticated vessels. As highlighted already, dry bulk vessels are considered the least sophisticated of vessel types.

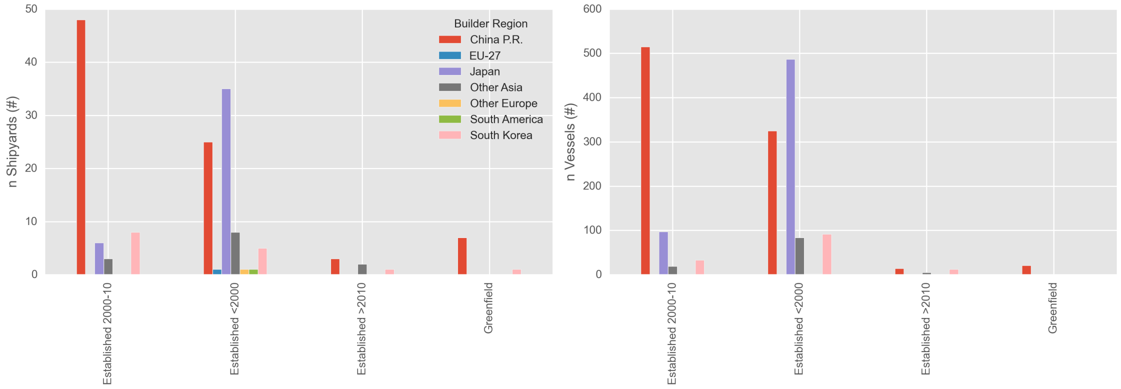


Figure 9.14. The left plot shows the number of drybulk shipyards in each region and grouped by period of establishment. The right plot shows the number of vessels in construction in these yards at the time of reporting (07/02/2013) Source: Clarksons (2013)

Second hand market The sale and purchase market thrives on price volatility with 'asset play' profits earned from well-timed buying and selling activity an important source of income for shipping investors. Freight rates are the primary influence on ship price. Ship price is also affected by age, with ships depreciating at an average rate of 5-6% per year (Stopford 2009).

The participants in the sale and purchase market are the same mix of shippers, shipping companies and speculators who trade in the freight market. A ship may be sold with or without the benefit of an ongoing time charter. A ship may be sold for a number of reasons: company policy of replacing ships at a certain age; shipowners may be changing their trade; the shipowner believes that prices are about to fall; or, finally, there is a 'distress sale' in which the shipowner sells the ship to meet day-to-day commitments.

The top plot in **Figure 9.15** shows the effect of the global financial crash but also the short to medium term effect of time to build. The demand for dry bulk vessels was increasing from 2005 to 2008. Shipowners willing to pay more, in some cases as much as a new build price, for a vessel in the secondhand market in the expectation that freight rates would deliver significant profit over the return period.

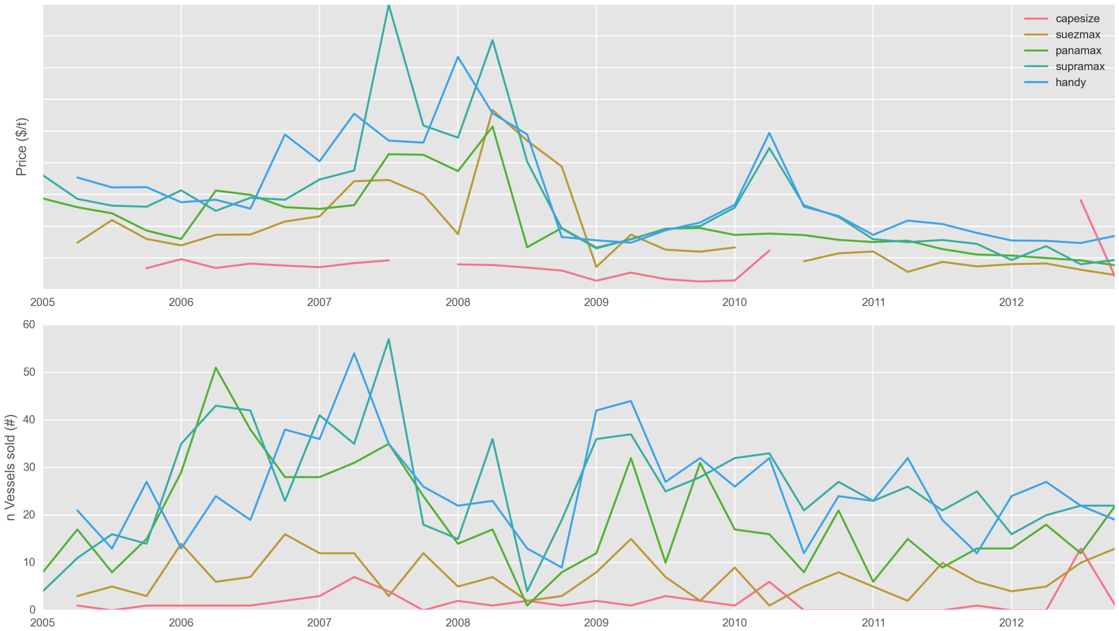


Figure 9.15. Mean quarter price in $/t for each size category in the top plot (where data is available) and the lower plot shows the number of recorded sales within that quarter. Source: Clarksons (2013)

9.8 Key stakeholders

As outlined above, the key stakeholders in the transport of cargo are the shipper and shipowner. These actors will be the focus for the remainder of this thesis. Christiansen et al. (2007) refer to three levels of planning within shipping that these stakeholders engage in: operational, tactical and strategic which range from short to long planning horizons. The spot market occurs at the operational planning level. On the shipowner side, this level of planning includes cruising speed selection for vessels, shiploading and environmental routing (Christiansen et al. 2007). These are facilities that shipowners can adopt to manage the provision of transport and their costs. However, shippers also have the facility to alter the time at which a cargo is deployed and the volume of that cargo to deploy. For the most part, cargo sizes are decided at the tactical level, but there are alterations that occur in the short run to take account for supply/demand imbalances. For example, in a tight capesize market iron ore cargoes can be deployed on panamax vessels, resulting in a cargo size change of 165,000t to 55,000t. Accounting for these short run fluctuations is key as it can provide insight into the effect of shocks on the system: for example, port flooding or spikes in demand. Operational planning as used by shippers considers the size of cargoes and when to charter a vessel that is not on a CoA. In the real case, a cargo size may be specified by the shipper (where the shipper is the purchaser of the cargo, for example a steel mill) and would be reluctant to split this cargo or ship on multiple vessels, although for smaller cargoes avoiding cargo rerouting may not be possible. This type of planning occurs at the spot market for voyage or trip charters. There is also some fleet management that occurs at this level where operators may have to redirect vessels to keep to schedules possibly due to port delays.

When considering what size range to allow for a cargo, the shipper considers a number of factors:

- Expected change in freight rate in each size category (contingent on how many vessels there are in a sea region)
- Expected current freight rate in each size category
- Cargo cost
- Cargo inventory volume
- Stock at destination and at port
- Allowable vessel size at load and destination ports
- Expected cargo size

What reserve price to suggest is contingent on a number of factors:

- The maximum bid price offered by the shipper if known
- The current state of the market. In other words, the probability of winning the contract at various ask prices. This information may not be available to the shipowner or may be unreliable.
- The empty return leg (or ballast journey) required to pick up the cargo as this will affect affect future expected costs for the next fixture.
- The ballast and loaded speeds, as these will voyage costs.
- The cost to the shipowner of not matching. This is the opportunity cost of taking the cargo.
- Once a cargo is delivered, a shipowner repositions to the area where the average number of cargoes is largest or a location that allows them to deploy to multiple potential load areas.
- The expected revenue from a contract at the destination port of the cargo.

- The technical characteristics of the vessel as these will affect the running costs of the vessel.

The shipowner is faced with a series of cargoes that require transportation and must provide an ask price for each of their vessels to transport this cargo. However, at this point they do not know how many other shipowners there are, nor do they know demand at the next timestep.

As noted by Stopford (2009), these contract types mean that the shipowner carries all the risk. If they are held up at a port due to congestion, it is they who must carry the cost. Although they would be able to claim any additional days above the laytime back from the shipper as demurrage, this is time out of the market for the shipowner, time which they would prefer to spend trading. Therefore, they must ensure a margin to allow them make a profit. This is balanced against the need to win the cargo, particularly if there is low market demand.

9.8.1 Shipper

There are three broad categories of shipper:

- Miner/Producer: Deliver the cargo as a cost, insurance, freight price (CIF) to the purchaser, which in the case of iron ore would be a steel mill. The shipper is looking to minimise cost of transport as the commodity cost is already sunk. However, included in this transport cost is the inventory cost involved with storing the cargo as well as any late fees arising from late delivery.
- End user/Customer: They are covering the costs of the transport along with initial purchase costs (free on board, FOB). This would be the steel mill organising its own transport.
- Trader/Speculator: They will not be the end user and are looking to profit on arbitrage or an expected upturn in the commodity price to sell it to the end user. This shipper type is maximising profit on the whole transaction.

At the strategic planning phase the shipper, regardless of whether they are of the first or second type above, looks to manage their inventory in a demand and supply elastic state. They create a projection of the demand and production of their good will evolve in the medium to long term (1-5 years) and plan for this in line with their risk preference. A major issue with this is the inherently unpredictable and volatile nature of these factors.

The key factors that the shipper must account for in developing their strategy are:

- The production costs for their goods
- The projected change in demand for their goods.
- The projected freight rate.
- The cost of new vessels and associated operational costs.
- The cost of time chartering vessels and associated operational costs.

The shipper has the following information available to them to a greater or lesser extent.

- Market analysis such as spot freight rates on routes for particular vessel size ranges.
- Annual trade in the sector. This could be disagregated into a country to country matrix for some commodities but often this is not the case and it is unlikely to be available at a port to port level.
- Overall transport costs.

9.8.2 Shipper Planning

Aside from transport costs, other factors are important when choosing how to transport your goods. Factors such as transport reliability, product time to market, product value, parcel size are also important. Where time is an important factor and the product is less sensitive to transport cost, transport by air is the mode of choice. Due to the low per unit transport costs, goods that travel by sea can be characterized as goods that are sensitive to these transport costs. On the other hand higher value, lower volume freight is better able to absorb this ”transport cost penalty” imposed by transport by air (Mangan et al. 2010).

Strategic planning The key factors that affect how a cargo is shipped in the long run is encapsulated in the economic order quantity (EOQ) model (Cachon & Terwiesch 2009) initially proposed in the shipping sector by Kendall (1972). The model is shown in **Equation 9.1**. Port costs, including handling costs, and storage costs are assumed to scale linearly with size and therefore are not dependent on parcel size.

$$TC = (\frac{Q_s VI}{Q_y}) + (\alpha_0 + \alpha_1 Qs^{\beta}) \tag{9.1}$$

where

$$\begin{aligned} TC &= \text{Total costs} \\ Q_s &= \text{Vessel size} \\ V &= \text{Commodity value} \\ I &= \text{Expected rate of return on the capital cost} \\ Q_y &= \text{Annual flow on the route, te} \\ \alpha_0, \alpha_1, \beta &= \text{freight cost model parameters} \end{aligned} \tag{9.2}$$

Figure 9.16. Approximate EOQ model consisting of two key terms (in parentheses): the opportunity cost of storing the cargo rather than transporting and hence selling it, and; the transport costs. The opportunity cost of storage increases as parcel size increases as the cargo is being held in storage until the parcel size is large enough for transport. Source: Author and Kendall (1972)

The two terms in the model (cost of capital tied up in the cargo and the transport costs) are both dependent on vessel size. Transport costs typically provide economies of scale that are offset by the cost of capital tied up in the cargo, as shown in **Figure 9.17**. In the long run low price high volume routes attract larger vessels. At first approximation an EOQ model can be used to assign commodity flows to vessel sizes. However, a commodity is not shipped in isolation and indeed many shippers can be involved in the transport of cargo thus reducing the economies of scale that can be achieved. Together with this, shippers will control an origin-destination flow as part of a larger operation. For example, Vale in Brazil, own and charter a large number of vessels for which they use to ship iron to a number of destinations in Asia (dominated by Chinese demand).

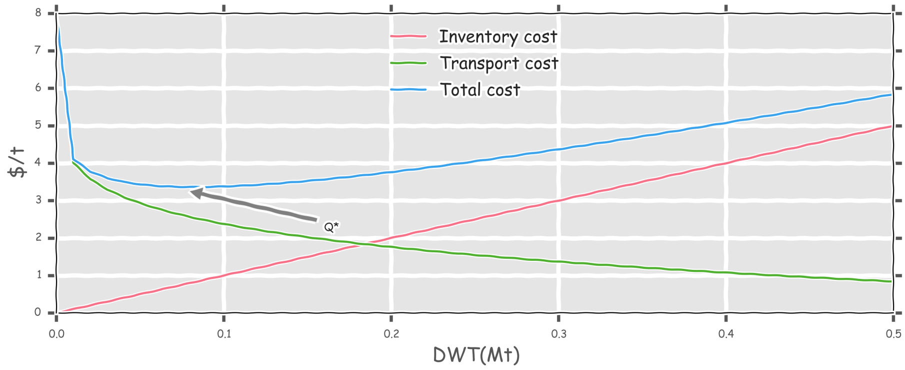


Figure 9.17. Indicative illustration of EOQ model. Transport costs reduce according to a power law from economies of scale, whilst inventory cost increase linearly. The optimum vessel size is indicated by Q∗

Optimisation of systems of transport at various planning stages has allowed shipping companies improve their operations. Operations research developed in the aviation industry with optimisation of crew scheduling, from its origins in branch and bound theory (Land & Doig 1960), and has been late coming to shipping. Nonetheless a significant amount of literature, albeit with limited applied research (Alvarez 2008) and focussed on the liner trade, has developed over the last ten years (Christiansen et al. 2004, 2013, Meng et al. 2013). However, these analyses treat the problem as closed systems with demand most often treated as inelastic and freight rate revenue constant. Work by Engelen et al. (2006, 2007, 2009), has looked to expand looking at individual companies to the whole sector, incorporating the dynamic behaviour of individual companies and their interactions.

Determining the allocation of commodity flows to vessels and routes requires modelling of the individual company operations and aggregating to the global level. Effectively, this requires understanding the system as a complex adaptive system. Engelen et al. (2007) has done some seminal work in this regard suggesting a move away from equilibrium model.

Charterers (shippers who charter a vessel) hedge against the spot freight rate and indeed availability of transport by using industrial shipping or through CoAs. This has significant benefits:

- Allows charterers remove risk from the cost of transport
- Guarantees transport of cargo, excluding any port impacts.

However, there are also disadvantages

- For industrial shipping, significant upfront cost for purchasing vessels.

- Assumption of stable demand

At the strategic level, the shipper looks long-term where demand is elastic and uncertain. The shipper selects long-term CoAs, whether to purchase vessels or engage in long-term time charters, a decision implemented over the selected planning period of the shipper. If the shipper has an industrial shipping operation, they require vessels. The decision to buy a vessel is determined based on the current time charter rate and the long run rate. If the current rate is above the long run rate, then it suggests the market is high and it would be better to build.

Similarly, the shipper reviews their existing fleet. If the costs of running any of the existing vessels is greater than the current spot rate and the vessels have a low capacity utilisation, then the vessel is likely scrapped. This effectively means that the vessel is being under utilised, possibly because the expected schedule was incompatible with this vessel and it would be cheaper to transport cargoes on the spot market or time charter a vessel in.

In effect they are managing the inventory through CoAs, industrial shipping, voyage chartering shipping or a mixture of the above.

Tactical Planning There are few options here for the shipper as they simply look to optimise their schedule. Shippers time charter vessels over various periods as shown in **Figure 9.12**. Often these vessels can be subchartered although this is unlikely to be the case for shippers, as they are less likely to engage in asset market play due to business focus on inventory flows. In most shipper cases, the time chartered vessels are used for industrial shipping to move regular cargo between ports in an optimised schedule. This would be done where cargo flows are large and predictable. As tactical planning occurs every 3-6 months, there is a possibility of a drop off in demand or indeed an increase requiring them to alter their schedule.

Operational Planning The Shipper, at this scale, manages their short-run demand for transport. Although there is some flexibility in terms of cargo timing, ultimately cargoes are set and require transport. To this end, Shippers either request transport through the spot market or manage the process through their inhouse time chartered or owned fleet. The agreed price is based on several factors, displayed in **Figure 9.18**, most important of which are voyage costs and local supply/demand balance.

Figure 9.18. Factors influencing agreed spot price

Shippers will meet the market price, with some alterations in layday adjusted in expectation of changing freight rates. Together with this, they may also adjust cargo sizes to account for high rates in a particular market.

9.8.3 Shipowner

Similar to the shipper definition above, a number of different types of shipowners exist:

- Shipowner and operator. The agent owns and operates the vessels, this could be on a spot, trip or time charter market. Or the agent could be managing contracts of affreightment.
- Shipowner but does not operate the vessels. In this case, the shipowner purely time charters out the vessels.
- Single vessel companies also exist, however these are often subsidiary to larger companies that have been created to allow the parent companies fold the subsidiary if losses are too great and thus insulates the parent company from the losses of the subsidiary.

The shipowner has similar information available to them as does the shipper:

- Market analysis such as spot freight rates on routes for particular vessel size ranges.
- Annual trade in the sector. This could be disagregated into a country to country matrix for some commodities but often this is not the case and it is unlikely to be available at a port to port level.
- Operational costs of their fleet. In some cases, shipowners do not have a good knowledge of the operational efficiency of their fleet, although this is improving, mostly brought about by the 2008 global recession and increasing fuel costs.

9.8.4 Shipowner Planning

Strategic Planning For a shipowner/operator the strategic planning phase is tasked with fleet size adjustment. The shipowner decides whether to purchase vessels, either new or from the second hand market and whether to scrap vessels. In addition, they would also look at retro-fitting their existing fleet.

Tactical Planning Negotiations would occur over a period of time during which the spot market may change creating upward or downward pressure on the time charter market.

The shipowner will hire the vessel based on how the spot market is performing and what their expected revenue will be over the period of the charter. The shipper on the other hand is is trying to reduce the risk of transport for the commodity flow they wish to transport. As a result, the time charter rate tracks the prevailing spot rate. Note that the shipper uses the spot rate in the region where the vessel will be deployed. This can push up this rate or reduce it depending on how well serviced this region is.

Operational Planning This is the day to day operation of their fleet. This may involve repositioning vessels that have not been matched to a cargo. The vessel ballasts to a typical load region and is then anchored offshore where it waits on a match.

Vessel operators often will hold off for the right cargo that places them in the correct part of the world. Also, they may include an additional premium, known as term structure, if the fixture is likely to be long or places them far away from the main market (Adland & Cullinane 2005).

9.9 Information problems and decision making under uncertainty

One of the key elements with shipping is its inherent unpredictability. Freight rates can vary enormously in the period of a few weeks due to radical changes in local demand and supply. This has significant knock on effects to learning from previous data. Due to the number of unknowns (number of ports and their respective distances, the variety of vessel types and size and the variety of cargoes) and the relative sparsity of observations it is very difficult to provide a statistical model of a robust quality.

9.10 Regulation

Shipping, alongside aviation, is unusual in its regulatory framework. An international UN body, the International Maritime Organisation, creates regulations through agreements between member states which are then enforced at port state level. As with many international regulatory bodies, progress is slower than the wishes of some member states, resulting in some members or groups of members enacting individual regulations. An example of this is the emission control areas around the North American coastline and also in Northern Europe. These areas control for pollutions, specifically SO_x and NO_x. Additionally, the EU has taken unilateral action requesting owners to report their GHG emissions within the EU from 2018 onwards (Parliament 2015).

Ship Energy Efficiency Management Plan (SEEMP) and Energy Efficiency Design Index thresholds (EEDI) came into effect in January 2013. SEEMP enforces the use of management with no quantitative targets; EEDI however requires vessels to achieve an efficiency level in their design state.

9.11 Summary

This chapter gave a brief outline to the relevant areas of the DBSS. This provides the context for the ABM framework and strategies outlined in the following chapters. The DBSS is dominated by two key stakeholders: the shipper and shipowner, effectively encapsulating the demand for transport and the supply of transport respectively. The decision making framework for each of these agents can be encapsulated in three stages: strategic, tactical and operational representing long term, medium term and short term planning respectively. The commodities transported are dominated by mined materials and agribulks, between few countries, particularly China, Australia and Brazil in the iron ore trade. The cost of transport, represented by the spot market, is susceptible to extreme price fluctuations and cyclical behaviour, which is damped to some extent by the three planning stages available to the shipper and shipowner.

Chapter 10

An Agent Based Modelling Framework

10.1 Introduction

This chapter outlines the framework for *GooFy*, the ABM of the DBSS, which is developed for this thesis using the Repast library (North et al. 2013) in the Java programming environment. Similarly to Bergkvist et al. (2005), the decision making is carried out by the interactions of the agents whilst the physical system is emulated using an object oriented approach (through vessels and cargoes).

Where expedient, *GooFy* endogeneously generates interactions, signals and responses from the fundamentals. For example, the spot rate is generated through a negotiation between *shippers* and *shipowners* resulting in a Nash equilibrium price. Where this is not done, a model of reduced form is deployed. For example, the scrappage price for vessels is generated from a model that relates vessel size to offer price.

The following sections discuss in detail the *GooFy* framework.

10.2 Execution environment

In an ABM, interactions between agents occur either through spaces or networks. Spaces are typically physical spaces with agents reacting due to co-location or proximity. *GooFy* utilises both of these types of interactions. Networks are created for each of the markets within the model, typically in two stages. Agents can enter the selection market (for example spot or CoA) meaning they wish to participate is the live negotiations.

Then once live negotiations occur, they enter the related live market network, adding vessels or cargoes in the case of the spot market, they wish to negotiate on.

10.2.1 Geographic network

The geographic network is the global maritime shipping network consisting of *ports* and the connections between those *ports*. There can be multiple edges between nodes, representing the different routes available depending on *vessel* size. This network can be theoretical, as long as *ports* exist as nodes and the network is not disjoint (it is fully connected). *Vessels* are assumed not to detour to collect fuel. It is assumed that fuel is picked up en route at either load or discharge port or at a port on route, and has a negligible time effect or voyage cost effect. Notwithstanding this simplification, the *vessels* are mapped geographically in the model as the geographic location of the *vessel* is integral to the costing element for the *shipper* and *shipowner*. Together with this, routes are defined by a threshold deadweight, above which *vessels* cannot enter to simulate constrained routes such as the Panama and Suez canals. Furthermore a *vessel* always takes the shortest route that it is allowed to.

10.2.2 Agent communication networks

These are either within their peer group (company size etc) or *vessel* size. The networks are dependent on the strategies that have been selected for a particular agent. Together with this they also represent shipbrokers. As a shipbroker, they would have a knowledge of the transactions that they are in control of. Therefore, they can provide market intelligence based on this information. Finally, it is also based on industry publications, for example Shipping Intelligence Network provided also by Clarksons, where these transactions are disseminated in a derived format for companies, through a market analyst agent. These are the main sources of market intelligence available to agents and are represented through the networks.

The other communication networks are the market networks themselves. These are directed networks to the *shipbroker* to indicate what is on the market.

10.3 Trade and commodity flows

The *GooFy* system is driven by the demand for transport, where each *shipper* controls one or more *shipper schedules* representing a flow of a single commodity between two *ports*. Typically, a *shipper* will manage all the *shipper schedules* exported from a *country* for a *commodity*. All the *shipper schedules* within a *commodity* for a single exporting *country* for a particular *shipper* are encapsulated as *commodity flows*, as shown in **Figure 10.1**. They are encapsulated as *commodity flows* as a single production process drives each *commodity flow* which is in turn disaggregated into its constituent *shipper schedules* in proportions set in input parameters.

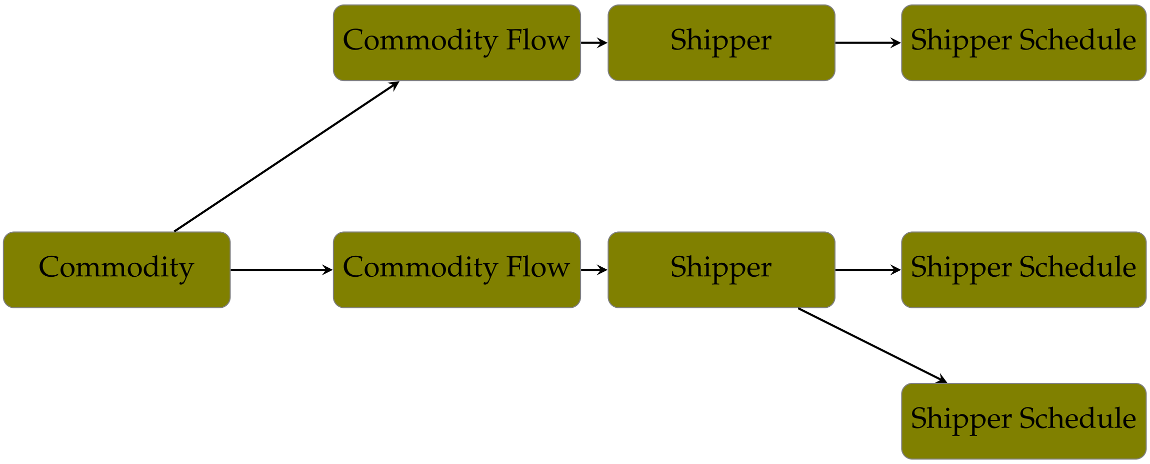


Figure 10.1. Commodity flow definitions within GooFy. A single commodity can have multiple commodity flows per country which are each allocated to a shipper. In turn these are split between origin-destination pairs to form shipper schedules. The graphic shows an example of a potential commodity disaggregation.

10.4 Agent Definition

In ABMs, the agents and indeed the interactions between agents can be anything from simple rule based interactions to complex multilayered interactions. Endeavouring to represent the actual system, the interactions in *GooFy* are multilevel. Each agent can be a self-aware economic entity that makes multiple decisions across different time scales. In the case of operational desisions for shipping, these decisions can be complex and not predictably verifiable or solvable in polynomial time (NP-Hard problem). Similarly, the interactions between agents are typically conducted through an intermediary (the *shipbroker* agent).

GooFy contains two types of entities: agent and objects, with agents defined as learning intelligent agents. The objects are described in **Section 10.6**.

10.4.1 Agents

There are three types of agents: *shippers*, *shipbrokers* and *shipowners*. Each of the *shippers* and *shipowners* represent companies on the demand and supply side respectively of shipping. The *shipbroker* is a single agent that controls the interactions on the various markets. This simplification of the shipping system will be explored in more detail in **Chapter 11** when we explore the various strategies that these agents can use.

Shipowners and *shippers* are defined at design time with no exits or entrants during the simulation.

Shipper

The *shipper* controls the flows of product between the source and sink controlling stock at either end. The sink location has an acceptable buffer which the *shipper* can use to control the flow. Through the strategies outlined in **Chapter 11** the *shipper* manages this flow process.

A *shipper*, depending on their strategy, can own *vessels* and at simulation instantiation are allocated *vessels* as indicated in the model inputs. However, their main purpose is to control their *shipper schedules* which are the commodity production and consumption demands at origin and destination *ports*.

Shipowner

The *shipowner* typically, has an overall goal to maximise their profit. They can have various strategies through which they can achieve this as outlined in **Chapter 11**. They manage their own fleet. All market interactions are done through the *shipbroker* so the *shipowner* has no direct contact with a *shipper*. Together with this, they have no actual physical presence within the model but they do control the locations of their *vessels*.

At instantiation, a *shipowner* is supplied with a number of *vessels*. Depending on the scenario, this may be representative of an actual company active currently in the market or it is a random allocation. The system is closed preventing new entrants and indeed, existing *shipowners* exiting the market.

The *shipowner* is not limited by capital and can therefore run at a loss. However, this may require them selling *vessels* if the *vessels* are not profitable, depending on their strategy.

10.4.2 Shipbroker

There is a single *shipbroker* agent that manages all market interactions on the transport market (ie CoA, Time and Spot Market).

10.5 Agent Interactions

The following sections outline the main process flows within *GooFy*. Within the model, actions are triggered either as a response to other actions (for example, through a potential cargo being added to the spot market) or through action scheduling (for example, a shipper may schedule a review of their strategic plan every 6 months). The Repast library runs the model chronologically through sequenced time steps with each time step representing a period of time (for *GooFy* there are 192 time steps in each year).

10.5.1 Spot Market

Cargoes that have not already been assigned to *vessels* are mapped to *vessels* through the freight rate mechanism. *Shipowners* and *shippers* agree a rate to ship a *cargo* from a load *port* to a destination *port* within an agreed time period. In recent years, the price takes two forms: voyage charter or trip charter. A voyage charter includes the operational cost of the vessel in the price and is thus provided as a $/t price. The trip charter is an agreed daily rate where the shipper pays the voyages costs and is also at risk due to any delays at load or destination port. Within *GooFy* only the voyage charters are used.

The freight rate mechanism consists of bargaining between shippers and shipowners who are represented by brokers. Within a transaction, there can be any number of brokers but in most situations there is a single representation for each party. Due to the sparsity of the market at any time, prices can largely be a result of the bargaining skills of the protagonists. Within *GooFy*, the freight rate mechanism is modelled as an auction system: the process is displayed in **Figure 10.3**.

The system allows for strategic behaviour on behalf of *shippers* and *shipowners*. The non-Walrasian approach means the allocation of *vessels* to cargoes allows for information asymmetries and mutual learning whilst remaining pareto efficient. For a Walrasian auctioneer, strategic behaviour is removed and interactions are "passively mediated through payment systems" (Tesfatsion 2006). This pareto efficiency occurs for the allocation of cargoes that are available for transport on the spot market at a point in time. This should not be conflated with the overall efficiency of the allocation of cargoes over a longer period. In other words, although the allocation of cargoes on the spot market at any one time is pareto efficient, the allocation of cargoes to vessels over a full year is not necessarily (and highly likely not to be) pareto efficient.

The measure of an efficient double auction that is typically used is the allocative efficiency, shown in **Equation 10.1**. This tells how close a market is to theoretical equilibrium, the closer E_a is to 100, the more efficient the market. For a continuous double auction with agents, including zero intelligence plus, Cai et al. (2014) estimated an allocative efficiency of 90% typically. An allocative efficiency of up to 100% (allowing for inefficiencies in the convergence of the genetic algorithm solution method) is assumed for the double auction in *GooFy*. This is a strong assumption, that within the system *cargoes* are allocated *vessels* to maximise system utility. The double auction, it has been suggested, is expected to lead to efficiency irrespective of the way the traders behave, and in fact trader intelligence is not necessary for the market to achieve high efficiency and that only the constraint on not making a loss is important (Cai et al. 2014). The problem that determines the winners of bids is formulated as an NP-Hard set packing problem (SPP) (Dai & Chen 2011). Moreover, allowing a reduced allocative efficiency, the author assumes, should not significantly affect results unless there was a systematic bias for some agent strategies.

$$E_a = 100\frac{P_a}{P_e} \tag{10.1}$$

$$P_a = \sum_i |v_i - p_i| \tag{10.2}$$

$$P_e = \sum_i |v_i - p_o| \tag{10.3}$$

Where
E_a = Allocative Efficiency
P_a = Actual Profit
P_e = equilibrium Profit
v_i = Private value of agent i
p_i = Actual price of trade made by agent i
p_o = Equilibrium price

Figure 10.2. Allocative Efficiency of a double auction (Cai et al. 2014)

The clearing of the market results in what Stopford (2009) refers to as momentary equilibrium. The momentary equilibrium price varies between regions as there is likely to be inconsistent supply/demand relationships at each region (and for each *vessel* size category). The process itself resembles a dynamic game involving sequential moves by *shipper* and *shipowner* (Gibbons 1992).

The *shipper* (through the *shipbroker*) provides a signal to the *shipowner* that they wish *cargo* to be shipped within a minimum and maximum parcel size. They achieve this by first identifying *cargoes* that are requiring transport. For each *shipper schedule* that the *shipper* manages, the *shipper* estimates *cargoes* that can be shipped with a price distribution for each allowable parcel size (in ranges of 5000t). On generating an ask price distribution for each *cargo*, the *shipper* repeats for the other *shipper schedules* that it controls. This process is then repeated for each *shipper* that is involved in the spot market. Once all parcel price distributions have been generated for that time step, the *shipbroker* passes the *cargoes* to the *shipowners* that have opted to be involved in this market and requests their reserve prices for shipments.

The *shipowners* respond with a reserve price, for each suitable *vessel* in their fleet, which in turn is followed by the *shipper* offering a price for one or more *vessels* based on their own preferences and the reserve price of the *shipowner*. This results in an ask and offer price combination for each potential *cargo* to *vessel* match. The process is a game of incomplete information as the *shipowner* does not know the payoffs to other *shipowners* nor do they know the offer prices of the *shippers*. This is likely to resemble the real situation: shipbrokers representing either party do not know how many other offers (reserve prices) are available to the shipowner (shipper). The market is then cleared to a Nash Equilibrium, where the price for matches the agreed price is bounded by the ask and offer price.

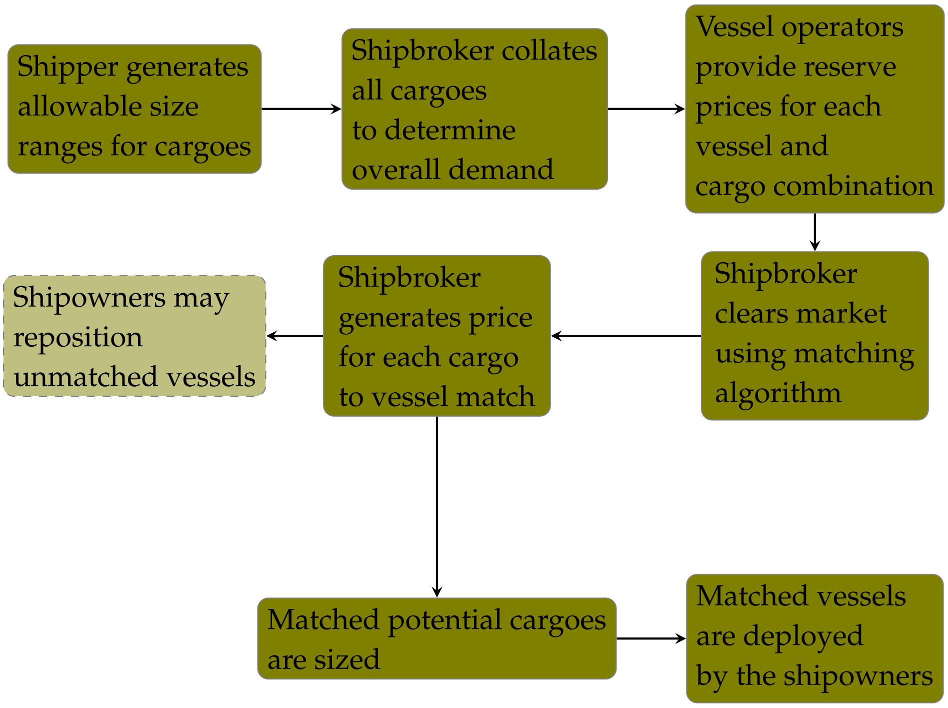


Figure 10.3. Spot Market Flow process in GooFy. The arrows indicate sequence of execution. The process occurs within a single timestep - and is repeated at each timestep there are potential cargoes awaiting transport and vessels to transport them. The dotted boxes indicate options that are taken in some strategies.

Algorithmically, this takes place in two distinct steps. The matching occurs through a bespoke genetic algorithm (GA), maximising social welfare (see **Figure 10.4**).

$$argmax_Z = \sum_{i}^{N^{CARGOES\_SPOT}} \sum_{j}^{N^{VESSELS\_SPOT}} \left(P_{ij}^{OFFER} - P_{ij}^{ASK}\right) X_{ij}$$

subject to

$$\text{Single cargo matching} \quad \sum_{i}^{CARGOES\_SPOT} X_{ij} \leq 1$$

$$\text{Single vessel matching} \quad \sum_{j}^{VESSELS\_SPOT} X_{ij} \leq 1$$

where:

P_{ij} = Either $OFFER$ or ASK price($/t) given by shipper or shipowner respectively

with quantity variables:

X_{ij} = Binary indicator, where 1 is matched

with indices (sets):

$i(CARGOES\_SPOT)$ = index of cargo on spot market

$j(VESSELS\_SPOT)$ = index of vessel on spot market

(10.4)

Figure 10.4. Spot Market, genetic algorithm formulation

Then pricing of the matches occurs, shown in **Figure 10.4**, where the pricing problem is defined as a constraint satisfaction problem (CSP), with the bespoke solution algorithm approximately following a heuristic search algorithm (Shoham & Leyton-Brown 2010). Match prices are adjusted sequentially until convergence occurs, which for a large number of *vessels* and *cargoes* can be computationally expensive. However, the algorithm is complete (Shoham & Leyton-Brown 2010). As mentioned above, the final match prices are bounded by the ask and offer prices set by the *shipowner* and *shipper* respectively.

Figure 10.5 walks through the pricing algorithm process with an example: C_1 and V_1 have been matched in the GA with the price initially set as the reserve price of the *vessel* but can be adjusted up to the offer price of $C1$. However, it cannot increase greater than the utility offered by matched $V4$ or $V3$ with $C1$. In the case of $V3$, this adjustment must satisfy $P_{12} \leq P_{11}^{OFFER} - P_{13}^{OFFER} + P_{31}^{ASK}$, which is the reserve price adjusted by the difference in offer prices. The difference in offer prices is a measure of the utility to the charterer of matching with one *vessel* over the other. In the case of $V4$, the match price must satisfy $P_{12} \leq P_{11}^{OFFER} - P_{14}^{OFFER} + P_{41}^{ASK} + P_{34} - P_{43}^{ASK}$. This is the same limit definition as set by $V3$ but adjusted upwards for the additional value in the price match with $C3$ above the reserve price of $V4$ in that match. A price match between $C1$ and $V1$ would result in $V4$ instead matching with $C1$ as the utility to $V4$ would be greater than that achieved in its match with $C3$.

These two cases create an upper bound on the price match, but a lower bound is also set by the potential match of $V1$ with $C2$ and $C4$. In the case of $C4$, the price must satisfy $P_{11} \geq P_{41}^{OFFER} - P_{14}^{ASK} + P_{11}^{ASK}$, which is the offer price of $C4$ less the difference in the reserves prices. If $V1$ has a higher reserve price on $C4$ then the price is adjusted downwards as the utility of that match is less than the utility of a match with $C1$. The corollary causing P_{11} to be adjusted upwards for a negative difference in reserve price. Similarly, for $C2$ where P_{11} is adjusted accounting for the price match of $C2$ with $V2$, $P_{11} \geq P_{21}^{OFFER} - P_{12}^{ASK} + P_{11}^{ASK} - P_{22} + P_{22}^{ASK}$.

Where the upper bound and lower bound of the match price do not converge, the price is set at the lower bound. This price adjustment occurs sequentially for each *vessel* to *cargo* match until convergence occurs, which is set by iteration change limits.

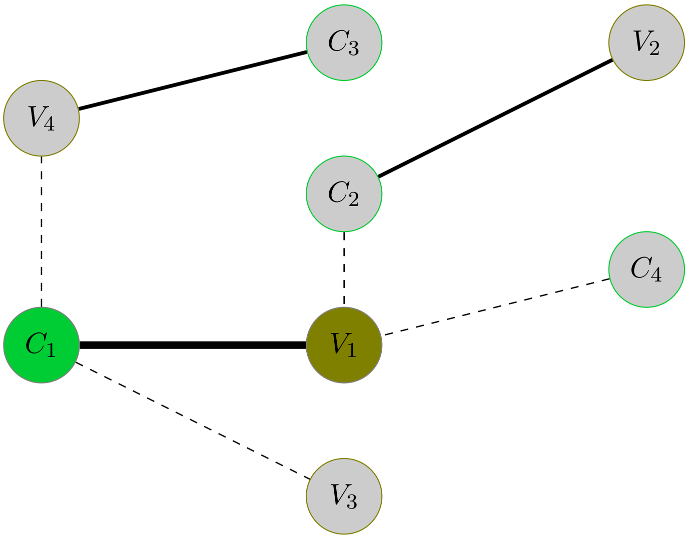


Figure 10.5. Exemplar pricing problem for two vessels in GooFy. The unbroken lines show vessel (V) to cargo (C) matches with dotted lines showing potential matches where an offer and reserve was presented by both parties. The setting of the match price between $C1$ and $V1$ is discussed in text.

Once the market is cleared, each *shipowner* is notified as to the success of the potential matches. The winning *vessel* operators schedule their *vessel* to pick up the *cargo*. The *shipper* reduces their load stock by the *cargo* in anticipation of the next time step to determine whether this stock and flow requires more transport. It should be noted that more than one *cargo* can be generated per timestep for a *shipper schedule*.

10.5.2 Time Charter Market

Within *GooFy*, a *shipper* or a *shipowner* can put *vessels* or request *vessels* from the time charter market following completion of strategic or tactical planning. Once a decision is made to enter this market, an offer is made for a *vessel* with a particular specification. When a *vessel* is requested, a specification is placed for the *vessel* involving a deadweight range for the *vessel* together with a period of hire (this is 1 year in all validation and scenario simulations covered in this thesis). Both *shipowners* and *shippers* can time charter *vessels*. As noted previously, the difference between *shippers* and *shipowners* is simply that *shipowners* do not own or manage any commodity flows. The negotiations for a time charter *vessel* is conducted in a single timestep.

Once the *shipbroker* receives the specification they immediately request prices from *shipowners* that are in the time charter communication network. Each *shipowner* then determines what *vessels* they have available and offers a reserve price for the *vessel* and an availability date. All *vessels* that are on the spot market are potential *vessels* for the time charter market, unless they are already engaged in a CoA. The *shipbroker* then selects the *vessel* that is the cheapest and the *vessel owner* and charterer are matched. Once the *vessel* becomes available (it must deliver already scheduled cargoes or it may be on an existing time charter), its operation transfers to the charterer.

GooFy is restricted to only allow vessel owners to time charter their vessels. Although *shippers* can charter out *vessels*, none of the strategies developed for this thesis allow this assuming instead that if a *shipper* has purchased a *vessel*, then they will most likely be doing so to deploy on their own industrial shipping operation.

It should be noted the difference between this market clearing mechanism and the spot market. In this instance, each time charter request is dealt with individually rather than in an auction based system. Therefore, the charterer is simply a price taker, where the price is set by the ask and reserve prices of the *shippers* and *shipowners*.

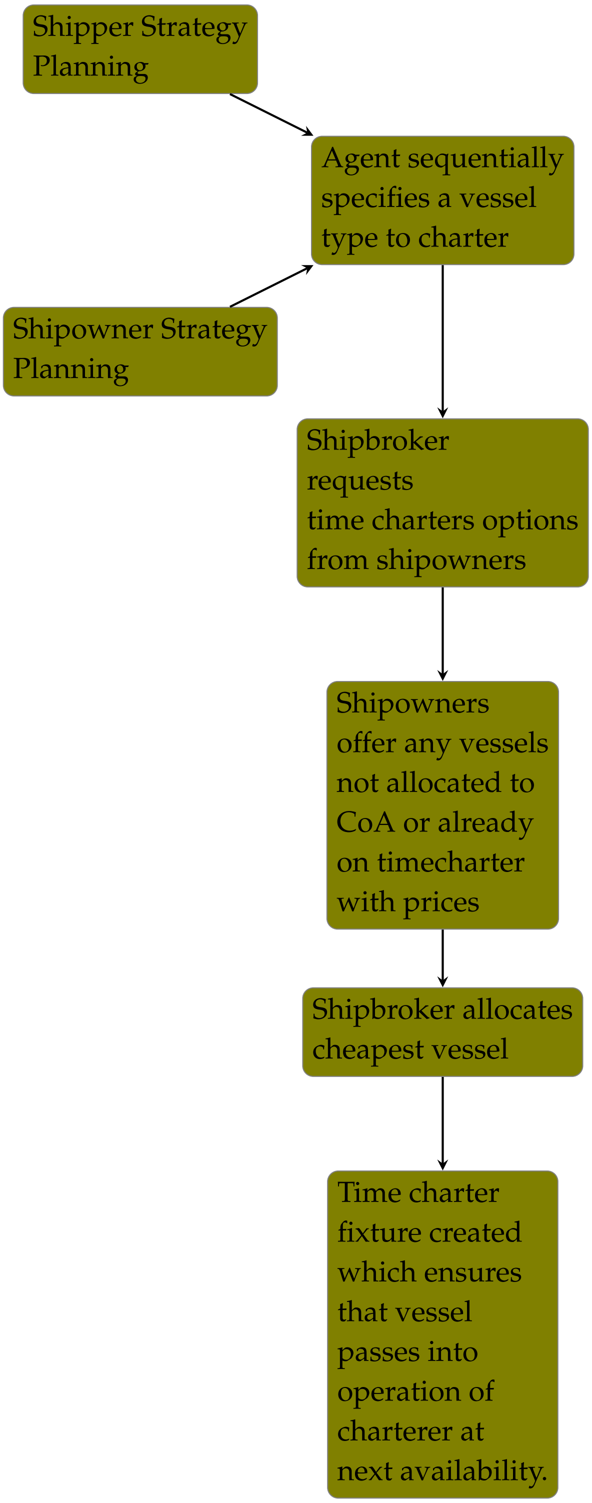


Figure 10.6. Process for time chartering the vessel within GooFy.

$$argminP_{iv}^{TC} = E\left[P_v^{SPOT}\right]_{3MONTHS} - E\left[C_i^{OPEX}\right] \tag{10.5}$$

subject to

Min vessel size: $\underline{Q_v} > Q_j^{COA_min}$

Max vessel size: $\overline{Q_v} < Q_j^{COA_min}$

where

$P =$ Price of time charter, TC, or spot, $SPOT$ for vessel, v

$C^{OPEX} =$ Operational cost

$Q =$ Size, t

with quantity variables

with indices (sets)

$v =$ Vessel size

$i =$

(10.6)

Figure 10.7. Formulation for selecting time charter vessel

The ask price from a *shipowner* for a *vessel* to time charter is updated every time a *vessel* delivers a *cargo*.

10.5.3 Contract of Affreightment

The decision to offer a *shipper schedule* for a CoA is made at the strategic planning stage by a shipper. Potential *shipowners* self select to be involved in the CoA market (which is restricted to *shipowners* with a fleet over a designated threshold). The *shipbroker* offers the contract to all offered *shipowners* who provide a price per tonne for shipping the *commodity flow*. The *shipper* sets a minimum and maximum CoA size based on an EOQ model.

Once a CoA is offered by a *shipper*, an acceptable *shipowner* offers a price per tonne based on their agent rules as set out in the **Chapter 11**.

This market works similarly to the time charter market. The *shipper* offers the contract to the *shipbroker* who in turn notifies all *shipowners* in the CoA communication network to tender for the contract. Any *shipowners* that are within this network are polled by the *shipbroker*. Each *shipowner* then determines if they can supply this contract. In a CoA, the shipper will specify the parcel size range that can be shipped. The *shipowner* offers a price per tonne of cargo that they are willing to transport the *cargo* at. The *shipowner* then determines how many *vessels* they have to service this CoA and how many they must time charter in. If this ratio is above 0.5 then they are willing to offer a price. The *shipowner* offers a price which the combined mean spot rate for the last 6 months plus the cost of time chartering however many *vessels* are required.The *shipbroker*, as with the time charter market, offers the contract to the *shipowner* who has offered the lowest price per tonne of cargo.

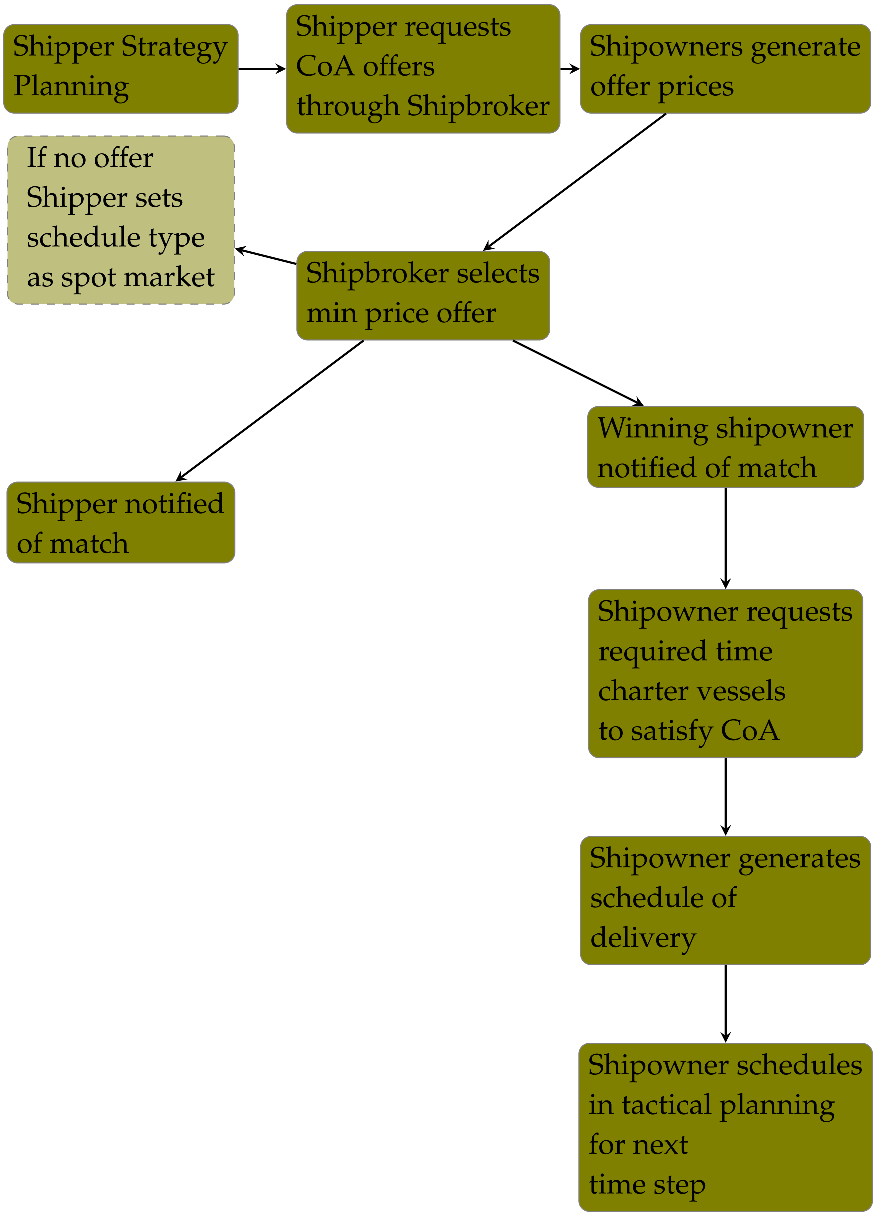


Figure 10.8. Process for CoA chartering within GooFy

10.5.4 New Build Market

A single *vessel* for each size category is established for a fuel efficient (FE) *vessel* and low capital cost (LCC) *vessel*. *GooFy* includes a *shipyard* agent who specifies the LCC or FE *vessel* that is currently available for a particular size category. This specification is generated through the GA defined in **Figure 10.9**. The running of this GA is expensive in computation time and thus the *vessel* specification is stored for a designated period of time defined at simulation design time (set at 2 months for the validation and scenario simulation runs in this thesis).

$$argmin\ C_v \tag{10.7}$$

$$C_v = \begin{cases} C_v^{EFF} & iff \text{ Efficient} \\ C_v^{LCC} & iff \text{ Low capital cost} \end{cases} \tag{10.8}$$

$$\begin{aligned} C_v^{EFF} = {} & C_v^{CAPITAL}(E\left[C_v^{OPEX}\right] + \\ & E\left[C_v^{FIXED\_OPEX}\right] + E\left[C_v^{FIXED}\right])\left(1 - d^{WACC}\right)^{R_{PERIOD}} \end{aligned} \tag{10.9}$$

$$C_v^{LCC} = C_v^{CAPITAL} \tag{10.10}$$

$$C_v^{CAPITAL} = E\left[C_v^{NB}\right] \sum_i^{TECH} C_i \tag{10.11}$$

subject to

Technologies compatibility constraints

where

C_v = Cost of efficient, EFF, or low capital cost, LCC, vessel
either total, capital ($CAPITAL/NB$) or operational ($OPEX$) costs
C_i = Cost of technology
d^{WACC} = Weighted average cost of capital

with indices (sets):

$i(TECH)$ = index of technology

(10.12)

Figure 10.9. Formulation vessel selection genetic algorithm

10.5.5 Other markets

The model does not contain a second hand market only a new build and scrappage market. The new build market consists of a single shipbuilder that offers a build price based on an input dataset. This is similarly the case for the scrappage market.

10.6 Object Definition

The *vessels* and *cargoes* are encapsulated as objects.

10.6.1 Vessel

A *vessel* exists on a geographic network picking up and dropping off *cargoes*. The *vessels* do not interact with each other - for example, if multiple *vessels* arrive at *port* coincidentally, there is no effect on port loading or discharge time. Port loading and discharge time for each *port* is sampled from an annual average of *vessel* calls. At all times, their location and status is observed by their operator (could be a *shipper* or *shipowner*) allowing the operator to manage what *cargoes* they pick up and whether they should be laid up. There is no restriction on where *vessels* can be laid up. They are simply laid up at their current *port* when the decision to lay up is made. *Vessels* are only allowed to call at *ports* that are within the maximum allowable draft of the *port*. The available commands for vessels are:

- Retrofit
- Booked
- Reposition
- Layup
- Scrap

The *vessel* coordinates its behaviour through a schedule. The operator of the *vessel* can schedule events (such as layup or *cargo* collection), as shown above, by specifying a date and *cargo* if required. The vessel manages its schedule by sailing to *port* of loading when it has determined it should leave.

10.6.2 Cargo

A *cargo* is derived from the *commodity flow* that is managed by a *shipper*. A *cargo* is only generated when it is matched to a *vessel* on the spot market or it is scheduled to be delivered by a charterer. In the case of the latter, the charterer, who may be a *shipper* or a *shipowner* on a CoA, matches the *cargo* to *vessel* which would be the maximum of the vessel size and the allowable parcel size. As was discussed previously, when a charterer decides to ship, they decide on a parcel size range rather than an exact parcel size. The *cargo* is generated at the source *port* and awaits the *vessel* that must engage on a ballast voyage from its current location. It is then loaded onto the *vessel* at the rate of loading of the port for that *commodity* type.

10.6.3 Commodity flow schedules

Trade data is unavailable at the level of fidelity required for this model. For this thesis, a bespoke system dynamics approach to transport demand is created. *GooFy* attempts to model the stock buffer and stock reduction at either end of the transport system, essentially utilising system dynamics approaches where trade can be modelled as stocks and flows. Transport demand between two ports is approximated using a Brownian Motion process using the model of Engelen et al. (2006) shown in **Figure 10.10** and **Figure 10.11**. Note that this has no subscript for t or *commodity* for the expected change in demand, $E[\frac{dD_{k,t}^{Com}}{dt}]$, so it is taken from a distribution across all of these. Engelen et al. (2006) had the units of this as billion tonne miles rather than tonnes. This representation of stock is deployed in *GooFy*, but using volume of trade, in tonnes, rather than transport demand, in tonne miles.

The trend is only first order differentiable so the trend increases/decreases linearly and is homoskedastic. This approach is in contrast to gravity model or computed general equilibrium approaches that provide trade estimates for equilibrium conditions. The benefit with this approach is that it allows the highly volatile trades to be modelled.

$$\Delta\_D_{k,t}^{Co} = E[\frac{dD_{k,t}^{Com}}{dt}]D_{k,t-1}^{Co} + STD[\frac{dD_{k,t}^{Com}}{dt}]D_{k,t}^{Co}\Delta\_Z_{k,t-1}^{Com} \tag{10.13}$$

$$\Delta\_Z_{k,t}^{Com} \sim N[0, \Delta\_t] \tag{10.14}$$

$$D_{k,t}^{Com} = D_{k,t-1}^{Com} + \Delta\_D_{k,t}^{Com} \tag{10.15}$$

$$D\_t = \sum_k D_{k,t}^{Com} \tag{10.16}$$

where

$\Delta\_D_{k,t}^{Co}$ = Change in demand for commodity k at time t

$E[\frac{dD_{k,t}^{Com}}{dt}]$ = Expected change in demand.

$D_{k,t}^{Com}$ = demand for commodity k at time t.

D_t = Total demand is the integrated (summed) demand across all commodities

Δ_Z = This is the increment of a standard Brownian motion.

(10.17)

Figure 10.10. Commodity flow process modelling

Some commodities like iron ore, once detrended, are effectively time invariant but with agribulks, in particular, an additional spherical disturbance process must be added. The model is augmented to reflect this by adding cyclical variations of annual frequency. **Equation 10.13** then becomes **Equation 10.18**.

$$D\_t = \sum_k D_{k,t}^{Com} + A^{com} sin(2\pi \left(\frac{t}{t^{year}}\right) + \tau^{com}) \tag{10.18}$$

Where

A^{com} = Amplitude of variation - seasonality

τ^{com} = Offset in the year to account for when peak and trough occurs

t^{year} = Number of time steps in a year - or the wavelength of the cycle

(10.19)

Figure 10.11. Brownian demand

To approximate the flows between two *ports* from an overall annual figure, an input trade scenario is inputted which provides a total annual flow between two countries by commodity, which is then disagregated between the constituent ports using a literature review on the major ports by commodity. The port combinations are then assumed independent as shown in **Equation 10.20**.

$$p(Exp\_Port, Imp\_Port) = \quad p(Exp\_Port)p(Imp\_Port) \tag{10.20}$$
$$\tag{10.21}$$

Figure 10.12. Independence of port combinations

For each commodity flow, a given origin destination pair is then assigned to one or more *shippers*. Each *shipper* is in control of a trade demand out of a particular *port*. Albeit a simplification, it is representative of typical conditions particularly for the larger trades, where an individual shipper is in control of the flow out of a particular port. For example, the port of Dampier is controlled by BHP Billiton. This simplification has been employed due not to limitations of the model itself but instead due to a lack of high fidelity information about the control of trades at this scale. Therefore, simplifying to a single *shipper* per *commodity* and exporting *port* where no other information on flow disaggregation is available is considered prudent.

Coupled with the production process, there is a consumption process with a stock at the destination *port*. This follows the same brownian motion as that outlined in **Equation 10.20**.

10.7 Time Dynamics

The model runs sequentially with time steps consisting of a fraction of a month. Each of the agents and sub-agents schedule actions to run at various time intervals depending on their strategy. The *shipbroker* runs the spot market every timestep if there are *cargoes* available for transport but the CoA and time charter are only run when triggered by a *shipper* or *shipowner*. Similarly the *shipper* and *shipowner* run strategic planning either at discrete intervals such as annually or schedule them dynamically within the functioning of the scenario. The *shipper* runs their operational planning at every tick to determine if there are any potential *cargoes* while the *shipowner* runs operational planning at the request of the *shipbroker* (ie if there are potential *cargoes* on the spot market) or through an event triggered by one of their *vessels* such as notification of delivery of a *cargo*. Tactical planning for both the *shipper* and *shipowner* are carried out following strategic planning but also when a *vessel* changes operator, effectively when the operation of the fleet must be optimised.

As a result of this functioning, there is no equilbrium imposed on the model, with agents triggering and responding to each others actions and price signals within the markets.

10.8 Solution Algorithms and Computational Complexity

The complexity of agents and the formulation of the problems in the planning algorithm are of a scale that exceeds most desktop computing potentials. For example, the strategic planning problem, as will be outlined in **Chapter 11**, is in most cases an NP-Hard problem in each individual case. The most recent advances in the mixed integer optimisation field require the most up to date modelling tools to run a single instance. With this in mind, the solution advanced for this work is the application of genetic algorithms. This approach has been adopted for solving problems of this kind, with some success, and is therefore considered a sufficient approach.

10.8.1 Infrastructure

As previously discussed, *GooFy* is developed on the Repast Environment (North et al. 2013) in Java (Oracle 2017), an object-oriented programming language. The environment allows users to run their model locally or batch run it in a cloud environment. For this work, *GooFy* was prototyped and tested locally before deploying to Amazon Web Services (Amazon 2017*a*). Each scenario was run on a single EC2 instance. The EC2 instance was specified as an r3.large instance with 2vCPUs, 15.25GB of Memory and using high frequency Intel Xeon E5-2670 v2 (Ivy Bridge) processors (Amazon 2017*b*).

The runtime for a projection scenario was approximately 10 days.

10.9 Parameter settings

The following parameters are set at scenario design time.

- Input population fleet specification. Not all the *vessels* are used at execution. The *shippers* and *shipowners* select from this baseline fleet. When a new *vessel* is built its baseline specification is drawn from this.
- The number of *shipowners* and their associated fleet, specifying the number of *vessels* in each size category. Each *vessel* is drawn randomly from the input fleet specification.

- The number of *shippers* and their associated strategies and the *shipper schedules* they control.
- The number of time steps per month.
- Maximum transport cost. This is an upper bound on the maximum price a shipper is willing to pay for shipment of a cargo and is specified as an ad valorem value.
- Cargo late fee: This is set as an ad valorem cost of the commodity.

10.10 Summary

This chapter outlined the framework on the which the agent based model, *GooFy*, is based. The formulation and rules for each agent are defined according to their strategies outlined in the following chapter, **Chapter 11**. *GooFy* is developed on the Repast Library with each simulation evolving through time steps known as ticks. In a typical scenario, there are approximately 500 shippers, 750 shipowners with vessels upwards of 1000. The spot market is cleared at every tick, following generation of cargoes with offer prices and shipowners offering a price for each potential match. At each tick, there are typically around 10000 prices generated that are then cleared through a genetic algorithm.

Chapter 11

Agent Strategies and Evaluation

11.1 Introduction

One of the key aspects in understanding the DBSS is understanding how shippers and shipowners make decisions. This chapter outlines various decision making strategies that are applied in *GooFy*. Following the discussion of the various strategy types, strategy suites are outlined which are internally consistent strategies that would be used by an agent.

The decision making is largely based on the operational research general class of problem called fleet composition and routing. This research area deals with the question of how to satisfy geographically distributed demand in the most efficient manner. Academic research in this area, albeit less so in marine transport, is strong with acronyms being as confusing as the algorithmic formulations themselves. Since the seminal work of Dantzig G. B. (1954), research has expanded making incremental improvements over the years. This has included significant improvements to solution methods, aided by computational improvements, as well as expansion of parameters including heterogeneous fleets and time dimensions.

ABM is descriptive of the system, modelling the actual or plausible behaviour of the individuals rather than the normative behaviour (Macal & North 2010). The normative strategies are outlined in the next section for background to those strategies adopted in the framework.

11.2 Review of Agent Strategies

There are typically three modes of operation: liner, tramp and industrial, as defined by Lawrence (1972). Liner ships operate on published schedules transporting less than vessel load cargoes, typically containerised, for a large number of customers at a time. In industrial shipping, the shipper also controls the ships transporting their own cargo. Finally, tramp ships are vessels for hire on an ad hoc basis, operating like a taxi service. In the case of dry bulk shipping only tramp shipping, industrial shipping and CoAs apply as vessels typically carry full loads from a single shipper.

Planning for the shipper and shipowner occurs across several time-scales:

- Long run (scale of years): Vessels are purchased and scrapped and the overall fleet supply is adjusted for fleet size and mix decisions. On the demand side, there is port terminal location, size and design and opening of new sources of production to adjust the aggregate demand.
- Medium term (scale of weeks to months): Vessels are brought in and out of lay up and routing operations are adjusted for fleet deployment for medium term changes in flows. Although overall supply is inelastic, this allows some medium term flexibility. Demand for shipping is adjusted to suit changes in stocks at the load and destination ports.
- Short term (scale of days to weeks): Vessels adjust operational speed to reduce cost and are repositioned to meet spikes in demand. On the demand side, cargo sizes are adjusted to account for local changes in supply and spikes in freight rate.
- Immediate term (voyage scale): Environmental routing of vessels to account for weather impacts on vessel performance. Additionally, it includes operational changes due to port delays.

The following review and the modelling of *GooFy* includes the first three types of planning. These are typically referred to as strategic, tactical and operational planning. As noted by Christiansen et al. (2004), some authors refer to the medium term as operational and the short term as immediate.

As mentioned in the introduction, these operational research questions are typically considered fleet composition and routing problems. As noted by Hoff et al. (2010) there are few attempts to combine the fleet composition and routing problem. These are typically split up into strategic and tactical problems respectively. Although Hoff et al. (2010) suggests that this split may be due to the lack of test instances. Due to the long lead in time of vessel building and delivery, if routing were included at the strategic level, then the commodity flow for which it is designed would need to be stable in the long run.

The tactical planning stage, is about routing the fleet (with/without some flexibility) to transport a known demand, also called the vehicle routing problem (VRP), through routing and scheduling (Christiansen et al. 2004). Ronen (1993) defines routing as the assignment of sequences of ports to be visited by a defined fleet. The inclusion of scheduling brings the time dimension in.

Since Dantzig G. B. (1954), the formulation of the problem has been a mixed integer formulation. Advances since that point have resulted in extensions to the objective function or additional constraints. However, the problem conception has changed little.

Depending on the perspective, there are effectively the two competing objectives. The shipper is looking to maximise their profits on the cargo typically by minimising the cost of transport. The shipowner on the other hand is looking to maximise the profits on transporting the cargo.

11.2.1 Strategic

For strategic planning, the shipowner is looking to select the optimum fleet to deploy over the proceeding years, while the shipper is looking to maintain inventory flows and integrate them with an overall supply chain. To a large extent, fleet size has not had the same attention as the VRP problems in the academic literature.

As the cost of vessels is so great and asset life up to 30 years, the strategic decision is the key decision a shipper and shipowner will make. Although some authors merge the fleet sizing and inventory problem (FSM) to include routing, typically, they are separated out due to the complexity in the formulation and uncertainty surrounding parameters (Pantuso et al. 2014). The basic optimisation is shown in **Figure 11.1**.

$$argmin_{v_T} Z = \sum_c \int_t (R(Q,x,t) - C(c,Q,v_T,t)))dx$$

where

$R(c,x) =$ Revenue from the sale of the commodity

$C(c,x,v_T,t) =$ Cost of transport of the commodity as a function of commodity, volume, transport type and time.

with indices (sets)

$c =$ Commodity

$t =$ time

$v_T =$ Type of vessel transport adopted including market type

Figure 11.1. Maritime inventory routing problem (MIRP) as a basic formulation. The cost is integrated across the flow as the flow is continuous while the each individual flow (between origin-destination pairings) is discrete. No closed form solution of this model in this form exists. The cost function is a discontinuous function and inherently uncertainly and under determined.

Pantuso et al. (2014) ignore the revenue (as this would be assumed not to vary with assignation) and split the costs between fixed costs and operating costs as shown in **Figure 11.2**.

$$argmin \sum_{v \in V} C_v^F y_v + \sum_{v \in V} \sum_{r \in R_v} C_{vr}^O x_{vr} \tag{11.1}$$

subject to

$$\sum_{r \in R_v} Z_{vr} x_{vr} - Z y_v \leq 0 \tag{11.2}$$

$$\sum_{v \in V} \sum_{r \in R_v} Q_v A_{ij} x_{vr}^k \geq D_r^k, i \in N, k \in K \tag{11.3}$$

where

C^F = Fixed costs
C^O = Operating cost for running the vessel
Z_{vr} = Time consumed every time ship v sails route r
Q_v = Vessel capacity
A_{ij} = Route representing 1 if contains edge from i to j

with quantity variables

$x \in \mathbb{Z}_2$
$y \in \mathbb{Z}^+$

with indices (sets)

i = Port
j = Port
k = Commodity
r, R = Route index, set of routes
v, V = Vessel index, operated vessels

Figure 11.2. Formulation of the FSM shipping problem (Pantuso et al. 2014). The constraints are generalised to all commodities assuming that different commodities cannot be mixed on the same vessel. In addition, transhipment is not allowed at this point and no time windows are considered. Also, the volume on route is an assumed demand.

As highlighted by Christiansen et al. (2013), there are few studies that focus on this area in tramp and industrial shipping given the high risk involved in this decision.

Typical formulations of this problem seek to minimise the cost of shipping (Christiansen et al. 2013, Pantuso et al. 2014), but applied to an industrial shipping problem. Presented here is the tramp shipowners problem which can be considered the dual formulation of profit maximisation, outlined in **Figure** (11.3)

$$argmin_{X,Y} \sum_{v \in V} REV_v X_v - \sum_{v \in V} C_v^F Y_v - \sum_{v \in V} \sum_{r \in R_v} C_{vr}^O X_{vr} + \sum_{v \in V} P_v max(X_v^0 - X_v, 0) + \sum_{v \in V} P_{vt'} X_v \tag{11.4}$$

subject to

$X_v \geq 0$

where

C_v^F = Fixed cost of running vessel type v v

C_v^O = Variable cost of running vessel type v v

REV_v = Revenue expected on the market for vessel type v

P_v = Scrappage/sale price of the vessel

$P_{vt'}$ = Expected scrappage/sale price of vessel at time t'

t' = The time of the next strategic planning period commencement

V = {size ranges} × {technology sets} × {owned,time-chartered,newbuild}

ϕ_v = The routes that the vessel can be deployed on

with quantity variables

$X \in \mathbb{Z}_+$

$Y \in \mathbb{Z}^+$

X_v = Final number of vessels in category v

X_v^0 = Initial number of vessels in category v

X_{vr} = Final number of vessels in category v deployed on route r

Y_v = Number of retrofitted vessels in category v

with indices (sets)

$r(R_v)$ = Route

t = Time

$v()$ = Vessel

Figure 11.3. Basic formulation of the maritime fleet sizing problem (MFSP)

The revenue, REV_v of a vessel, can be that returned on a spot market for the planning period or that returned on a time-charter basis. Indeed, if the shipowner has contracted cargoes over this period, then revenue is highly dependent on routing decisions and should be incorporated into this model, however incorporating detailed routing at the strategic level should only be done if demand is highly predictable (Hoff et al. 2010). The model is unbounded in the sense that any number of vessels can be purchased.

11.2.2 Tactical

Most of the focus of the research in this planning stage is on industrial shipping, where the shipper is looking to transport the cargo themselves (Christiansen et al. 2004). This is classically formulated as a cost minimisation for the sum of the costs for all the ships in the fleet while ensuring that all cargoes are lifted from their loading port to their port of discharge (Christiansen et al. 2004).

For industrial shipping, there are two possible formulations: one where the cargoes are predefined; and where the problem is one of inventory routing. The size of the cargoes are unlimited, with the problem being to maintain stocks at load and destination ports. According to Christiansen et al. (2004), the maritime inventory routing problem (or MIRP), as it is called, is rarely discussed in the marine context. Indeed, this problem spans the strategic and tactical planning periods, where the choice of vessel to transport the cargo is contingent on what is available within the fleet and therefore the routing problem is driven by the strategic selections. The typical objective for the MIRP is to minimise freight, discharge, and inventory holding costs (Christiansen et al. 2004).

Christiansen et al. (2013) provide the exemplar MIRP problem in **Figure 11.4**. The first term is the transport cost of the vessels to transport the cargoes and the second term is the waiting costs at each port. This function is subject to flow conservation constraints, berth capacity constraints and physical constraints.

These problems have typically focussed on a single homogeneous commodity but recent research is looking at mixed cargoes (Christiansen et al. 2011). What's most notable about the research in this field is that these problems are typically applied on coastal transport and not large international flows.

$$argmin \sum_{v \in V} \sum_{r \in R_v} \sum_{t \in T} C_{rv} x_{rvt} + \sum_{v \in V} \sum_{i \in N_v} \sum_{t \in T} C_v^W w_{ivt} \tag{11.5}$$

where

C_{rv} = Cost of transport for vessel v on route r
C_v^W = Waiting costs for vessel, v

with quantity variables

$x \in \mathbb{Z}_2$
$w \in \mathbb{Z}_2$

with indices (sets)

$r(R_v)$ = Route
$t(T)$ = Time
$v(V)$ = Vessel
$i(N_v)$ = Number of vessels

Figure 11.4. MIRP formulation in discrete time for a single product as defined in Christiansen et al. (2013) with some alterations to be consistent with the symbol definition employed in this chapter. For succinctness we have omitted the constraints but these are available in the publication.These can be described as flow conservation constraints and physical limitations such as berth constraints.

This problem is referred to as the cargo routing and scheduling problem, hereafter referred to as SRPTP (ship routing problem of tramp shipping). The shipowner in this case is assumed to be a tramp shipper as they have designated parcel sizes they are to ship. The problem is formulated as an arc flow problem in **Figure 11.5**, where the objective of the Shipowner is to maximise their profit. Any shortfall in supply for an inventory is placed on the spot market.

$$argmax_Z = \sum_{v \in V}^{spot} \sum_{m \in M} R_m x_{vm} - \sum_{v \in V} C_v x_{vm} - \sum_{v \in V} C_k^{spot} x_{vm} - \sum_{v \in V} C_v^{tc} x_{vm} \tag{11.6}$$

where

R_m = Revenue for transporting cargo, m

x_{vm} = Binary indicator for assigning cargo m to vessel v

C_v = Cost of transport using vessel v if on industrial shipping

C_k^{spot} = Cost of transport if using spot market

C_k^{tc} = Cost of transport if using time charter

with quantity variables

$x \in \mathbb{Z}_2$

$w \in \mathbb{Z}_2$

with indices (sets)

$v(V)$ = Vessel

$m(M)$ = Cargo

Figure 11.5. SRPTP formulation. The returns are the revenue less the cost of transportation whether industrial with owned or time chartered vessels or spot chartered vessels.

Christiansen et al. (2004) suggest that due to the relatively long duration of each ship voyage and to the high uncertainty involved, it is unlikely that a vessel is scheduled for more than a few voyages into the future.

For a shipowner, the tactical planning problem is the routing and scheduling of CoA and is formulated in the same way.

11.2.3 Operational

For a shipowner and shipper, operational planning involves the transport of spot cargoes. This can be included in a vehicle routing problem similar to a tactical planning stage problem but over a shorter time horizon. Such a model is discussed by Christiansen et al. (2004) and replicated in **Figure 11.6** for a shipper who has non scheduled cargoes (ie spot) cargoes to route. As before, the total cost of transport is minimised with spot cargoes already selected.

$$argmin \textstyle\sum_{v \in V} \sum_{r \in R_v} C_{vr} x_{vr} + \sum_{i \in N_v} C^{spot} S_i \tag{11.7}$$

subject to

Vessel assignment: $\displaystyle\sum_{v \in V} \sum_{r \in R_v} a_{ivr} x_{vr} + s_i = 1, \forall i \in N_v$

Binary requirements: $\displaystyle\sum_{r \in R_v} x_{vr} = 1, \forall v \in V$

where

C_{vr} = Cost of transport for vessel v on route r

X_{vr} = Binary indicator mapping vessel v to route r

C_{SPOT} = Cost of transport on spot

with quantity variables

S_i = Binary

N = Number of cargoes on spot

$x_{vr} \in \mathbb{Z}_2$

with indices (sets)

$r(R_v)$ = Route

$v(V)$ = Vessel

$i(N_v)$ = Number of vessels

Figure 11.6. Shipper operational planning routing problem

The formulation is different for the shipowner, in that spot cargoes are optional resulting in the formulation being a profit maximisation as shown in **Figure 11.7**.

$$argmax \sum_{v\in V} \sum_{r\in R_v} (P_{vr} - C_{vr})\, x_{vr} + \sum_{i\in N_c} \pi_i s_i \tag{11.8}$$

subject to

$$\text{Vessel assignment: } \sum_{v\in V} \sum_{r\in R_v} a_{ivr} x_{vr} + s_i = 1, \forall i \in N_v$$

$$\text{Binary requirements: } \sum_{r\in R_v} X_{vr} = 1, \forall v \in V$$

where

P_{vr} = Price from deploying vessel v on route r

C_{vr} = Cost of deploying vessel v to route r

π_i = Profit for transporting cargo i on spot market

with quantity variables

$x_{vr} \in \mathbb{Z}_2$

$s_i \in \mathbb{Z}_2$

with indices (sets)

$i(N_c)$ = Cargo i on spot market

$i(N_v)$ = Number of vessels

$r(R_v)$ = Route

$v(V)$ = Vessel

Figure 11.7. Shipowner operational planning routing problem

11.2.4 Contract Evaluation

As stated by Christiansen et al. (2004), CoAs have received little attention in the academic literature. This refers to the evaluation on the shipowner side of an offer of a CoA from a shipper. Whether the contract will be profitable or not depends on the assumptions about how the future spot market will evolve (Christiansen et al. 2004), with stochastic modelling being a typical approach.

11.2.5 Solution Approaches

Early approaches adopted a linear programming approach, but as the number of variables increases (eg. through addition of time windows and multiple potential port stops) the solution space becomes too great and the problem quickly becomes an NP-Hard problem. Therefore, it became clear that further solution methods were required.Typically, in the 1980s and 1990s these approaches involved mixed integer programming supported by a heuristic (Pantuso et al. 2014). Other approaches were also adopted such as genetic algorithms and stochastic programming. Additionally, and as previously mentioned, the focus within shipping has been on the liner industry with solution approaches developed for organising schedules for regular liner trades.

11.2.6 Limitations of current approaches

Shortcomings exist for all the models above. Most notably, the level of unknowns in the equations - this makes the optimisation intractable in many cases. Indeed, it is only in recent years that models have started to include risk in them.

Moreover, the more complex models are simply not applicable as the uncertainty surrounding the inputs is both large and not possible to parameterise. For example, iron ore is a predictable, regular flow but grain flows contain more variability and are subject to seasonality. In addition, the CoA rate is an assumed rate at this point. If no contracts have been done by this shipper before, then they use the long run average spot rate.

Once the vessels have been chartered and paid for, the shipper checks if it is cheaper to run their own fleet rather than charter vessels in. As the risk associated with purchasing increases with each new vessel, the equation is non linear in N_v^{owned}.

According to Hoff et al. (2010), speed and cost are typically modelled as constant. In addition, the authors state that proper consideration of uncertainty in travel times, particularly in the case of marine transport, and travel costs is called for. Moreover, the application of hard constraints, according to the same authors, such as capacity and cargo sizes is not realistic. They state that for bulk goods in particular, order sizes are often flexible. In summary, there is little treatment of uncertainty, risk and flexibility in the literature (Hoff et al. 2010), with Christiansen et al. (2004) echo these points. Pantuso et al. (2015) found that adopting a stochastic programming noticeably improved the solution when compared to using average values. In fact, there is a general tendency to focus on simplified versions of real problems Fagerholt & Ronen (2013).

Historically, the test cases have been abstract, but this has evovled into real world aspects represented in their models and problem descriptions (Hoff et al. 2010, Hemmati et al. 2014) However, with the increasing complexity, the models cannot, in general, be solved to optimality (Hoff et al. 2010) and completeness (for example Homsi et al. (2018)) with current approaches and computational power. As will be the case in the application of these methods, formulations are a balance between computational complexity and realistic conditions.

As stated by Hoff et al. (2010), ship operators will typically ask the question: "What is the best fleet size and mix to maximise my profits for the next period?". Existing commercial software appears inadequate to answer this, often only set up to routing a given fleet with constant prices (Hoff et al. 2010). However this author, believes that a perturbation approach rather than blank canvas approach would suit, where operators are given options to alter fleet and routing along with associated expected increased profit and changes in risk.

An additional problem can be the formulation of the problem as a minimum cost. This assumes constant revenue irrespective of routing solution but also in the case of a stochastic formulation, it assumes no correlation between costs and revenue.

As highlighted above, these are normative approaches and thus not necessarily practiced. However, it can be assumed that applications of these do arise, as enterprise applications, within the industry although to what extent is unknown. As Engelen et al. (2007) has suggested, agents with the DBSS can be considered as bounded rational agents who use rules of thumb and filter to make decisions. They use the example of firms scrapping any vessels over 20 years old.

Although not a limitation per se, most research has focussed on coastal operations and less on trans-oceanic operations. This is likely because of the integration of logistics in the supply chain for coastal operations. Furthermore, trans-oceanic transport is likely not to have the option of integration of various different pick up and drop off points that could be shared across a fleet.

11.3 Applied Strategies

The follow sections describe the different strategies implemented within *GooFy*. Each agent has a number of options of what strategy to adopt. In most cases, there is a also a random strategy which serves as a benchmark strategy.

The main difference between the approaches below and those typically found in academic literature is the treatment of the problem in a stochastic way. As stated by Hoff et al. (2010), this is virtually non-existent in the literature. In addition, cargo sizes are considered and defined as ranges, which an associated price for each sub-ranges.

We outline a number of different options for planning because there are various approaches used in the real situation. As noted by Christiansen et al. (2004), traditionally scheduling and routing were based on knowledge and experience and most likely still are, particularly for shipowners with smaller fleets. Therefore, we wish to represent a range of strategies and not the current gold standard as shown in the literature.

For the most part, we assume the weak-form definition of rational expectations, shown in **Equation 11.9** suggested by Muth (1961). It effectively states that the agent expected value of variable v at time $t + k$ is unbiased.

$$E_{t-1,iv_{t+k}} = E\left[v_{t+k}|I_{t-1,i}\right] \tag{11.9}$$

where

$I_{t-1,i}$ = Information set available to agent i

$E\left[v_{t+k}|I_{t-1,i}\right]$ = Objectively true expection for v_{t+k} conditioned on $I_{t-1,i}$

$E_{t-1,iv_{t+k}}$ = Agents i's subjective expectation that a variable v will take on at $t + k$

with indices (sets)

t = Time t

k = Commodity k

i = Agent i

Figure 11.8. Rational Expectations (Tesfatsion 2015)

11.3.1 Shipper

Strategic

Fleet deployment does not occur at this planning stage, the tactical planning stage is immediately triggered on completing this planning stage.

This is a mix of the models shown above. However each of the variables within the models inherently contain significant uncertainty at different time scales.

$$argmin \sum_{v \in V} C_v^F y_v + \sum_{v \in V} \sum_{r \in R_v} C_{vr}^O x_{vr} + \sum_{k \in K} C_{coa}^k x_{vr}^k + \sum_{k \in K} C_{spot}^k x_{spot}^k \tag{11.10}$$

where

C = Either fixed(F), opex O, CoA (CoA) or spot ($spot$)

with quantity variables

y_v = Number of vessels

with indices (sets)

$v(V)$ = Vessel

$r(R_v)$ = Route

$k(K)$ = Commodity

Figure 11.9. Shipper fleet sizing (FSM)

Equation 11.10 has an additional two terms to **equation 11.1**. The first is the cost of deploying a *cargo* on the spot market and the second is the cost of CoAs. The fixed costs can be extended to include existing vessels and deciding between FE *vessels* and LCC *vessels*.

Solely maximising revenue, as in the case of the mixture model, is insufficient here as the risk of *cargo* not being deployed is not accounted for. The shipper has a requirement that stocks must be maintained but also account for the variation in cost of transport and not just the average transport cost. Therefore, the cost of transport variable, C, becomes a probability distribution which must be integrated over.

For an optimised *shipper* that looks to transport *cargo* through a CoA, industrial shipping and on the spot market depending on prevailing market conditions, a risk model is adopted. The formulation is shown in **Equation 11.11**. The combined estimated cost of transport based on historical prices against the revenue earned from the sale of the commodity is profit maximised subject to the combined risk (variance). The variance is estimated assuming that the cost of each option (eg. industrial shipping) is uncorrelated.

$$\begin{aligned} argmin\pi = & \sum_{r}^{R_v} E\left[R_k\right] - \sum_{r}^{R_v} E\left[C_r^{SPOT}\right] x_r^{SPOT} \\ & - \sum_{r}^{R_v} E\left[C_r^{COA}\right] x_r^{COA} - \sum_{r}^{R_v} E\left[C_r^{IND\_TC}\right] x_r^{IND\_TC} \\ & - \sum_{r}^{R_v} E\left[C_r^{IND\_NB}\right] x_r^{IND\_NB} \end{aligned} \tag{11.11}$$

subject to

Risk Constraint: $\frac{var\left[\pi\right]}{E\left[\pi\right]} < d^{RISK}$

where

R = Revenue
C_r = Cost for route r superscripted by mode
d^{RISK} = Risk preference rate of shipper
D_r = Leg distance on route r
P_k = Price of commodity k
Q = Volume of cargo

with quantity variables

N_{vr} = Number of vessels of size v deployed on route r
$x \in \mathbb{Z}_2$

with indices (sets)

$r(R_v)$ = Route
v = Vessel size v
k = Commodity flow k

Figure 11.10. Risk based shipper strategy for strategic planning

In additional to a full risk model, there are some *shippers* that select to remain in one market. A *shipper* selects either to place all transport on the spot market, industrial shipping or on CoA irrespective of market conditions. The purpose of this strategy is to represent the full spectrum of *shippers* in terms of the amount of risk they wish to internalise, for example for commodity traders who wish to manage the risk associated with variations in the spot market but do not want the associated risk of vessel asset ownership. *Commodity flows* are put out to market at EOQ parcel size for *shipper schedules* greater than 500,000te annual flows. The model uses similar cost minimisation as the industrial shipper but it is less an optimisation as a risk preference strategy. If no operator offers a CoA then the *cargo* is placed on the spot market.

For a pure play industrial *shipper*, the model is shown in **Equation 11.12**. The formulation is solved based on the average costs of the existing fleet. When the required number of vessels in each size category have been determined, a FE or LCC *vessel* is selected depending on a cost benefit analysis using the *shippers* internal return rate and discount rate (i.e. an EOQ model).

$$argmin \sum_v^{V^{5000}} E\left[C_v^{FIXED}\right] Y_v + \sum_v^{V^{5000}} \sum_r^R E\left[C_v^{VAR}\right] Y_{vr} + \frac{E\left[Q_r\right] E\left[P_r^{COM}\right] d^{WACC}}{2E\left[Q_v\right]} \tag{11.12}$$

subject to

Flow Constraint: $\frac{E\left[Q_r\right]}{\sum_v^{V^{5000}} E\left[Q_{vr}\right] Y_{vr}} = 1$ for all r, v

Route constraint: $r \in \{$source port;dest port;commodity$|shipper\}$

where

C_v^{FIXED} = Annualised vessel type fixed costs
C_v^{VAR} = Annualised variable costs for the vessel
d^{WACC} = Weighted average cost of capital
P = Price of commodity
Q_v = Vessel size in dwt

with quantity variables

Y_v = Number of vessels of type v to purchase

with indices (sets)

$r(R_v)$ = Route
$v(V^{5000})$ = Index of vessel size within ranges of 5000dwt

Figure 11.11. Pure play (industrial) shipper strategy: The EOQ size for each flow is estimated followed by the required number of vessels to fulfill that flow. Vessels are then purchased and scrapped to meeting this demand for each size category. For every vessel required to be built, the discounted costs of a LCC versus FE model is calculated, with the lower being used. The shipper discount rate is a parameter input to the model.

Min flow Constraint:$Q_r > Q_{threshold}$

where

$$Q_{threshold} = \text{Minimum flow constraint}$$
$$Q_r = \text{Annual demand on the shipper schedule}$$

Figure 11.12. Pure Play (CoA) shipper strategy: All flows greater than the min flow threshold is deployed on coa irrespective of the cost of the coa. If the coa is not taken up by a shipowner then the flow is deployed on spot.

Tactical

There are two things that must be completed for industrial shipping, the *vessels* must be organised to transport the *cargo*. Secondly, the *shipper* must select an optimum parcel size range for the next planning period. In many sectors for specific *commodity flows* between regions, *cargoes* tend to converge around parcel size ranges. The reason for this is twofold: it allows *shippers* to plan their flows, particularly for regular *cargoes*, and; it sends a signal to *shipowners* so that they know if they have a *vessel* in this size category it allows then to reposition to these regions.

In this case, a travelling salesman approach would ideally be adopted to ensure the *cargo* is transported at least cost. However, for computationally tractable formulation, cargoes are deployed on a round trip shuttle service. This is a risk free but non optimal approach. Any delays that occur on a journey do not cascade to other deliveries. This greatly simplifies the formulation.

The tactical model is run at regular intervals, set by the shipper but also the timestep following delivery of a time charter vessel. For industrial shipping, the schedule has been defined in the strategic plan, resulting in this being a cargo routing problem (CRP).

Similar to parcel size selection, the *shipper* looks to select a parcel size range to focus on with the size based on a random sampling of the current fleet. The *shipper* adjusts the sample sizes to account for the required number of vessels to ship the *cargo* and randomly draws an upper bound and lower bound to the cargo parcel size.

In addition to industrial shipping, we introduce a random approach to setting the spot cargo size.

$$Q_{rt}^{SPOT} = \begin{cases} Q_{r,t-1}^{SPOT} & iff EOQ[Qr] = Q_{r,t-1}^{SPOT} \\ \sim p(v) & \text{where } v \in V^{equal} \end{cases} \tag{11.13}$$

$$Q_{rt}^{SPOT_{min}} = Q_{rt}^{SPOT} - 5000$$
$$Q_{rt}^{SPOT_{max}} = Q_{rt}^{SPOT} + 5000$$

subject to

$$Q_{rt}^{SPOT} \geq \frac{\int_t^{FORTNIGHT} E\left[Q_r\right] dt}{1 - \frac{E[Q_r]}{Q_r^{LOAD}}} \tag{11.14}$$

where

Q_r = Cargo size which is set within 10000te ranges

V^{equal} = Size range of vessels where each bin contains an equal number of vessels

Figure 11.13. Pure play industrial shipper strategy. The shipper selects the cargo size based on the EOQ estimated size or a distribution of its vessels sizes.

For *shippers* that place *cargoes* on CoA or who are risk averse and transport cargoes on spot, they must set a mean parcel size that designates the spot cargo volumes. The spot size is selected as a weighted number of *vessels* of that size in the fleet factored by the inverse of the number of *cargoes* required of that size. The probability distribution for size range is estimated as shown in **Figure 11.14**.

$$p\left(Q_{ir}^{SPOT}\right) \sim \frac{\left(N_{ir}^{CARGOES}\right)^{-1}\left|Q^{SAMPLE} = Q_i\right|}{\sum_i^{Y^{GLOBAL\_FLEET}}\left(N_{ir}^{CARGOES}\right)\left|Q^{SAMPLE} - Q_i\right|} \tag{11.15}$$

subject to

Berth constraint: $Q_r^{SPOT} \leq Q^{SOURCE_max}$

where

$$\begin{aligned} Q &= \text{Capacity, t} \\ Q^{SAMPLE} &= \text{Total capacity of sample} \end{aligned}$$

with quantity variables

$$\begin{aligned} N^{CARGOES} &= \text{Number of cargoes} \\ Y^{GLOBAL_FLEET} &= \text{number of vessels in the global fleet} \end{aligned}$$

with indices (sets)

$$\begin{aligned} v &= \text{Vessel size} \\ r &= \text{Commodity flow} \\ i(Y^{GLOBAL\_FLEET}) &= \text{Time} \end{aligned}$$

Figure 11.14. Setting the operational cargo size

Operational

Here the *shipper* decides on *cargoes* that require transport on the spot market. The *shipper* must decide, for each *commodity flow*, what parcel size and offer price they should provide. These are dependent on historical average freight rate, any short run market changes and indeed any commodity specific requirements. To some extent this is restrained by flow and stock demands, but the parcel size range will be flexible. Together with this, it may be a *cargo* that has already been scheduled during the strategic planning but has not being allocated to a *vessel*. The *shipper* has a volume of *cargo* that must be transported, which is likely based on an EOQ model. However, at this level there is flexibility in how this is transported. For example, a capesize full load can be split into two cargoes if panamaxes are cheap or a panamax can be transported in a capesize if capesize rate is down.

The *shipper* has complete flexibility in designating parcel size, accounting for restrictions due to the stock available at the load port and restrictions on vessel size for berths at ports. The minimum parcel size is also contingent on what is required at the destination port. Following the consumption process at the destination port, the *shipper* must maintain a buffer as shown in **Equations 11.20** and **11.21**. The required storage buffer is a function of the consumption rate and the average time between deliveries. The effect of this is that during erratic periods of delivery, the buffer size requirement is higher even though some cargoes may be small.

The *shipper* has a range of prices they are willing to offer for a particular *vessel* size category. The *shipper* calculates the expected cost of transport at the current timestep,t. This is a linear regression model for prices in the last month in the regions for that *vessel* size (taken as *cargoes* matched in that size $\pm 5000t$). The addition of $C^{Buffer}(q*)$ allows the *shipper* to raise their prices in a tight market. It is assumed the *shipper* is not willing to pay high prices until their buffer stocks start to reduce below acceptable buffer levels at the discharge *port*.

The pricing for non-optimimum parcel size are then below this price,as the *shipper* is less willing to price away from their optimum parcel size.

For a risk averse strategy, the offer price is a premium above the expected spot rate for the *vessel* size that the *shipper* has selected. The principle is that the *shipper* is more focussed on delivering the *cargo* on time and in the selected long run optimum parcel size. This would be the case where the revenue from the sale of the *commodity* greatly exceeds the price of transport.

Finally, the *shipper* could randomly select an allowable parcel size and then randomly select a reserve price from the *vessels* that are offering transport. Once the stock awaiting transport (less any contracted *cargo* not yet picked up) is greater than the minimum parcel size set in the tactical plan is achieved, the parcel size is drawn from a non-parametric distribution based on a random sample of the global fleet. Based on this, a maximum and minimum possible parcel size is generated. This is the same model as that used to set the parcel size range. The number of *cargoes* requiring collection at each tick is then calculated assuming that the maximum size is matched.

$$N_t^{SPOT\_CARGO} = \left\lfloor \frac{Q_t^{SPOT}}{Q_t^{SPOT\_CARGO\_max}} \right\rfloor \tag{11.16}$$

subject to

$$\begin{aligned} \text{Assigned size constraints: } & Q_t^{SPOT\_CARGO} \geq Q_t^{SPOT_CARGO\_min} \\ \text{Berth constraints: } & N_t^{SPOT\_CARGO} \leq 3 \end{aligned}$$

where

$$\begin{aligned} N_t^{SPOT\_CARGO} &= \text{Number of cargoes for shipper to place on spot market} \\ Q_t^{SPOT} &= \text{Allocated volume of commodity flow for shipper to place} \\ &\quad \text{on spot market} \\ Q_t^{SPOT\_CARGO\_max} &= \text{Max cargo size as set at the tactical planning stage} \end{aligned} \tag{11.17}$$

Figure 11.15. Setting the operational cargo size

$$P_{vr}^{OFFER\_SPOT} = EOQ_{vr} \tag{11.18}$$

Figure 11.16. Setting the random offer price for a cargo for a shipper. The max price is set as the economic order quantity price for a vessel in that size category for the commodity flow

$$Q_{tr}^{SPOT} = Q_{tr}^{LOAD} - \left(\int^{LAYCAN} Q_{tr}^{COA} + Q_{tr}^{IND} \right) \tag{11.19}$$

$$N_r^{SPOT\_CARGOES} = \frac{Q_{tr}^{SPOT}}{E\left[Q_{vr}\right]_{YEAR}}$$

subject to

$$\text{Model min allowable cargo size: } Q_{tr}^{SPOT\_CARGO\_min} = 1000 \tag{11.20}$$

$$\text{Load stock limitations: } Q_{tr}^{SPOT\_CARGO\_max} = \frac{Q_{tr}^{LOAD} + \int^{LAYCAN} Q_{rt}^{PROD} df}{N_r^{CARGOES_SPOT}} \tag{11.21}$$

where

Q_{tr} = Capacity/demand at time t route commodity flow r superscripted by source

$N_r^{SPOT\_CARGOES}$ = Number of spot cargoes required in the year

with indices (sets)

t = Time

Figure 11.17. Risk averse operational strategy for setting the number of cargoes to ship

$$P_{vr}^{OFFER\_SPOT} = C^{Trans}(q*) + C^{Buffer}(q*) \tag{11.22}$$

$$P_{vr}^{OFFER\_SPOT} = \begin{cases} s(q*) - (\delta C^{inv} + \delta C^{buf}(q) + \delta C^{rel}(q)) & , q \in [q_{min}, q_{max}] \\ 0 & , otherwise \end{cases} \tag{11.23}$$

subject to

Port Constraints:$q_{max} \leq q_{max,i}\ \forall i \in r$

where

$C^{inv} = r^{disc} t^{sea} p_k q/365$

$C^{trans} = E[p_{t+1,k}^{transport}]$

$C^{buf} = p_k e^{(Q_{delivery}^{bufferloss})/Q^{buffer} - 1}$

s = Offer price of shipper

C^{Inv} = Cost of capital tied up in the cargo

C^{Trans} = Cost of transport of the cargo

C^{Buffer} = Buffer penalising costs for using some buffer at discharge location

C^{Rel} = Cost of varying the cargo size

$q*$ = Economic order quantity size

δC = The change in the superscripted cost from the economic order quantity value

with quantity variables

$q \in [5000, 10000, 15000, ..., 400000]$

with indices (sets)

v = Vessel size

r = Commodity flow

t = Time

Figure 11.18. Risk averse and Responsive Shipper operational strategy for setting offer price for cargoes

Contract Evaluation

For CoAs, the *shipper* accepts the lowest bid price offered by the selected *shipowner* as identified by the *shipbroker*.

11.3.2 Shipowner

Strategic

Within *GooFy*, the *shipowner* has several key elements to consider: whether to buy, scrap, retrofit or time charter *vessels* at the strategic stage. In other words, this is a fleet composition and mix problem, alternatively called the fleet size and mix problem (FSM), shown in **Figure 11.19**.

Together with this they must also decide whether to engage in CoAs. However, this decision does not necessarily align with the timing of their fleet strategic planning and is responsive to the *shippers* request for tenders for this contract. However, their decision on whether to commit to a CoA must be consistent with the their overall strategic plan.

The first term in **Equation 11.24** sums the revenue gained from any CoA contracts, time chartering owned *vessels* and revenue returned from the spot market.This is followed by the capital gained from selling a *vessel*. The following term is the cost of time chartering in any *vessels* followed by the running costs of any *vessels* that are being operated. The only term that can be predicted confidently is the cost of running any operated fleet.There is high uncertainty surrounding the remaining estimates which are also time dependent. At this level, the *shipowner* decides whether to scrap or to buy new *vessels*. The *shipowner* employs a similar model to the *shipper* when selecting a new *vessel*. First the *shipowner*, adjusts the size of their fleet using the *vessels* on time charter. The discounted costs of purchasing a FE versus a LCC *vessels* are estimated (fixed costs and operational costs) as part of the solution. The value of the asset is also calculated at the end of the evaluation period and included in the optimisation. The scrappage value is estimated based on a simple relationship between light displacement (LDT) and value based on empirical data and estimated in an prior analysis of scrappage prices. The total revenue is the combined expected revenue from deploying *vessels* on spot as well as the assets value at the end of the period and any additional revenue gained from scrapping *vessels*. The option to purchase *vessels* is only allowed if there are less than 5% of the global fleet in layup.

$$\begin{aligned} argmin_{Y_v} & \sum_i \left(R_i(1-X_i)(X_i^{TC})\right) - \sum C_i^{FIXED} - \sum C_o^{OPEX} \\ & + \sum \left(P_i^{SCRAP} X_i^{SCRAP}\right) + \sum \left(P_i^{DEPREC} \left(1-X_i^{SCRAP}\right)\right) \\ & \sum P_i^{RETRO} \left(1-X_i^{SCRAP}\right) \left(1-X_i^{NB}\right) \left(1-X_i^{TC}\right) \\ & \sum C_i^{OPEX}(1-X_i^{TC}) \end{aligned} \tag{11.24}$$

subject to

where

C_i^{FIXED} = Fixed costs of vessel i ($/year)
$C_i^{FIXED\_COSTS}$ = Fixed costs of vessel i ($/year)
$C_i^{FIXED\_OPEX}$ = Fixed costs for vessel i operation($/year)
$E\left[P^{SCRAP}\right] = 400$
$Ldt = (3434.5 + 0.1111Q_v)$

with quantity variables

X_i = Indicator variables
X_i^{SCRAP} = Indicator of whether vessel to be scrapped
X_i^{TC} = Indicator of whether vessel is to be time chartered
Y_v = Number of vessels

Figure 11.19. FSM shipowner strategy.

For a random shipowner, if a vessel is not operating in profit, the shipowner randomly decides between continuing with leaving it in the market, laying it up or scrapping the vessel. In addition, if all vessels within a size category are operating at a profit, then the shipowner randomly decides whether to purchase new vessels. If they decide to purchase, then they purchase up to the number of vessels that the owner currently has in that category.

Moreover, if they have an existing vessel that requires retrofitting for regulatory compliance this is completed if possible. If a retrofit will not meet compliance with regulation then it is scrapped. For all other vessels, the decision to retrofit is taken on a vessel by vessel basis, randomly selecting between not updating the vessel and updating the cheapest.

Additionally, for vessel size categories that the owner does have have existing vessels in, there is an additional variable,I_{pu} which allows a 20% probability that a vessel will be purchased. Each vessel purchased is randomly assigned to be a FE vessel or a LCC vessel.

$$X_i^{SCRAP} = \begin{cases} 0 & \pi_i > 0, Age_i > 2 \\ 0 & \pi_i > 0, \alpha_5 > 0 \\ 1 & \pi_i > 0, \alpha_5 = 0, \alpha_1 = 1 \\ 1 & \pi_i <= 0, \alpha_1 = 1 \\ 1 & Age_i > 30 \end{cases} \tag{11.25}$$

$$X_i^{RETRO} = \begin{cases} 1 & iff\ EEDI(i) < EEDI_v^{min} \\ 0 & otherwise \end{cases} \tag{11.26}$$

$$X_v^{NB} = \begin{cases} 0 & if \text{ for any } i \in Y_v : \pi_i < 0 \\ 1 & if\ \forall i \in Y_v : (\pi_i \geq 0) \cup (\alpha_1 = 1) \\ 1 & if\ (Y_v \in \varnothing) \cup (\alpha_{10} = 1) \end{cases} \tag{11.27}$$

$$Y_v^{NB} = \alpha_{Y_v+1} X_i^{EFF\_NB} = \beta_{EFF} \tag{11.28}$$

subject to

$$\beta_{EFF} \sim U[\text{FE}, \text{LCC}]$$

where

$\pi_i =$ Profit over period for vessel i

$\alpha_1 =$ Uniform categorical distribution upper bounded by the subscript , lower bounded by 0

with quantity variables

$X =$ Binary indicator

$Y_v =$ Number of vessels in size category v

Figure 11.20. Random strategic planning for shipowner: Each size category is treated separately. If a size category is in profit, then subject to a draw from a random distribution, a random number of vessels are purchased up to a maximum of the current number in that category.

For the shipowner solely targeting the spot market, the only option they have is to buy, scrap or retrofit owned vessels. This is solved using a GA, which selects the number of vessels to purchase or scrap. The formulation is shown in **Figure 11.21**. Using a game theoretic approach, it is assumed that the number of vessels to purchase is also done by other shipowners. Therefore, it is estimated what effect this would have on overall freight rate price using **Equation 11.33**.

$$
\begin{aligned}
& argmin_{Y_v} \textstyle\sum_i \left(R_i(1-X_i)\right) - \sum C_i^{FIXED} - \sum C_o^{OPEX} \\
& \textstyle\sum \left(P_i^{SCRAP} X_i^{SCRAP}\right) \\
& + \textstyle\sum \left(P_i^{DEPREC}\left(1 - X_i^{SCRAP}\right)\right) \\
& + \textstyle\sum P_i^{RETRO}\left(1 - X_i^{SCRAP}\right)\left(1 - X_i^{NB}\right)\left(1 - X_i^{TC}\right)
\end{aligned}
\tag{11.29}
$$

$$R_i^{SPOT} = \frac{E\left[P_v^{SPOT'}\right] E\left[T_v^{DAYS\_AT\_SEA}\right] E[Q_v]}{S_v} 24 P_{RETURN} \tag{11.30}$$

$$E\left[P_V^{SPOT'}\right] = E\left[P_v^{SPOT}\right] + E\left[\delta P_v^{SPOT}\right] \tag{11.31}$$

$$Y_v^{NB_GLOBAL} = \textstyle\sum^{OWNERS} Y_{vo}^{NB} \tag{11.32}$$

$$\delta P_v^{SPOT} = -0.001 \left(\frac{E\left[Y_{v'}^{GLOBAL}\right] + E\left[Y_{v'}^{GLOBAL}\right]}{E[Y_{c'}] + E[Y_c]} - \frac{E\left[Y_v^{GLOBAL}\right]}{E[Y_c]} \right) / \left(\frac{E\left[Y_v^{GLOBAL}\right]}{E[Y_c]} \right) \tag{11.33}$$

$$Y_v \in \begin{cases} Min(30, Y_{v,t-1}) & iff \frac{Y_{v,t-1}^{GLOB\_SCRAP}}{Y_{v,t-1}^{GLOB}} < 0.1 \\ Min(Y_{v,t-1}, 1) otherwise \end{cases} \tag{11.34}$$

$$P_i^{DEPREC} = P_i^{SCRAP}\left(1 - d^{DEPREC}\right)^{P_{return}}\left(1 - d^{WACC}\right)^{P_{return}} \tag{11.35}$$

$$P_i^{SCRAP} = E\left[P^{SCRAP}\right] Ldt \tag{11.36}$$

$$C_i^{FIXED} = C_i^{FIXED\_OPEX} + C_i^{FIXED\_COSTS} \tag{11.37}$$

$$C_i^{REPAYMENT} = \left(P_i^{NB} d^{WACC} \frac{(1+d^{WACC})^{T^{LOAN}}}{(1+d^{WACC})^{T^{LOAN}-1}} \right) \tag{11.38}$$

$$
\begin{aligned}
& C_i^{FIXED\_OPEX} = \left(T^{DAYS\_AT\_SEA} + T^{DAYS\_IN\_PORT}\right)\left(0.15 + \frac{0.15}{25 - Age_i}\right) \\
& + \left(\frac{0.05 C_i^{REPAYMENT}}{365}\right)\left(365 - T^{DAYS\_AT\_SEA} - T^{DAYS\_IN\_PORT}\right)
\end{aligned}
\tag{11.39}
$$

$$C_i^{FIXED\_COSTS} = 365 P_{RETURN} C_i^{REPAYMENT} \tag{11.40}$$

$$
\begin{aligned}
& C_i^{OPEX} = T^{DAYS\_AT\_SEA}(Fuelcon_i^{ME} P_i^{Fuel\_ME} + Fuelcon_i^{AE} P_i^{FUEL\_ME} + \\
& Fuelcon_i^{ME} C^{CARBON} CF^{FUEL\_ME}) + \\
& T^{DAYS\_IN\_PORT}(Fuelcon_i^{AE} P_i^{FUEL\_ME} + \\
& Fuelcon_i^{ME} C^{CARBON} CF^{FUEL\_ME})
\end{aligned}
\tag{11.41}
$$

$$P_i^{RETRO} = \textstyle\sum_i^{TECH} C_i \tag{11.42}$$

Figure 11.21. Pure play spotmarket Shipowner strategy

subject to

where

$$
\begin{aligned}
E\left[P^{SCRAP}\right] &= 400 \\
Ldt &= (3434.5 + 0.1111Q_v) \\
C &= \text{Costs specific to the superscript,} \\
&\quad \text{eg. fixed costs, } FIXED\_COSTS \\
Fuelcon &= \text{Fuel consumption} \\
CF &= \text{Carbon Factor} \\
P &= \text{Price} \\
R &= \text{Revenue}
\end{aligned}
$$

Figure 11.22. Pure play spotmarket Shipowner strategy (cont'd)

Tactical

The *shipowner* optimises their fleet to ship the *cargoes* they are contracted for as well as maximising their opportunity on the spot market. The *shipowner* must also decide whether to allow *vessels* to be time chartered out. Within *GooFy*, the options available to the *shipowner* are:

- Overall fleet speed reduction
- Put vessels into layup
- Time charter vessels or put vessels onto time charter
- Optimise fleet that are on CoAs

The tactical planning algorithm defined in *GooFy* can be considered in two parts. The fleet is optimally assigned to CoA cargoes. Remaining vessels are then separately altered so they are in lay up, slow steaming or normal steaming.

$$Status_{it} = \begin{cases} \text{OP\_NORMAL} & iff\ E\left[R_v\right]_{3MONTHS} \geq E\left[C_i^{OPEX\_NORMAL}\right] \\ \text{OP\_SLOW} & iff\ \left(E\left[R_v\right]_{3MONTHS} < E\left[C_i^{OPEX\_NORMAL}\right]\right) \\ & \cup \left(E\left[R_v\right]_{3MONTHS} \geq E\left[C_v^{OPEX\_SLOW}\right]\right) \\ \text{LAID\_UP} & iff\ E\left[R_v\right]_{3MONTHS} < E\left[C_i^{OPEX\_SLOW}\right] \end{cases} \tag{11.43}$$

where

$$i \in \left[0..Yv^{OWNER\_OP}\right]$$

Yv^{OWNER_OP} = Number of vessels operated by the vessel owner

, both time chartered and owner

$Status$ = Classifier to show status of vessel

Figure 11.23. Shipowner tactical planning

In the case of a random strategy, this *shipowner* does not take any cargoes on CoA. The random strategy randomly decides whether to lay up or not. They will only consider laying up if the *vessel* is not in profit over the last tactical planning period. Additionally, if the *vessel* is laid up, they randomly decide whether to take it out of lay up or not.

$$Status_i = \begin{cases} \text{LAID\_UP} & if\ R_i^{OP\_SLOW} < E\left[C_i^{VAR\_OPEX}\right] T^{PERIMAIN} \\ \text{OP\_SLOW} & if\ \left(R_i^{OP\_SLOW} > E\left[C_i^{VAR\_OPEX}\right] T^{PERIMAIN}\right) \\ & \cup \left(R_i^{OP\_NORMAL} < E\left[C_i^{VAR\_OPEX}\right] T^{PERIMAIN}\right) \\ \text{OP\_NORMAL} & if\ \left(R_i^{OP\_NORMAL} < E\left[C_i^{VAR\_OPEX}\right] T^{PERIMAIN}\right) \end{cases} \tag{11.44}$$

$$E\left[P_v^{SPOT}\right]_{2MONTHS} E\left[C_i^{VAR\_OPEX}\right] + E\left[C_i^{PERIMAIN}\right] \tag{11.45}$$

$$R_i = E\left[P_v^{SPOT}\right]_{2MONTHS} E\left[Caputil_i\right] Q_i S_i^{OP} 24 \tag{11.46}$$

where

Q_i = Vessel size

S_i^{OP} = Operational speed, km/hr

Figure 11.24. Responsive strategy for tactical planning for shipowner

$$V^{STATUS} \sim \begin{cases} U(LAID\_UP, op\_slow, op\_normal) & iff \quad V_i \in V^{LAID\_UP} \\ \text{op\_normal} & iff \quad \pi_i > 0 \& V_{t-1}^{STATUS} = \text{op\_normal} \\ U(\text{op\_slow,op\_normal}) & iff \quad \pi_i > 0 \& V_{t-1}^{STATUS} = \text{op\_slow} \\ U\,(\text{op\_slow,laid\_up}) & iff \quad \pi_i < 0 \end{cases} \tag{11.47}$$

subject to

Vessel must have no schedule cargoes

where

$$\begin{aligned} LAID\_UP, op\_slow, op\_normal &= \text{Indicate the vessel state} \\ \pi_i &= \text{The profit earned during the period} \\ V^{STATUS} &= \text{Status of vessel eg. OP\_NORMAL} \end{aligned}$$

Figure 11.25. Random strategy for tactical planning for shipowner

In addition, at this planning stage they are attempting to control their stock in the medium term by taking *vessels* in and out of lay up. This would be for a *shipowner* that is an owner operator but does not engage on CoA.

Similar to the *shipper* problem, it is assumed that *vessels* are deployed on a round trip shuttle service. Therefore, once assigned to a contract they are not available for any other transport. The *vessels* adjust their speed accordingly to reduce cost.

If a *vessel* is not deployed on a schedule or to pick up spot *cargoes* then it is place in layup. This function is not solved as a MIRP formulation, but rather parcel sizes are matched to *cargo* size ranges with any missing *vessels* chartered in. Finally, it is checked whether the potential revenue the *vessel* could earn is greater than the market freight rate. If not then the *vessel* is laid up.

Operational

In reality, vessel speeds can be adjusted at the operational planning stage, and indeed are altered during the journey to account for such issues as port congestion. It is considered that the decision to slow steam is taken with a medium term view in response to prevailing market conditions or overall fleet efficiency management. Consequently, the operational speed of the *vessel* is only altered within *GooFy* at the tactical level. In fact, it is considered to be the decision that pre-empts *vessel* layup.

Therefore the decisions at this stage are limited to the pricing strategy for winning *cargoes* and the placement of the fleet for winning *cargoes* in future timesteps.

For the pricing strategy, the reserve price is the combination of the marginal cost of transporting the *cargo* plus what they believe the market will accept as shown in **Equation 11.48**. The expected price of the market is the maximum of what is expected in this timestep and what is expected in the next timestep. This means in a tightening market, the *shipowner* will request higher prices, but in a reducing market, they will take the current price. The expected market price is calculated using a linear regression model of prices within the *cargo* size range for the local region in the last month. The *shipowner* has the option of offering any *vessel* to transport a *cargo* subject to minimum parcel size constraints as specified by the *shipper*. However, the *shipowner* limits options such that the maximum parcel size is greater than half the available deadweight of the *vessel*. The marginal cost of transport can include the expected cost to reposition the *vessel*. The reposition location is the probability of getting a match at any *port* in the world based on the matches of the last 3 months. The reposition *port* is then randomly selected from these.

$$Res = max(p^{spot}, c^{marg}) \tag{11.48}$$

where

$$p^{spot} = max(p_t^{spot}, p_{t+1}^{spot}) \tag{11.49}$$

$$c^{marg} = c^{ballast} + c^{loaded} + c^{repos} \tag{11.50}$$

$Res =$ Reserve price passed for transporting a specific cargo

Figure 11.26. Estimation of reserve price

For a redeployment *shipowner*, each *vessel* is offered for transport for a *cargo* but the reserve price includes the cost of redeployment of the *vessel*. The redeployment region is dependent on expected *cargoes* in each region with the selected port within that region the port with the largest number of flows.

A random shipowner randomly decides to offer the *vessel* to transport the *cargo*. Once selected the *shipowner* then offers the marginal cost of transport. When a *cargo* is discharged, the *shipowner* randomly decides a region to deploy the *vessel* to from all the ports that it previously matched at.

Algorithm 1 Algorithm for ask price for random shipowner

```
for $vessel$ in $vessels\_available$ do
  for $cargo$ in $cargoes\_on\_spot$ do
    {only offer price for cargoes in same region as vessel}
    {and if the vessel has time in its schedule to transport it}
    if region(vessel)==region(cargo) and time_to_ship(vessel,cargo) then
      {Check if cargo can fit in vessel}
      if $max_size(cargo) > (size(vessel) * 0.5 + 10000)$ and $min_size(cargo) < size(vessel)$ then
        $Price[vessel, cargo] = marg_cost(vessel, cargo)$
      end if
    end if
  end for
end for
```

$$P_{ij}^{OFFER} = \begin{cases} Max(E\left[C^{MARG}\right] E\left[C^{REPOS}\right], E\left[P_{vr}^{SPOT}\right]) & T_j^{WAITING} < 1WEEK \\ Max(E\left[C^{MARG}\right] E\left[C^{REPOS}\right], E\left[P_{vr}^{SPOT}\right]) & 1WEEK < T_j^{WAITING} < 2WEEK \\ E\left[C_{ij}^{MARG}\right] & otherwise \end{cases} \tag{11.51}$$

Figure 11.27. Shipowner operational planning responsive

As well as competing to transport *cargoes*, *shipowners*, if operating CoA, may need to put *cargoes* on spot.

$$\begin{aligned} P_j t^{OFFER} = E\left[P_i^{SPOT}\right] \forall \left(i \in V^{SPOT\_VESSELS}\right) \\ \cap \left(T_j^{LAYTIME} \leq T_t + 1MONTH\right) \end{aligned} \tag{11.52}$$

where

$$j \in Y_v^{SHIPOWNER\_CARGOES}$$

Figure 11.28. Shipowner operational placing cargoes on spot

For responsive and repositioning strategies, *vessels* sail to the reposition *port* from their current location after 3 weeks, if there have received no other orders in the intervening period.

$$P_{ij}^{ASK} = E\left[C_{ij}^{MARG}\right] + E\left[C_{ij}^{REPOS}\right] \tag{11.53}$$

$$L_l^{REPOS\_REGION} = \begin{cases} L_m^{REGION} & if\ \frac{Q_l^{LOAD}}{Q^{GLOBAL\_LOAD}} < \frac{1}{N^{REGION}} \\ L_l^{REGION} & otherwise \end{cases} \tag{11.54}$$

$$L_l^{REPOS\_PORT} = L_p : Q_p^{LOAD} \geq Q_{p'}^{LOAD} \tag{11.55}$$

Figure 11.29. Shipowner operational planning reposition

$$E\left[C_{ij}^{MARG}\right] = E\left[T^{FIXTURE}\right]\left(E\left[C_{ij}^{MARG}\right] + E\left[C_{ij}^{FIXED\_OPEX}\right]\right) \tag{11.56}$$

$$\begin{aligned} E\left[C_j^{MARG\_NONECA}\right] &= E\left[P^{ME}\right]E\left[Fuelcon\right] + E\left[P^{AE}\right]E\left[Fuelcon\right] \\ &+ P^{CARBON}E\left[Fuelcon\right] \end{aligned} \tag{11.57}$$

$$\begin{aligned} E\left[C_j^{MARG\_ECA}\right] &= E\left[P^{ME}\right]E\left[Fuelcon\right] + E\left[P^{AE}\right]E\left[Fuelcon\right] \\ &+ P^{CARBON}E\left[Fuelcon\right] \end{aligned} \tag{11.58}$$

$$E\left[C_j^{MARG}\right] = \begin{cases} E\left[C_j^{MARG\_NONECA}\right] iff L_i^{REGION} = L_j^{REGION} \\ E\left[C_j^{MARG\_NONECA}\right]_{LESS\_200KM} if (L_i^{REGION} = L_j^{REGION}) \\ +E\left[C_j^{MARG}\right]_{200KM} \cup (L_i^{REGION} = ECA) \cup (L_j^{REGION} = ECA) \\ E\left[C_j^{MARG}\right](L_i^{REGION} = ECA) \cap (L_j^{REGION} = ECA) \end{cases} \tag{11.59}$$

$$E\left[C_i^{JOURNEY}\right] = E\left[T^{FIXED}\right]\left(E\left[C^{FIXED}\right] + E\left[C^{OPEX}\right] + E\left[C^{PERIMAIN}\right]\right) \tag{11.60}$$

$$P_{ij}^{ASK} = \gamma_1 \int^{JOURNEY}\left(E\left[C_{ikt}^{MARG}\right] + E\left[C_i^{FIXED}\right]\right) dt \tag{11.61}$$

where

$$\gamma_1 \sim \text{U[0,1]} \tag{11.62}$$

$$\tag{11.63}$$

Figure 11.30. Shipowner operational planning random

Contract Evaluation

Contracts of Affreightment For CoAs, the *shipowner* can only use *vessels* within the size range of the *cargoes* (above 50% of the capacity of the *vessel*).The *shipowner* identifies the *vessels* that could serve the CoA, restricting the size range further so the *cargoes* can be consistently of the same size. On determining the required number of *vessels* in this size range to serve the route, then they determine if they have over 50% of the required *vessels*.This limit is to manage the risk of chartering *vessels* in and is an assumed rule of thumb. If not then they do not request to service the flow. The model for calculating the reserve price is in **Figure 11.31**. The price is based on the current state of the spot market and the estimated cost of hiring the additional *vessels*. Note that the estimated spot price is factored by the total fleet required to service the contract including the time chartered *vessels* as the time chartered vessels could be deployed on the spot market. Pricing the CoA assumes a shuttle service is implemented.

$$argmin P_i^{COA} = P_{COA,s} \tag{11.64}$$

$$P_{is}^{COA} = N^{TC\_REQ} E\left[P_v^{TC}\right] + E\left[P_v^{SPOT}\right] D_r N_{vis}^{VOYAGES} \tag{11.65}$$

$$N_{vs}^{TC\_REQ} = Max(0, N_{vis}^{COA} + \textstyle\sum_j^{COA\_EXISTING} N_{vjs} - N_{vs}) \tag{11.66}$$

subject to

Capacity requirments: $\dfrac{N_{vs}^{TC\_REQ}}{N_{vs}}$

$$N_{vis}^{VOYAGES} = 365/\left(\frac{Q_r^{COA}}{E[Q_r^{LOAD\_RATE}]_{DAY}} + \frac{Q_r^{COA}}{E[Q_r^{DIS\_RATE}]_{DAY}} + \left(\frac{2E[S_{vs}]24}{D_r}\right)^{-1}\right) \tag{11.67}$$

where

$$\begin{aligned} s, j &\in [shipowners] \\ v &\in V^{CAT} \\ E\left[Q_{rv}^{COA}\right] &= \text{Mean cargo size in CoA} \end{aligned} \tag{11.68}$$

Figure 11.31. Formulation for selecting time charter vessel

11.3.3 Strategy Suites

This section groups the strategic, tactical and operational strategies in a consistent narrative to define agents.

In the case of market share *shippers* (see **Table 11.1**), this would represent mining companies or large commodity traders who have the buying power and predictability in demand to be able to optimise their supply network. Also, for pure play (spot), it would consist of shippers that possibly have a highly volatile production and demand, for example the grain trade is largely transported on the spot market.

The strategies that are modelled range from simple decision rules to complex risk based approaches.

Shipper Types

If they do decide to expand their fleet, they have several options that are deployed within *GooFy*.

- The *shipper* does not purchase, they simply time charter a vessel when required. This is a risk averse strategy with the *shipper* not willing to internalise the risk of vessel ownership.
- The *shipper* looks to only replace *vessels* that are time-chartered with a new *vessel*. In this case, the *shipper* is willing to buy but only when the deployment of a *vessel* within their network is shown to be profitable.
- The *shipper* looks to expand their fleet to reduce the overall costs of their commodities to undercut other competitors. This is a high risk strategy, adopted by Vale, and others Scott (2016), for their Valemax vessels, which assumes a projected growth in the market demand for their commodity.

Random Shipper This *shipper* places all *cargoes* on the spot market and allows their *cargo* to be shipped at any size and does not engage in any tactical or strategic planning. The number of *cargoes* requiring shipment at each timestep is based on the mean size of all previous *cargoes*. The maximum offer price for transport for the *shipper* is set at 20% of the value of the *commodity* which is assumed to be the *shippers* profit margin (no information is available, to the authors knowledge, on what the typical margin is within the industry and how this varies with market conditions). As the *shipper* has no market intelligence they have no understanding of what an acceptable market price is.

At every time step, this *shipper* is looking to ship *cargo*, at the very least at the production rate at that port for that flow.

Risk averse shipper This *shipper* type places all their *cargoes* on the spot market unless the total volume on route is over 5Mte then it is passed out on CoA. As a result, there is no tactical planning for this Shipper, aside from deciding the economic order quantity cargo size for each *commodity flow*. This *shipper* heavily favours shipment in the EOQ parcel size and is consequently willing to pay a premium for such a shipment. The reason for this is the predictability of flow, both parcel size and frequency, is of great

ID	Type	Strategic	Tactical	Operational
s_t1	Random	Random	None	Random
s_t2	Risk Averse	Risk Averse	Parcel size selection	Risk Averse
s_t4	Optimised	Risk based	Optimised	Market Responsive
s_t5	Market Share	Pure Play (Industrial)	Optimised	Risk Averse
s_t6	Pure Play (Spot)	Pure Play (Spot)	Parcel size selection	Market Responsive

Table 11.1. Shipper Types

importance. Together with this, they enter the spotmarket at an early point, 1 month, before a cargo requires shipment.

This *shipper* is representative of some production companies to focus on their core business rather than looking for to be vertically integrated (Christiansen et al. 2004).

Optimised Shipper This shipper is happy switching between markets and makes decisions incorporating risk of each strategy where possible.

Market Share Shipper This *shipper* is looking to enlarge their market share in the markets they are involved in. Their strategy is to undercut the CIF price delivered by other *shippers*. They are heavily capitalised through their own operations and are most likely a mining company. Their strategy is to transport as much *cargo* as possible on industrial shipping allowing them to optimise their systems and not be exposed to fluctuating market rates. As they are looking to the long run, they are assumed to have a low discount rate of 6% and return period of 10 years.

Pure Play Shipper This *shipper* is wholly focussed on their core business: production of the core commodity. They do not want to take on any of the risk of managing non core business assets, i.e. vessels.Therefore, they look to ship all there commodity using the spot market.

Shipowner Types

Not all these options are open to all fleet operators. For example, the DBSS is mostly made up of single vessel owners with fewer than 5 vessels. These fleet operators would not have the option of CoAs as they don’t have a large enough portfolio or capital base in order to manage it.

ID	Type	Strategic	Tactical	Operational
so_t7	Fleet Manager	Risk based	Optimised	Market Responsive
so_t8	Random	Random	Random	Random
so_t9	Simple Spot	pure Play (Spot)	Responsive	Redeployment

Table 11.2. Shipowner types

Fleet Manager This *shipowner* engages in CoAs, charters in and out *vessels* and conducts trade on the spot market. This narrative would describe a large fleet manager with a large number of in house economists and shipping experts that analyse trade data and market data to minimise risk under a profit making strategy.

Random This *shipowner* conducts trade across all sectors, but has no intelligence on the market aside from the most recently reported spot rate. They will accept a transport of any cargo as long as it is above the marginal cost of shipment and have no preference regarding layday (the day the vessel must present itself at the load port). Together with this, they never layup a *vessel* and the *vessel* always operates at design speed. Once it is not possible to run the *vessel*, the *shipowner* chooses between retrofitting and replacing it with a like for like *vessel* that meets regulatory standards. They never reposition a *vessel*, but offer a price to all possible *cargoes* they can reach before layday.

Simple Spot This owner, typically an owner of fewer than 10 vessels, offers transport purely on the spot market. They use very simple strategies, returning to the region where they picked up their last cargo. Their marginal cost of transport is therefore the cost of a round trip, which is their reserve price for any transport they provide plus the ballast to pick up. The strategy is that the load port is located in an area where there are other cargoes available for transport. They will always maintain a market in each size sector by not laying up every vessel they hold in a particular market. They do not time charter in vessels, preferring instead to buy. They are extremely myopic in how they invest in new assets, by having a return period of 3 years, but in looking at return on investment they use the average spot rate over the last 6 months, thus ignoring long term trends and any cyclic behaviour in the market. If a vessel is in layup, in order to bring it out, the freight rate must on average be higher than average cost for the last month. Vessels are placed in layup if the average month rate is below average costs and the vessel is operating at a loss. Vessels are never repositioned as the owner has no market intelligence as to where to reposition.

11.4 Summary

In this chapter, the various operational strategies identified in the literature are outlined, albeit not exhaustively. It was identified that there are some areas that have received little attention within the field that are applicable to this thesis. Furthermore, weaknesses of these strategies were discussed, particularly in dealing with operational research models typically not taking a stochastic approach. From there a series of strategies were outlined that covered the different planning levels available to the *shipper* and *shipowner* that are implemented in *GooFy*. These planning levels (strategic, tactical and operational) are an attempt to be reflective of those used in the actual DBSS. The models used in these strategies were described and outlined in a series of equations. Finally, the strategies were grouped into strategy suites to create coherent narratives for *shipper* and *shipowner* agents, resulting in five strategy suites for *shippers* and three for *shipowners*.

Chapter 12

Model evaluation

12.1 Introduction

This chapter evaluates the performance of *GooFy* on a validation period of 2000 to 2014 for which there are various validation datasets. The results of the validation are discussed outlining limitations of the validation process, particularly focussing on the type and amount of validation data available. The purpose of the chapter is to both investigate the robustness of *GooFy* but also elucidate the various strategies and the emergent properties in the system.

Four scenarios are run: two of which are a mix of multiple strategies; one a random strategy for both *shipper* and *shipowner*, and; a pure play strategy where all transport is provided by the shipowner through the spot market. The chapter discusses the validation in a number of areas:

- Global trade
- Vessel stock and build and scrappage rates
- Strategy efficiency
- Networks
- Vessel operation
- Fuel consumption and emissions
- Markets

Results are typically displayed per vessel size category, which is based on the IMO categorisation (Smith et al. 2014). This is for the most part for convenience in displaying results and for comparison with reported statistics in those categories.

12.2 Limitations to validation

The validation is limited on the macroscopic and microscopic level. For example trade data is available, but it is not available at the level of detail required (i.e. actual vessel flows) and is only available at monthly trade amounts which contain a number of errors. At the supply side, although a baseline dataset of vessels is available, it is only available for 2011 for this research and not for each year in the validation dataset.

A key part of the shipping systems is the allocation of cargoes and vessels to their contract type - ie. industrial, coa and spot, which is not available. Furthermore, little is known (only anecdotal) about what flows are on CoA, industrial or on spot markets and indeed what the average parcel size is for various cargoes.

Notwithstanding these limitations, there is some aggregate data available which is investigated below that the model results are compared against. However, differences in results against validation data should not necessarily be assumed to be flaws in the underlying model structure or assumptions. Deviations may be due to incorrect inputs (for example baseline fleet) rather than model performance.

It should be noted also that the strategies are not being validated. These are simply a representation of how it is believed decisions are made.

Finally, as explained previously due to the model complexity and size the number of runs is extremely limited so there was no opportunity to conduct a Monte Carlo simulation so the results could be treated stochastically. Indeed, sensitivity analysis is limited to two runs of the mix strategy which gives an indication of the potential variability in results in this scenario. The approximate runtime for each of the scenarios was 2 hours per year of the scenario.

12.3 Verification

Verification is the process of confirming that the design is correctly implemented, but as implementations vary across disciplines, there is no strict approach to verification. As ABM is based on simulation it does not produce point estimates that must be matched like in the case of an analytical solution. As Ormerod & Rosewell (2009) suggest "testing the range of outcomes provides a test only in respect to a prior judgement on the plausability of the potential range of outcomes". Furthermore, they suggest "seeking...models which explain more than their predecessors and are not falsified".

This has been completed through a number of approaches derived from teaching and professional sources (MITRE 2013):

- Visual: The Repast framework contains a graphical user interface (GUI) for through which charts can be dynammically generated. For each of the model run, a visual check of outputs was conducted, before deploying for parallel simulation.
- Antibugging: Additional checks and outputs to ensure model is working as expected. A testing environment was set up where standard and corner cases were tested using the junit test framework.
- Simplified models: This work was initially tested over theoretical networks of 10 ports with various trade flows and shipper/shipowner configurations.
- Seed independence: Alteration to the seed for the random number generation should not significantly affect results.
- Continuity testing: Minor alterations to input parameters, should not, in general, significantly affect model outputs.
- Degeneracy testing: This involves checking values at the extreme end of input ranges and ensuring that the model works for these values. This was applied in a very limited capacity, largely limited by the runtime of the model. For example, running the model across a scenario with a large initial baseline fleet would use significant processing resources which were not available.

12.4 Validation

As discussed above, there is a significant lack of data available for validation. However, it should not be direct quantification comparison, rather a systems dynamics validation. Are we seeing the same mechanisms at work in the modelled system as we see in the real world system? Are we seeing similar profit/cost ranges? Are the vessel operational parameters similar to those reported, even on a sample basis?

The model is run in the baseline scenario using 2000 to 2014 trade volumes and multiple baseline stock size mixes. The scenarios are split between four options shown in **Table 12.1**.

run	scenario
1	validation_mix_mix_seed_10
2	validation_mix_mix_seed_20
3	validation_pureplay_simplespotreturning_seed_10
4	validation_random_randomtact6months_seed_10

Table 12.1. Scenario names run for the validation hindcasting

ID	Type	Strategic	Tactical	Operational
s_t1	Random	Random	None	Random
s_t2	Risk Averse	Risk Averse	Parcel size selection	Risk Averse
s_t4	Optimised	Risk based	Optimised	Market Responsive
s_t5	Market Share	Pure Play (Industrial)	Optimised	Risk Averse
s_t6	Pure Play (Spot)	Pure Play (Spot)	Parcel size selection	Market Responsive

Table 12.2. Shipper Types

ID	Type	Strategic	Tactical	Operational
so_t7	Fleet Manager	Risk based	Optimised	Market Responsive
so_t8	Random	Random	Random	Random
so_t9	Simple Spot	pure Play (Spot)	Responsive	Redeployment

Table 12.3. Shipowner types

Other parameters are set, including minimum and maximum time to build vessels, but these are set equally between the scenarios. The mix scenarios use the criteria set out in **Table 12.5** and **Table 12.4** to assign a strategy randomly (which is set through the seeding of the scenarios, indicated as 10 and 20 in the two scenario names) to an agent.

In **Table 12.4**, the flow_size shows the volume ranges which the strategy can be assigned to a *shipper* for. Equally, the vessel_count shows the *vessel* ranges over which the strategy can be applied to a *shipper*. 1 (0) indicates that a *shipper* categorised in this row can(not) be assigned this strategy. For example, if a *shipper* has only commodity flows below 1m tonnes, it can s_t1, s_t2, s_t4, s_t5 or s_t6. The *shipper* definitions are shown in **Table 12.2**.

flow_size	vessel_count	s_t1	s_t2	s_t4	s_t5	s_t6
0	0	1	1	1	1	1
10000000	0	1	1	1	1	1
10000000	1	0	0	1	1	0

Table 12.4. Criteria for mix scenarios for shipper agent. The vessels_count field indicates the minimum number of vessels for which a particular strategy can be applied to the shipper. The flow_size field indicates the minimum annual volume that the shipper must be shipping.

.

vessels_count	so_t7	so_t8	so_t9
30	1	0	0
20	1	0	1
10	0	0	1
0	0	1	1

Table 12.5. Criteria for mix scenarios for shipowner agent.The vessels_count field indicates the minimum number of vessels for which a particular strategy can be applied to the shipowner. The criteria is based on the initial fleet of each shipowner.The shipowner defintions are shown in ***Table 12.3****.*

12.4.1 Trade and transport demand

As outlined in **Chapter 10**, the trade is input as a monthly transport demand which is converted to a transport demand flow (modelled as a Brownian motion process) for each *shipper* and origin-destination pair resulting in approximately 2700 different flows (or *shipper schedules* as they are referred to within *GooFy*). When and how this transport demand is transported is internally generated by matching supply with demand through the various markets. The resulting cargo volume transported is shown in **Figure 12.1** with the input trade scenario and that derived from UN Comtrade (COMTRADE 2018) also displayed. The input trade scenario is different from UN Comtrade because many lower volume trades have been removed. Despite reducing the number of flows captured within the validation scenario, over 95% of trade volumes are captured.

The difference between the model input trade (red line) and that produced within the model (blue line) is due to some trades not designated an associated shipper (smaller trades that are not accounted for in these scenarios). It can be seen from these plots that the transported cargo does not coincide exactly with the production volumes. This is not unexpected as there is not a forced equilibrium within the model. If there is no matched vessel to transport a cargo, that cargo will not be transported in that time period, or at all if no ship is matched to the cargo as is the case with Run 3. In this sense, trade is quasi-endogeneous, the input production is exogeneous (although modelled as a Brownian process), but whether this produced cargo is transported is internally generated within *GooFy*.

It should also be noted that more cargo can be transported than produced, as is the case in the mix scenarios. That is because scheduled cargoes (in the case of industrial shipping and CoAs which do not occur in Run 3 and 4) are based on current flow estimates which may be greater or less than those actually produced. Stock volumes (whether at the consumption or production end) are allowed to go negative for two connected reasons:

- Short run buffer capacity for early collection of cargoes. Preventing production stocks to go negative may in the long run lead to lower stocks at the consumption port.
- At the consumption end, a negative stock has penalty implications for a shipper whose willingness to pay for transport is thus affected.

Figure 12.1 also shows an initial phase (approximately of 1 year) where the transported cargo does not match production. This is effectively a configuration period where Shipowners learn where to place their vessels and Shippers start to set up industrial transports and CoAs. The period between 2004 and 2006 is a system feedback in the mix scenarios where shippers overestimate the demand (likely as a response to the earlier shortfall in 2000/2001). The mix strategies perform best out of the the strategy suites, albeit not transporting all cargo.

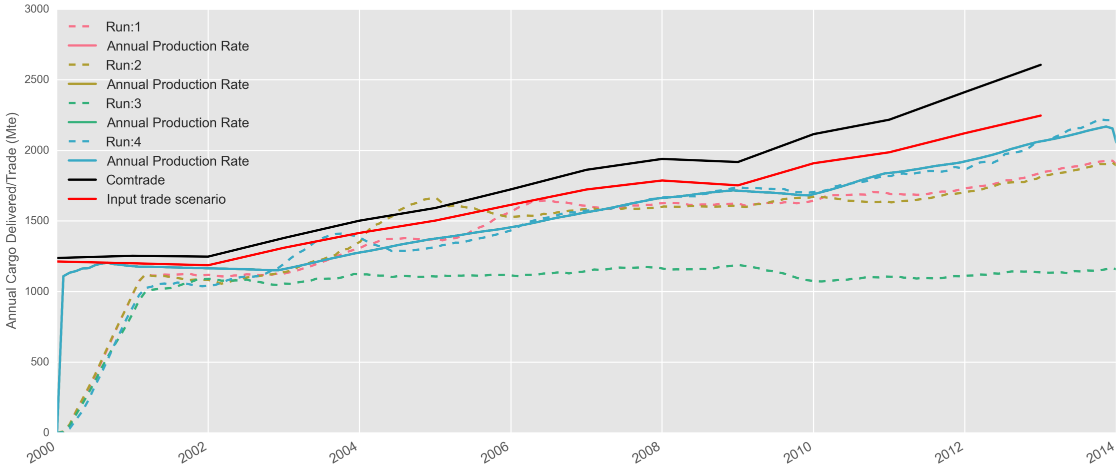


Figure 12.1. The broken lines indicates the annual total volume transported for each run. The black line is the trade demand as reported by UN Comtrade (COMTRADE 2018) and the unbroken red line is the input trade scenario. The production lines coincide for each scenario.

12.4.2 Stock validation

Vessel stocks, scrappage rates and build rates are shown in **Figure 12.2**, **Figure 12.3** and **Figure 12.4** respectively.

The number of *vessels* increases significantly in all runs from the baseline number of vessels, which is consistent with the increase of transport of stock in these scenarios. However, in all scenarios (except for run 1) the scrappage of vessels is significantly higher than in the real situation. After an initial steep increase in the scrappage of vessels, the fleet turnover increases steadily at a lower rate for Run 1, 2 and 4. It is interesting that Run 3 fleet size resembles the shape of the fleet tonnage in the real case.

There are large differences in both the tonnage and the number of vessels as evolved in the *GooFy* scenarios as compared with the actual data. There are a number of reasons for this:

- The starting conditions are different. As discussed previously, the baseline conditions are unknown and assumed for *GooFy*.
- Model setup and representation, from the number of shippers and shipowners and their strategies to how the trade is split between port to port origin-destination pairs.
- There is some trade removed in the scenarios but, as discussed previously, it is not expected that the difference would be significant. Furthermore, there may be trades that are transported by this fleet that have not been accounted for in the general cargo category.
- Cabotage and domestic shipping may be carried out by many of the smaller vessels in the fleets which is not accounted for in *GooFy*.
- Operational assumptions, encapsulated in the strategies of shippers and shipowners, and also cargoes are limited to single pick up and single drop off.

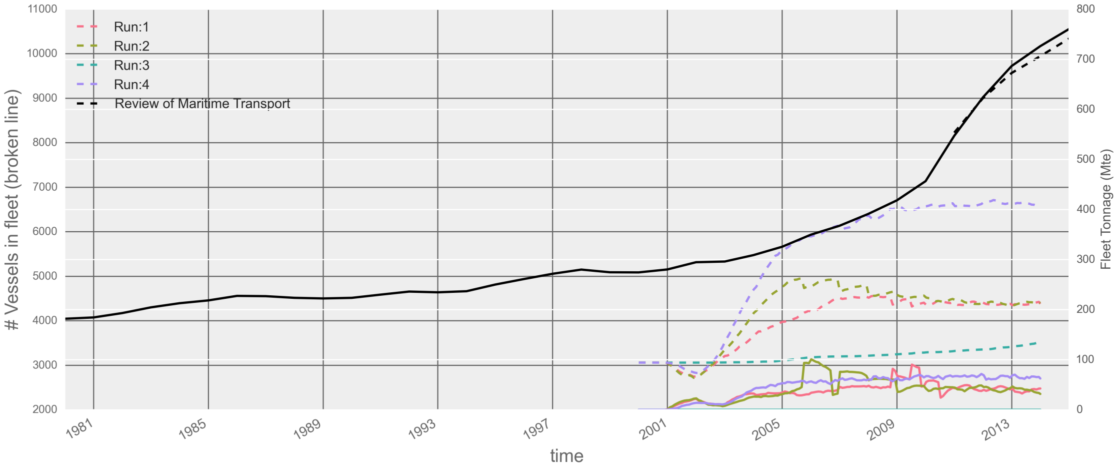


Figure 12.2. Number of vessels (broken lines, left axis) and tonnage (unbroken lines, right axis) for each scenario. Also shown is the Review of Maritime Transport (RMT) estimates for both number of vessels and total tonnage (UNCTAD 2016). Data on the number of vessels from RMT is only available from 2011.

In both mix scenarios, there is an initial spike in the building of *vessels*, which are subsequently scrapped. There is no noticeable trend thereafter in the scrappage rate, albeit punctuated by spikes in the numbers of *vessels* scrapped.

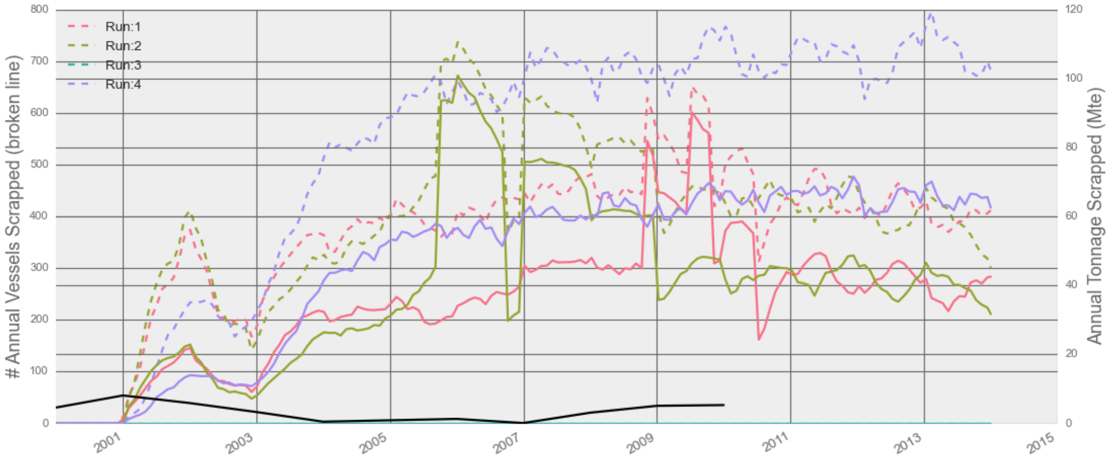


Figure 12.3. Number of vessels scrapped each year in each scenario and run. As for ***Figure 12.2*** *the black line data is from RMT (UNCTAD 2016)*

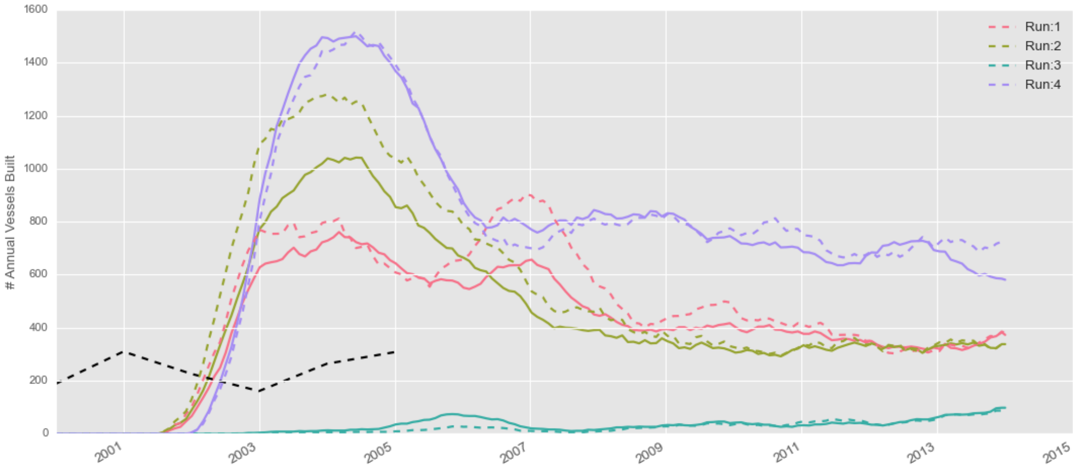


Figure 12.4. Number and tonnage of vessels built in each year. As for ***Figure 12.2*** *the black line data is from RMT (UNCTAD 2016)*

Unfortunately, no data is available that identifies the number of vessels in each size category throughout the period (the size categories are shown in **Table 12.6**). Broadly, the mix strategies favour the larger *vessels* (due mostly like to industrial transport and CoAs being able to optimise for cost). The pure spot strategies favour the mid range *vessels* potentially as these are the most flexible *vessels* and thus able to carry more varieties of *cargo* (i.e. favoured by both larger and smaller flows). Interestingly, the random strategy favours the largest size category and the two smallest size categories.

Common Name	*GooFy* Name	From (dwt)	To (dwt)
Capesize	Size 0	200000	450000
Suezmax	Size 1	100000	200000
Panamax	Size 2	60000	100000
Supramax	Size 3	35000	60000
Handy	Size 4	10000	35000
Feeder	Size 5	1000	10000

Table 12.6. Vessel size labels used in the GooFy scenarios

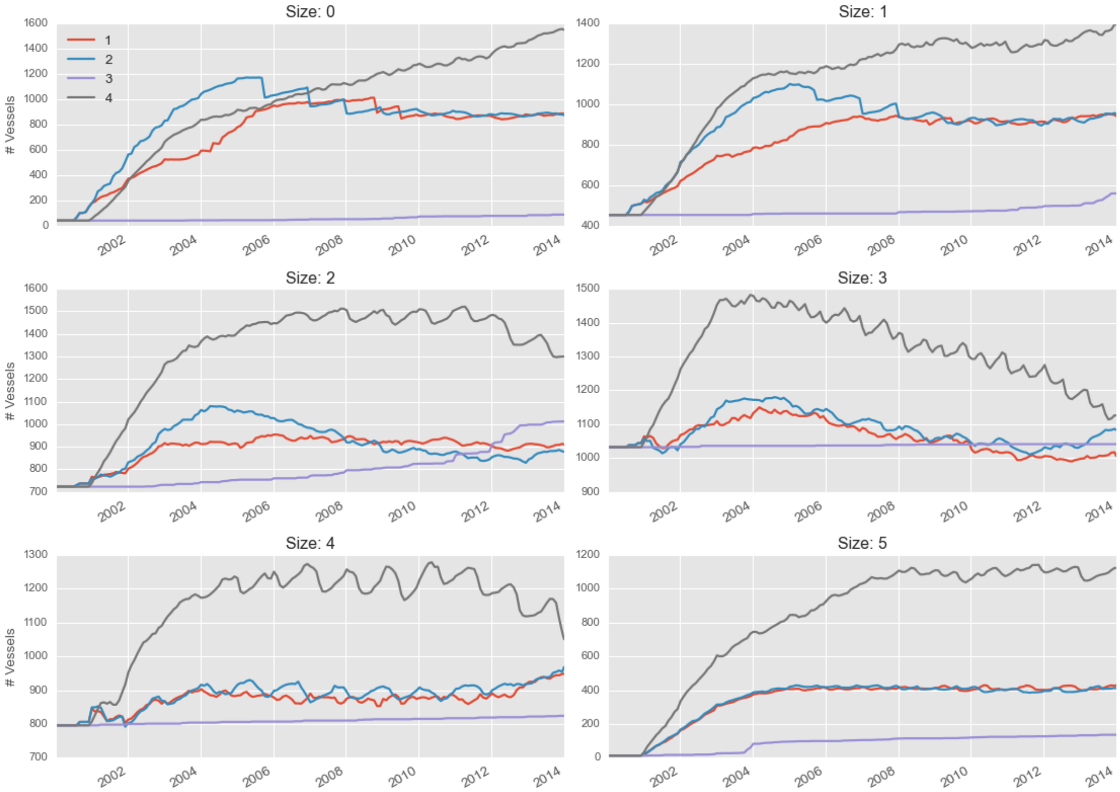


Figure 12.5. The number of vessels in each size category. The runs are labelled in the top left plot.

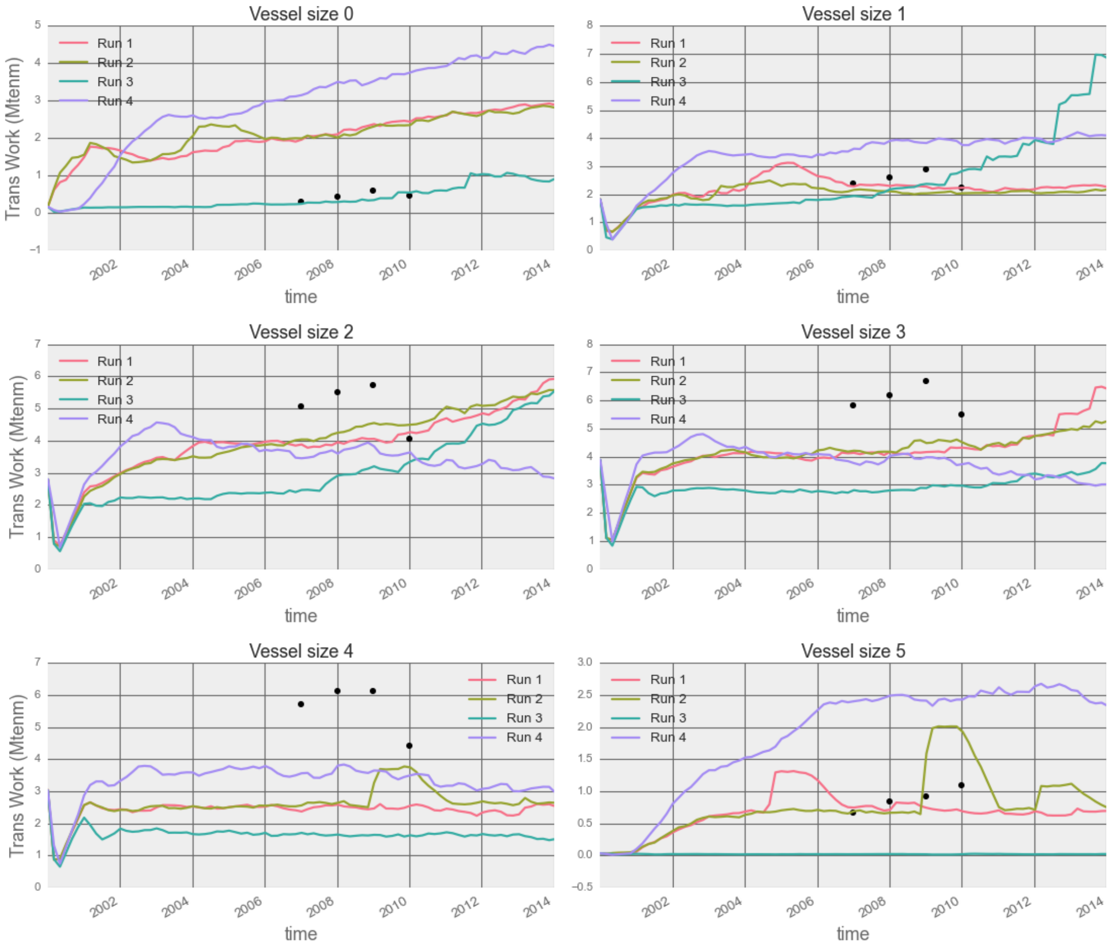


Figure 12.6. Transport work in each size category

12.4.3 Strategy Comparison

In this section we look at the effectiveness of each strategy of *shippers* in transporting *cargoes*. Although these strategies cannot be validated, it is possible to view their effectiveness in managing flows. All runs are compared in **Figure 12.7**. The optimised *shipper* (s_t4) manages its *cargoes* most effectively, in fact over delivering *commodity flows* in most cases. The random *shipper* (s_t1) is less effective than those *shippers* that proactively manage their trade flows, rather than responsively. This is particularly evident in run 4 when these *shippers* are unable to distribute the *commodity flows*, resulting in ever increasing stock build up at load as transport is not available. Market share *shipper* (s_t5) appears to be stabilising the extreme flows, largely meaning that these *shippers* have managed to either time charter or buy *vessels* for their fleet. The spot market shipper (s_t6) is least effective with stock buildup of up to 10% in run 1. In the scenario where all the *shippers* are of this type, the effect is more extreme with stock expansion of up to 30% by the end of the period.

Figure 12.7. Median percentage stock awaiting transport of annual flow in each scenario. The run are displayed consecutively from top left to bottom right.

Next is to focus on how efficient the system is at positioning *vessels* in the correct areas. In an efficient system, *vessels* will relocate to areas where *cargoes* are waiting. **Figure 12.8** shows the regional location of *vessels* (by size) together with demand for those *vessels*.

Region 7 provides an interesting juxtaposition of the effect of the strategy mixes in each scenario as it has most demand for loading and delivery. Runs 1 and 2 (mix strategies) see *vessels* increasingly deployed there over time as the system responds to the demand in that region. Run 3 shows little response from the system to this demand, and although there is an upwards trend in vessels located in this region in Run 4 it is not as significant as that in Runs 1 and 2.

Similarly for region 2, which has the largest demand for transport. Run 1 sees *vessel* sizes 0,2 and 3 being deployed in that region increasingly over time, while runs 2 and 3 sees an increasing demand for mid-range size vessels. The demand is largely taken up by size 0 and 1 for run 4.

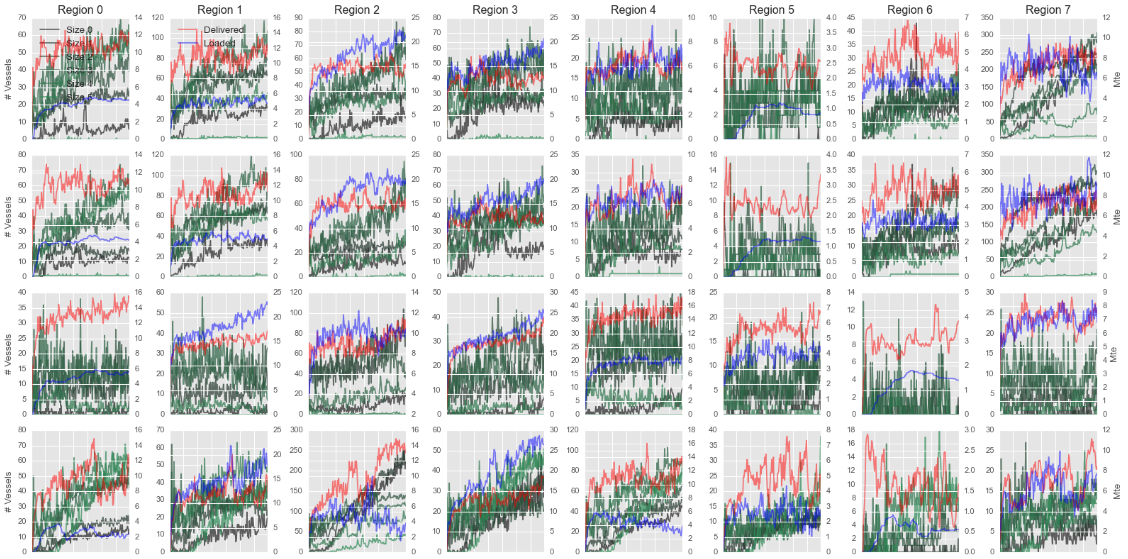


Figure 12.8. Vessels and cargoes in each run: Each run is shown on a distinct row (where run 1 is top and run 4 is bottom) with each column representing a different region. The left axis of each plot shows the number of vessels (broken line) with the right axis showing the volume of cargo loaded/delivered in each region.

12.4.4 System Efficiency

In this section, we look at system efficiency for the supply of transport. The figure shows that vessels are available in the run but nothing is being transported. Additionally, vessels appear to oscillate between layup and available.

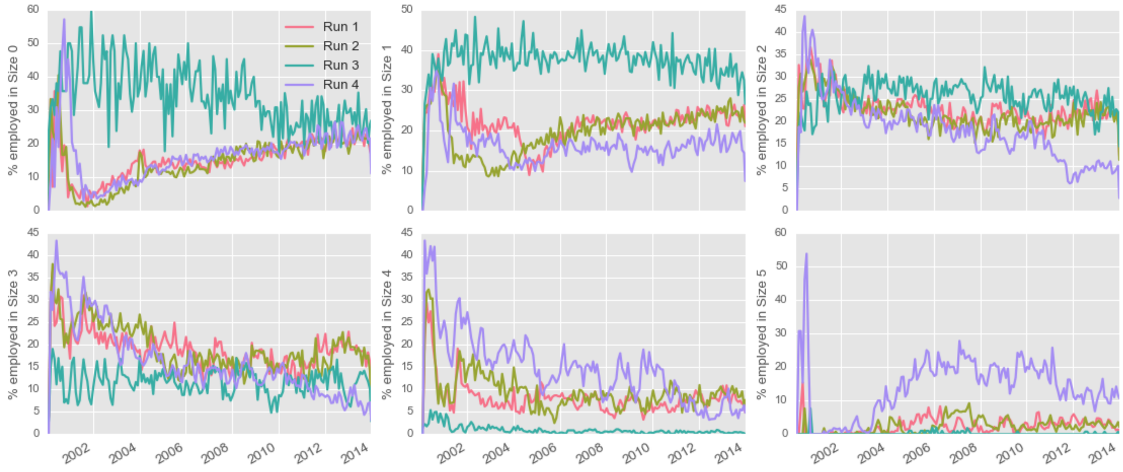


Figure 12.9. Percentage of vessels deployed on cargo transport for each run. Each plot shows a different vessel size. A vessel is considered deployed if it is loading, loaded or discharging.

Figures 12.10,**12.11**,**12.12** and **12.13** show the vessel states as compared with the global demand in capesize (size 0), suezmax (size 1) and panamax (size 2) size ranges. It is clear in all cases that there are always vessels looking for transport even when there is demand for transport that is not being fulfilled. This is likely due to instantaneous location of vessels as compared to instantaneous demand for transport. Secondly, it is clear that demand for transport, particularly in capesize stabilises in runs 1 and 2 while it increases in both mean and variance in runs 3 and 4, suggesting that the system is reaching a dynamic equilibrium for transport demand. Transport supply however, offers a different interpretation. Runs 1 and 2 show a dramatic increase in Panamax vessels offering transport, while in run 4 the transport offers become stable early in the run. Run 3 shows a significant increase in vessels offers across all sizes.

A stable system that matches supply to demand should see few vessels in layup. Run 3 shows a dramatic increase in vessel layup for sizes 0 to 4 from 2010 at the time that the demand for capesize vessels in particular is rapidly increasing. Although the layup rate is stable in run 4, it is a significant proportion of the fleet that is laid up. Similarly for runs 1 and 2, the layup rates are high but stable.

Run 1 and run 2 shows significantly more panamax vessel offers of transport than capesize or suezmax. This is due to the large number of vessels within that size category, their relatively lower utilisation and hte number of cargoes available for them to offer transport on (i.e. this includes cargoes below a panamax size vessel if the cargo meets minimum price criteria for the vessel which is related to both maximum cargo size but also location of cargo load port).

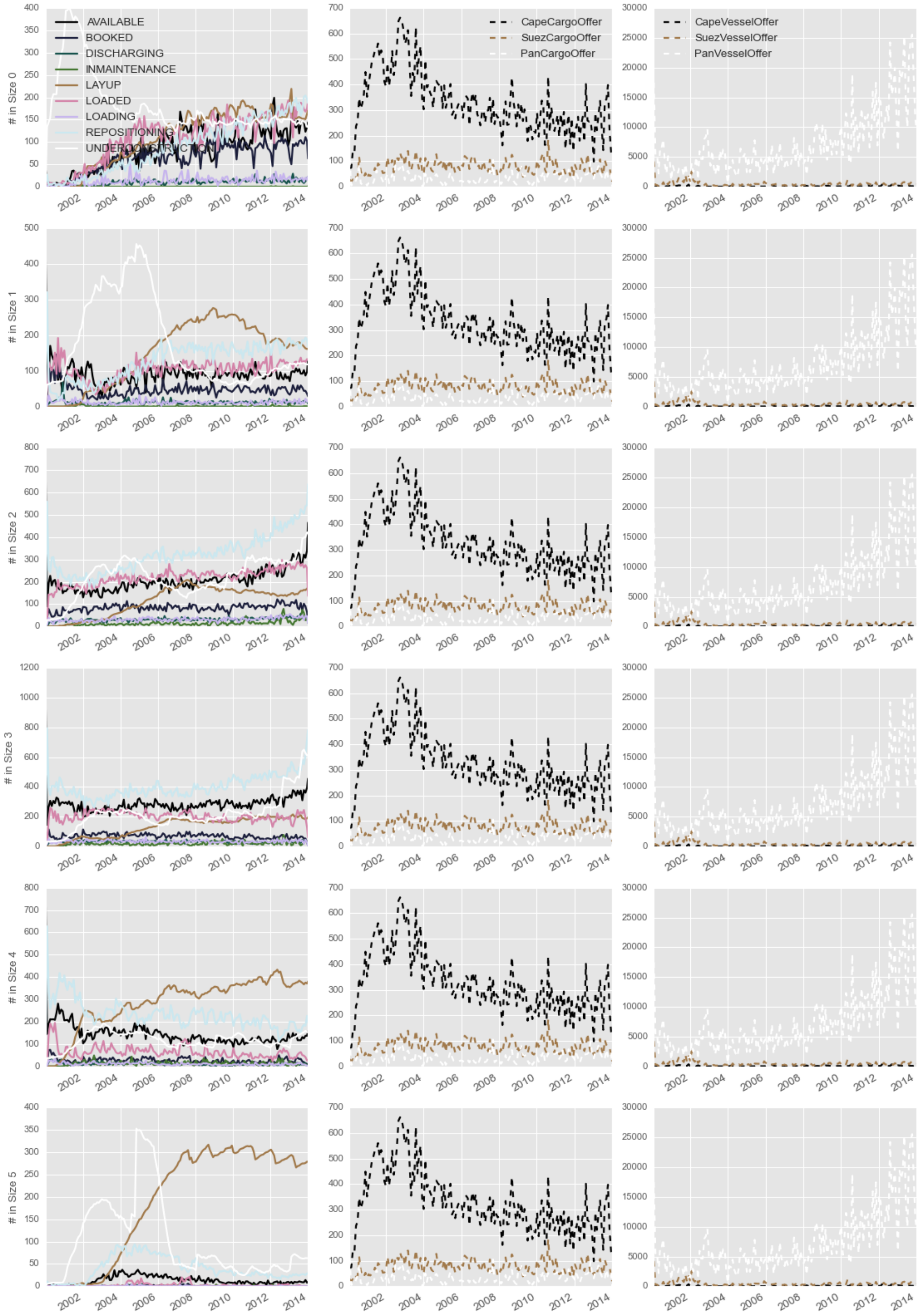


Figure 12.10. Count of vessels in a particular state (left column) and the number of ask cargoes in each size (middle column) and the number of cargo offers (right column) for Run 1.

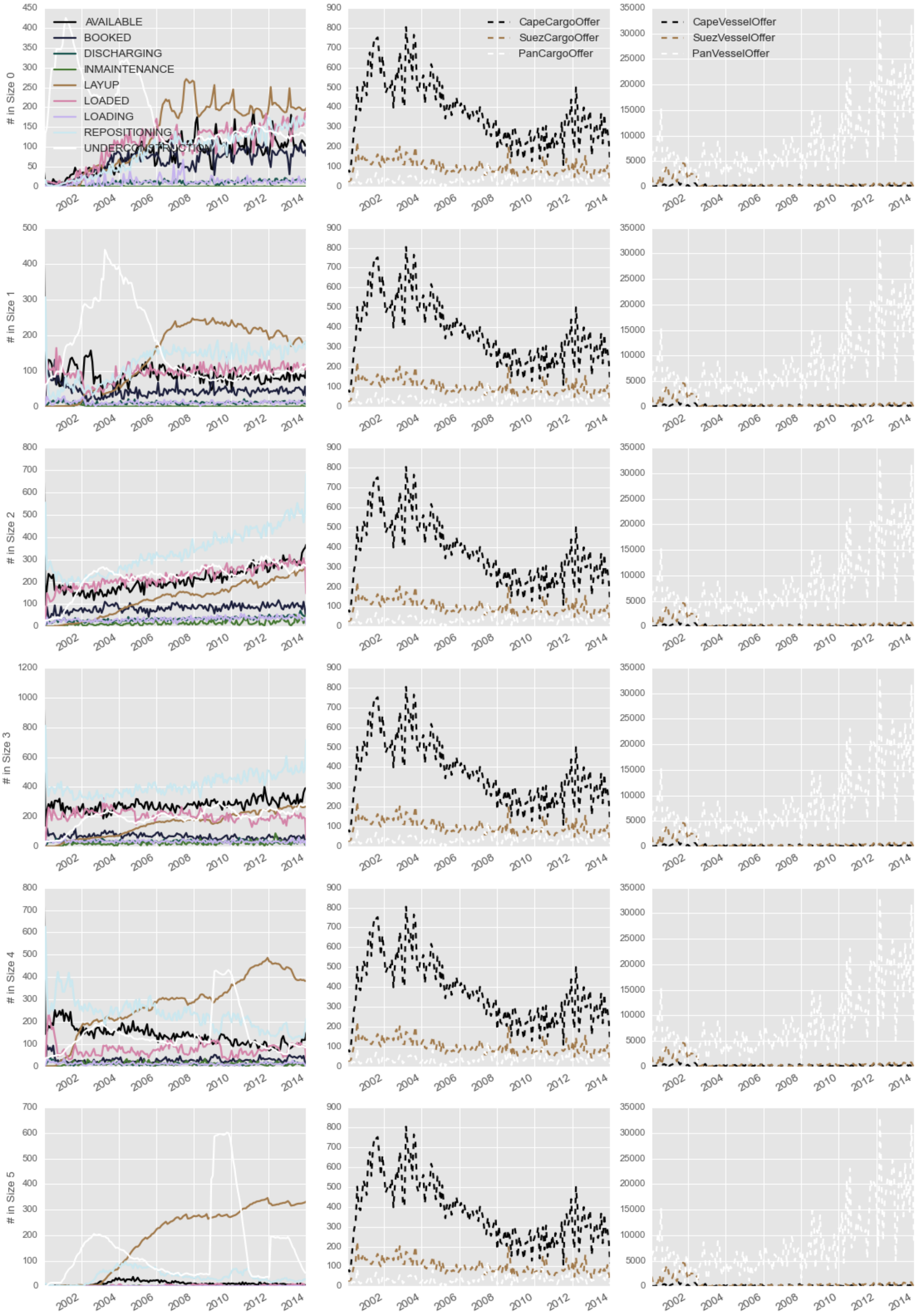


Figure 12.11. Count of vessels in a particular state (left column) and the number of ask cargoes in each size (middle column) and the number of cargo offers (right column) for Run 2.

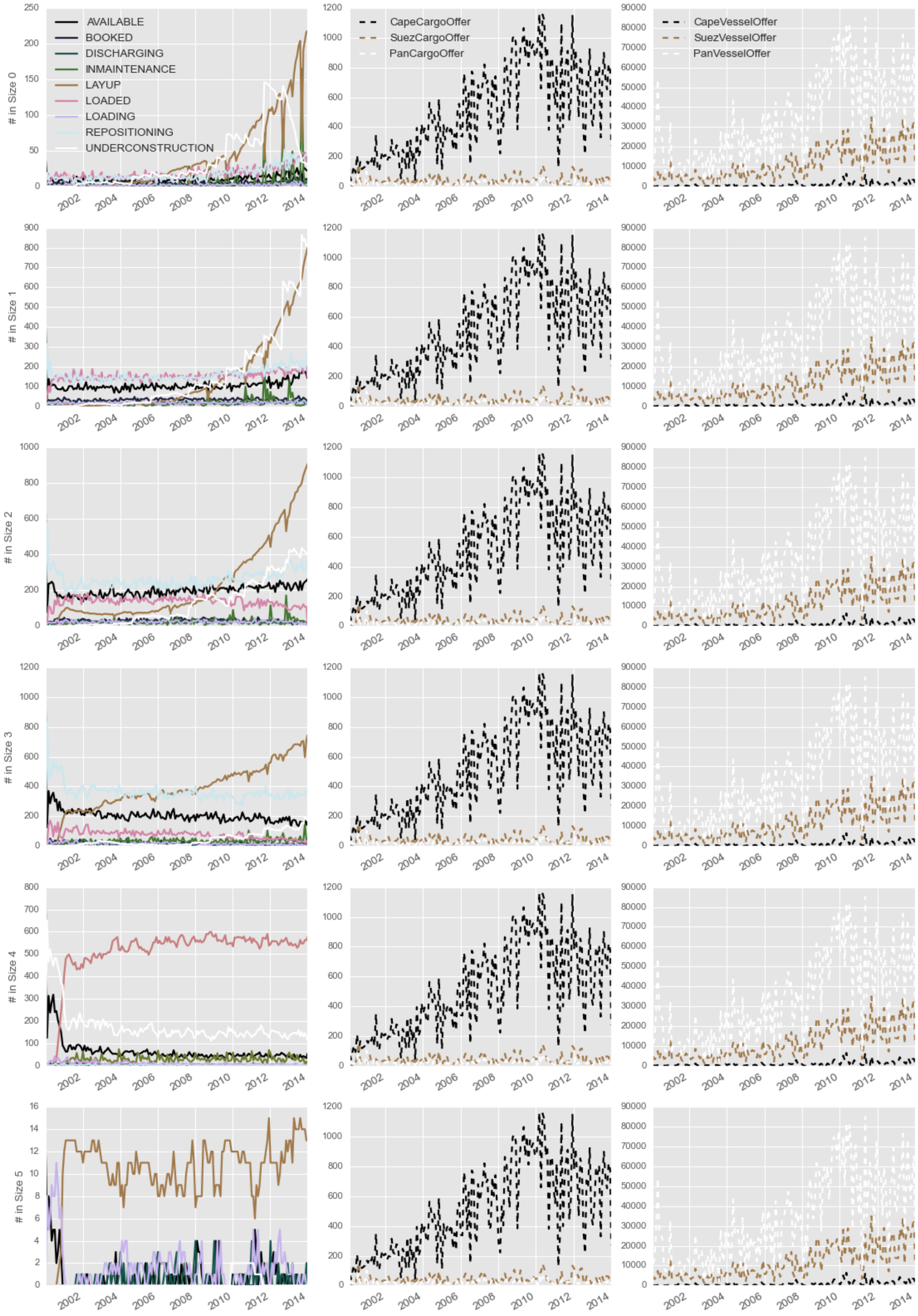


Figure 12.12. Count of vessels in a particular state (left column) and the number of ask cargoes in each size (middle column) and the number of cargo offers (right column) for Run 3.

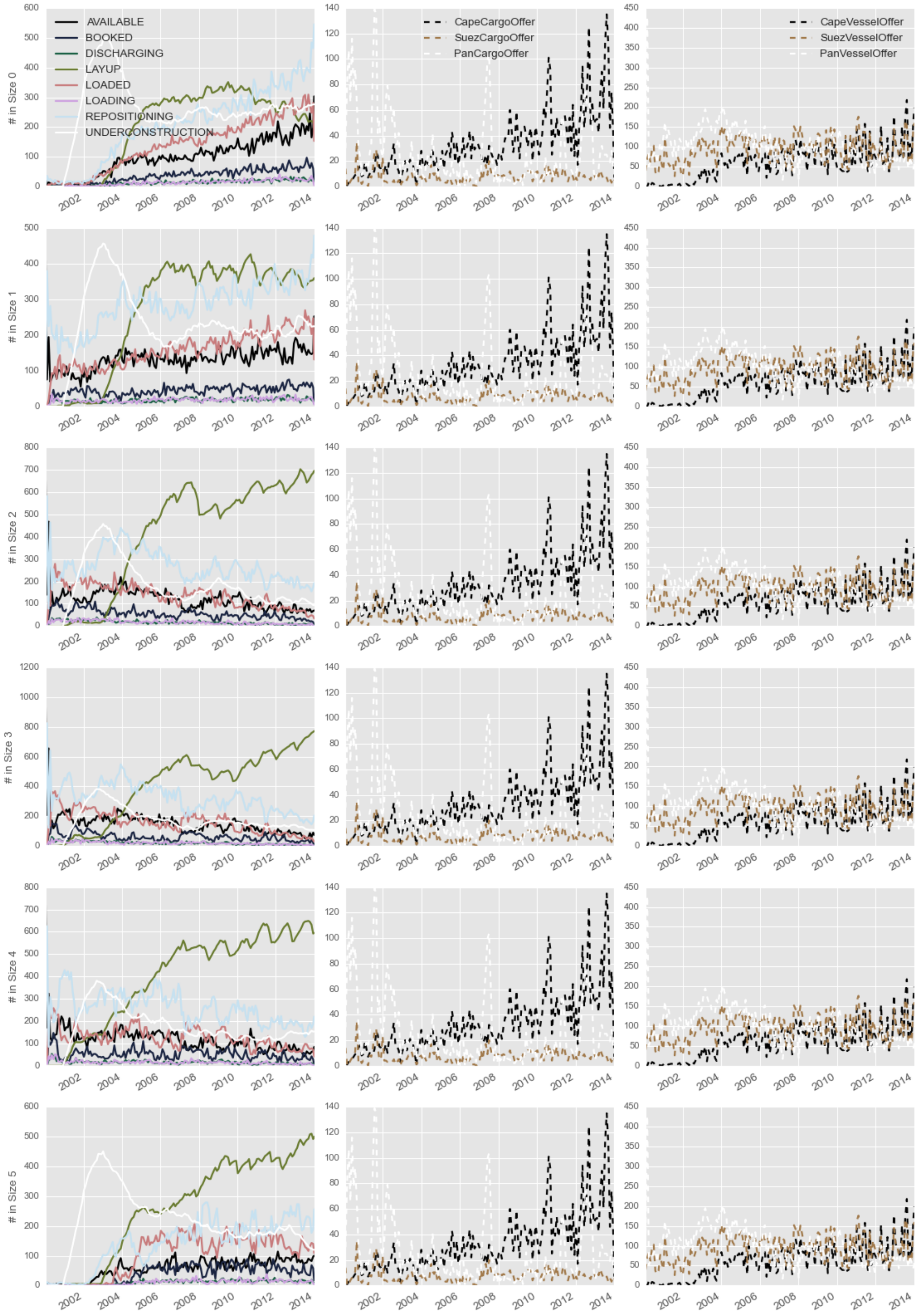


Figure 12.13. Count of vessels in a particular state (left column) and the number of ask cargoes in each size (middle column) and the number of cargo offers (right column) for Run 4.

12.4.5 Network validation

The network description is emergent as a result of operational and tactical decisions, and provides an aggregate description of the way in which cargo is transported. Kaluza et al. (2010) highlighted key emergent properties of the DBSS with a clustering coefficient of 0.43, mean degree of 44.6 and journeys per link of 4.65. The high mean degree shows that cargoes transported are typically transported directly from load port to destination port, rather than through a hub and spoke network. In addition, it also suggests that there are less multi stop cargoes than wet bulk trades.

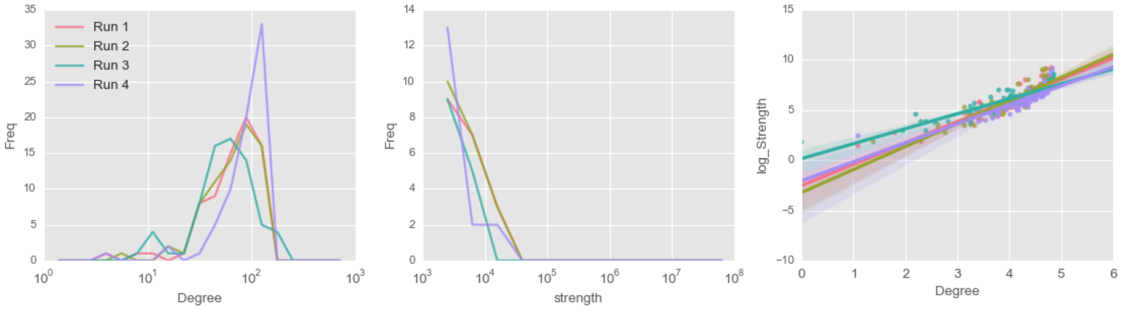


Figure 12.14. The plots show the mean degree distribution for ports (left), the node strength distribution (middle) and the average strength of node against node degree (right) for each run for the final time period.

The port degree distribution resembles more a normal distribution rather than a right-skew (Kaluza et al. 2010). This is likely because the scenario has limited the number of ports per country and only used the main ports. Therefore, there are very few instances where a port is only called at once as it is either a load or discharge port in constant use. Additionally, the shape may be explained by the lack of fuel stops to non cargo ports.

12.4.6 Operational validation

Figure 12.15 shows the modelled speeds across size categories compared with those reported in Smith et al. (2014). The vessels begin the run at their design speeds and in all cases the mean speed reduces either immediately and dramatically (size 4) or at slower trend as in runs 1 and 2 for size 3. Size 0, 2 and 5 see model estimates of mean speed approximately consistent with those reported in Smith et al. (2014). However, mean speeds are an emergent property of the system and strongly linked with the current supply-demand balance. As each of the runs has evolved from 2000, the supply-demand balance is different in each situation, therefore comparing real observations with model observations is likely to result in significant deviations. Rather, the mean speed as a system response to supply-demand imbalances should be considered.

In the real observations, there was a dramatic decrease (see **Figure 12.15**) in mean speed following the financial crash. A recovery over the next couple of years meant that speeds increased. However, the delivery of new vessels in 2010 meant an oversupply again leading to another drop in mean speed. Similarly, for all 4 runs, there was a large delivery of new tonnage in 2004 and 2005 (see **Figure 12.4**) leading to mean speeds reducing (dramatically in the case of size 0 and 1). A consequent scrappage of vessels in the following years resulted in an increase in vessel speed as supply reduced.

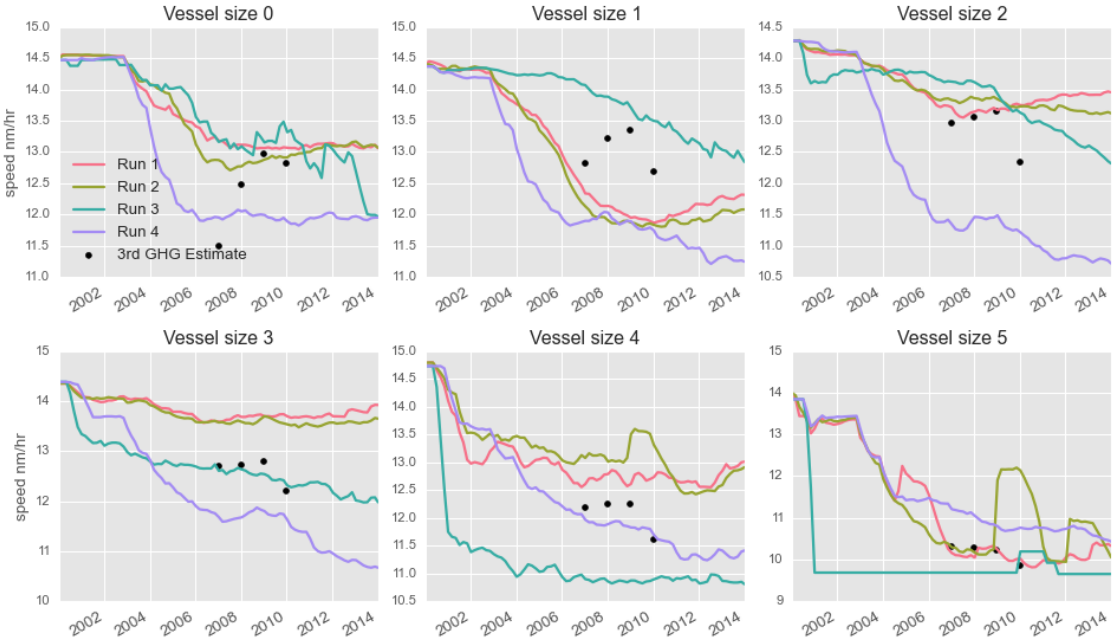


Figure 12.15. Mean operational speeds in each size category in all runs

No data is available on the types of contracts that are used to transport the cargo, although industrial shipping could be inferred from vessel ownership information aligned with vessel tracking information (typically AIS data). Typically, the larger predictable flows, such as iron ore, are expected to be on industrial shipping or CoAs. Runs 1 and 2 are the only scenarios that allow shippers create contracts of this type, specifically market Share (s_t5) and optimised (s_t4) *shippers*. The evolution of the number of shipper schedules on CoA or industrial shipping. In both runs, there is an initial move towards these managed flows before CoAs reducing to almost zero and industrial shipping stabilises from 2008.

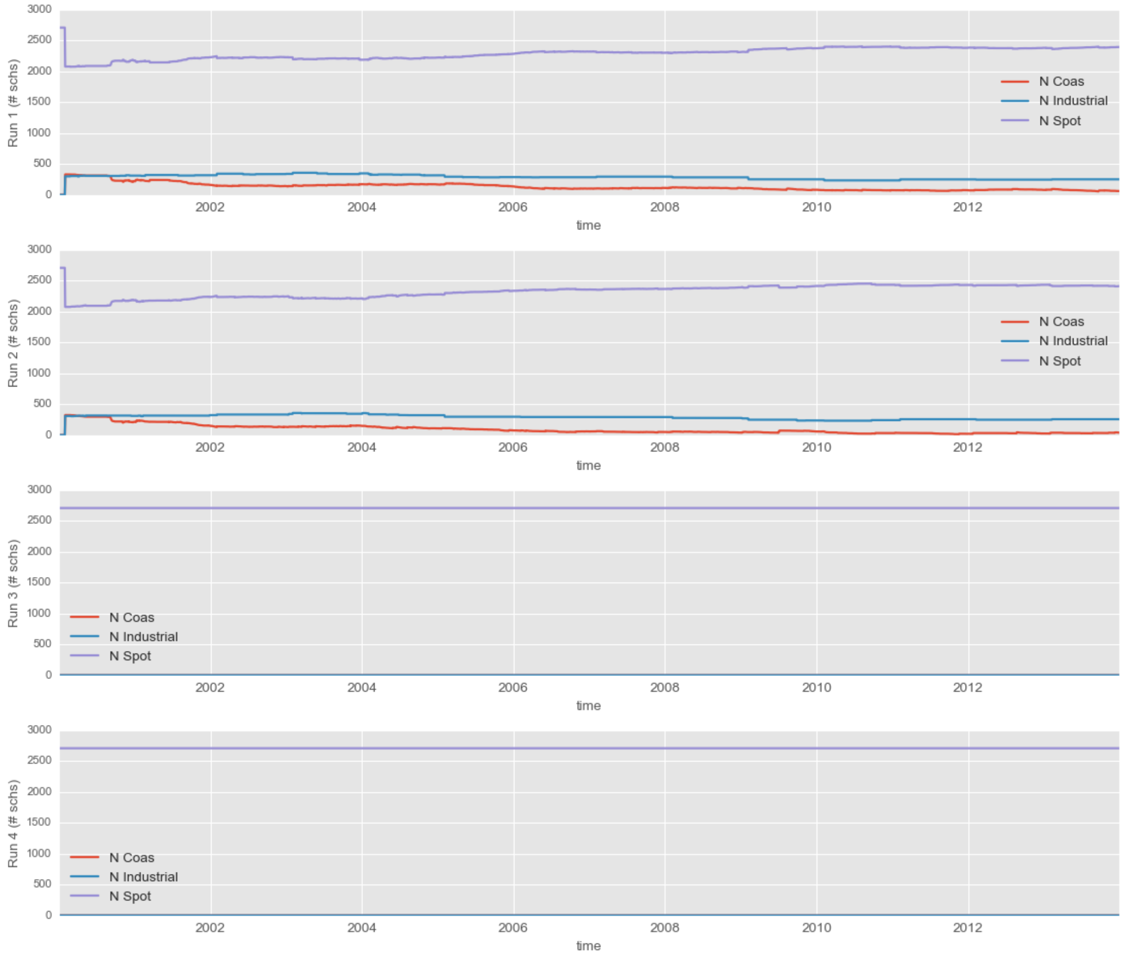


Figure 12.16. The plots show the number of shipper schedules on each of spot, industrial and CoA where each row represents a different run

Figure 12.17 shows the modelled mean days at sea for each size range compared with those estimated in Smith et al. (2014). Days at sea are likely strongly correlated with port load and discharge rates as well as other factors such as port congestion. Global port load rates are not available, with *GooFy* using assumed load and discharge rates, making any validation of days at sea statistics difficult. However, it can be seen that the mean days at sea increases with vessel size in the long run which is largely echoed in model runs 1 and 2. 2010 days at sea reduced significantly for sizes 0 to 4 from previous in the DBSS. The result of significant oversupply was *vessels* being laid up and remaining idle for long periods. A similar response can be seen in size 0 and size 1, particularly runs 1 and 2, as the system was being corrected. *Vessels* were incorrectly positioned and market rates were initially low as little matching was occurring. This resulted in *vessels* in waiting areas for long periods and being laid up. From 2002 onwards, the days at sea were steadily increasing in size 0 and 1 for runs 1 and 2, but in general were approximately stable.

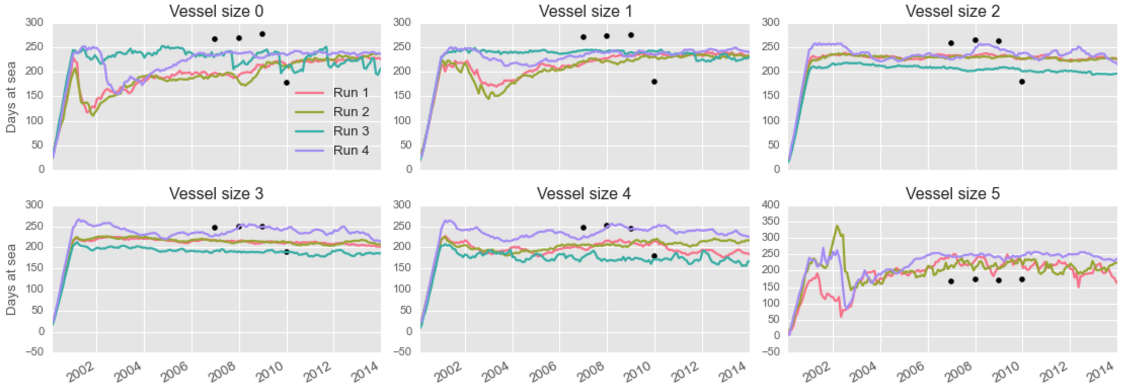


Figure 12.17. Days at sea for each size category. Only vessels that have carried cargo during the period are considered.

12.4.7 Fuel consumption and emissions

The dominance of size 0 vessels for runs 1 to 3 is clearly shown in **Figure 12.18**. Actual total HFO fuel consumption appears to be most similar to magnitude to the run 4 for sizes 0 to 4. In general, there is an underestimate of fuel consumption for smaller vessels likely due to exclusion of cabotage and coastal shipping, but also due to commodity flow inputs and shipper schedule assumptions.

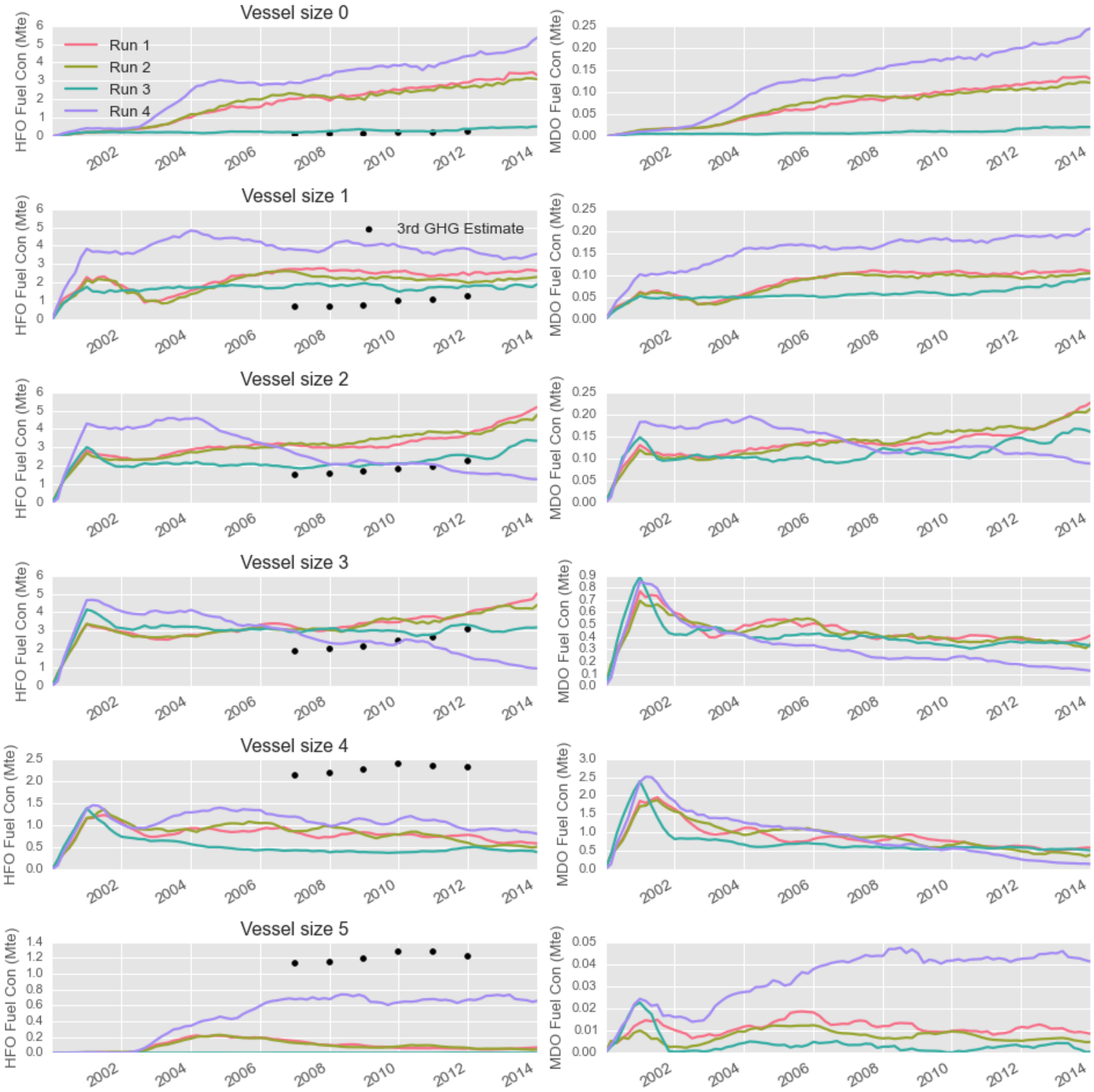


Figure 12.18. Total annual fuel consumption in each size category and each run comparing real world estimates (Source: Smith et al. (2014)) for HFO and modelled results.

Vessel operational indices show significant scatter but become stable, particularly in runs 1 and 2 for the mid to large vessel sizes.

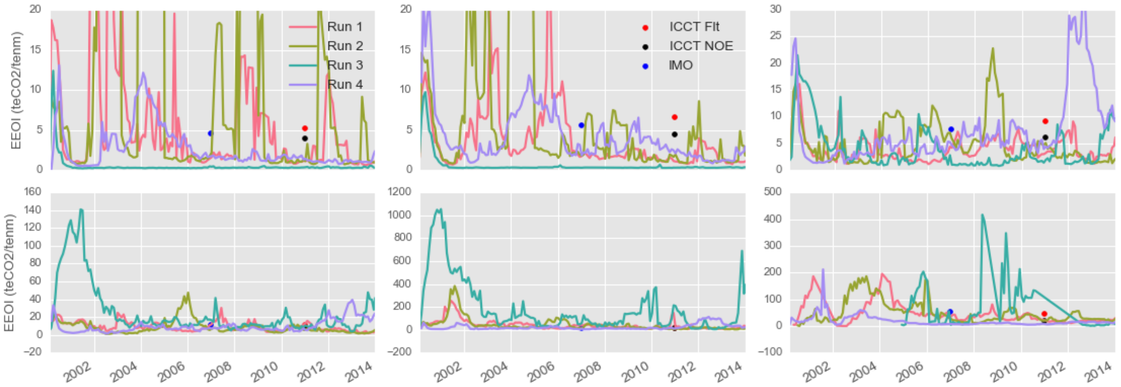


Figure 12.19. Mean operational efficiency index in each size category and each run where cargo has been transported by the vessel during that year (where the cargo carried by a vessel within the year is greater than 10,000t). Comparisons to those reported in other reports (Table 31 in Smith, O'Keeffe & Haji (2013a))

12.4.8 Market Validation

Initial periods in the market result in significant volatility both in price but also in cargo size selection for the different commodities. This is due to the uncertain price signal from the market. *Shipbroker*, *shipper* and *shipowner* are unclear as to what price to set and they flip flop from one market segment to another. All cargo is transported on this spot market initially as both *shipper* and *shipowner* are pure place entities. The market volatility is shown in **Figure 12.21**.

Following market price discovery and the development of some stability within the market, the time charter market opens up. Also at this point, the *shipper* looks to reduce the risk in their shipments and looks to provide a base transport for their regular cargoes.

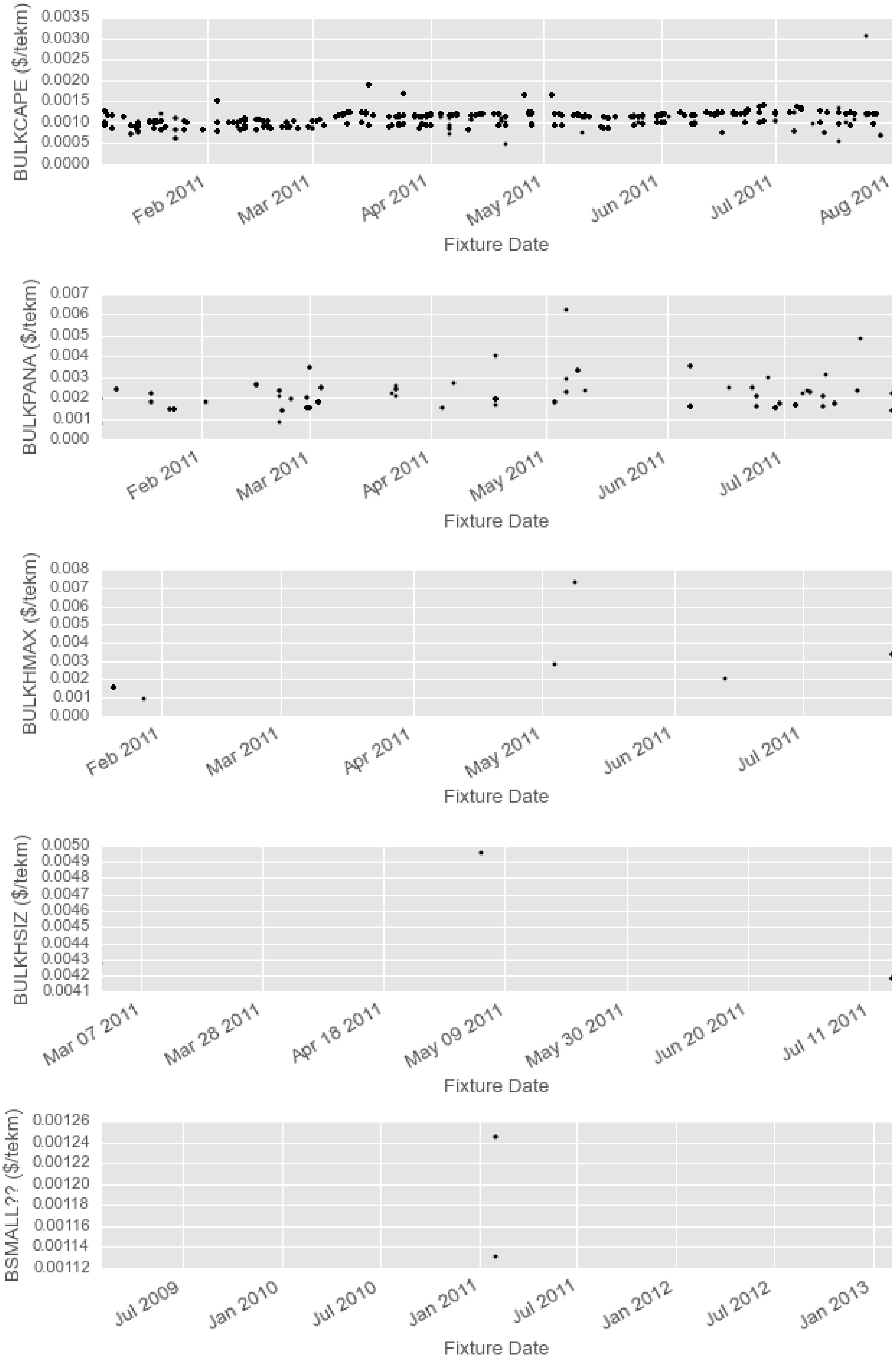


Figure 12.20. Actual fixtures prices with \$/tekm estimated

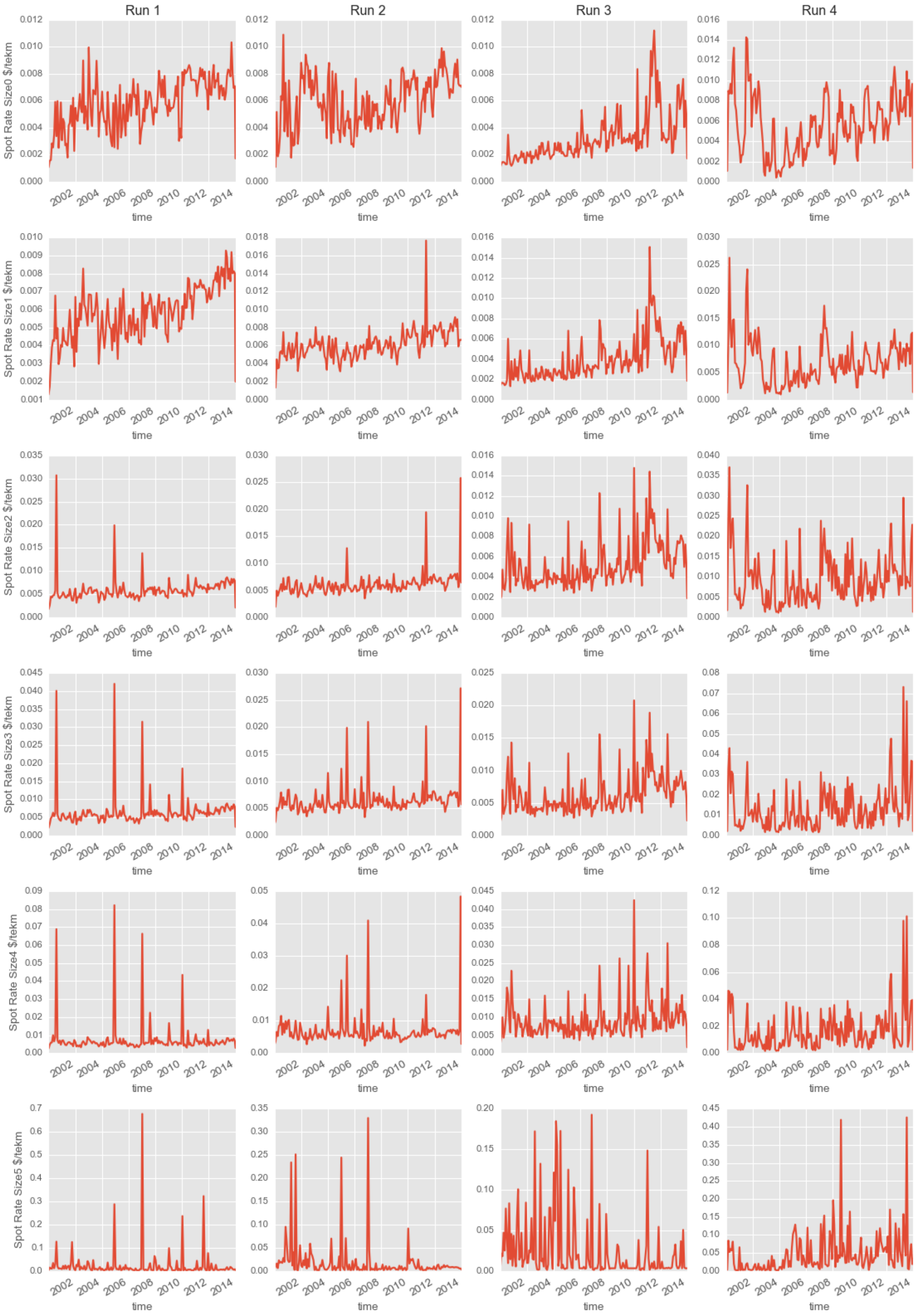


Figure 12.21. Time series plots of spot prices by run where each size is shown in a separate plot.

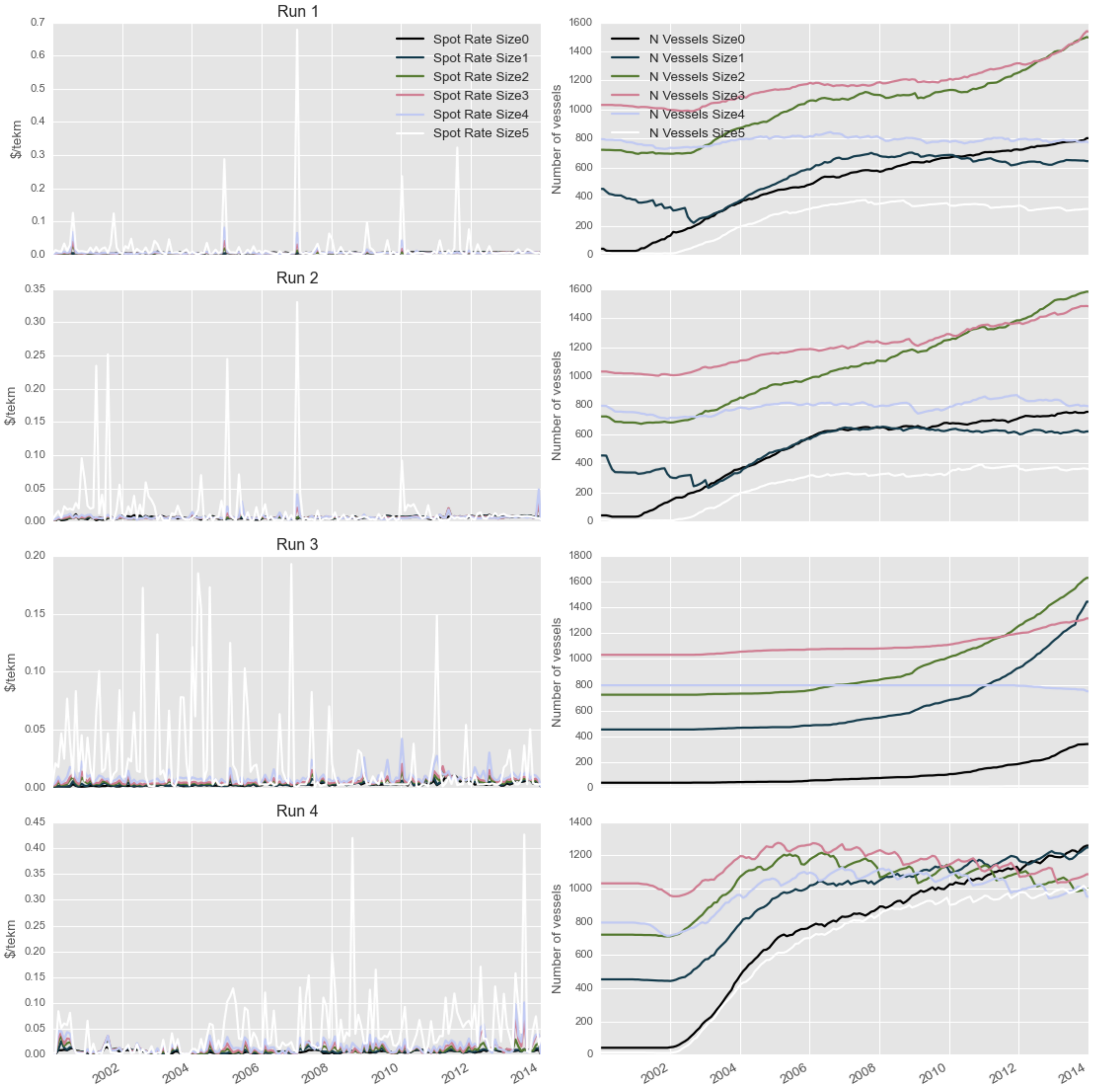


Figure 12.22. Model time series plot of mean spot price for each size category (left column) and count of vessels in each size category (right column)

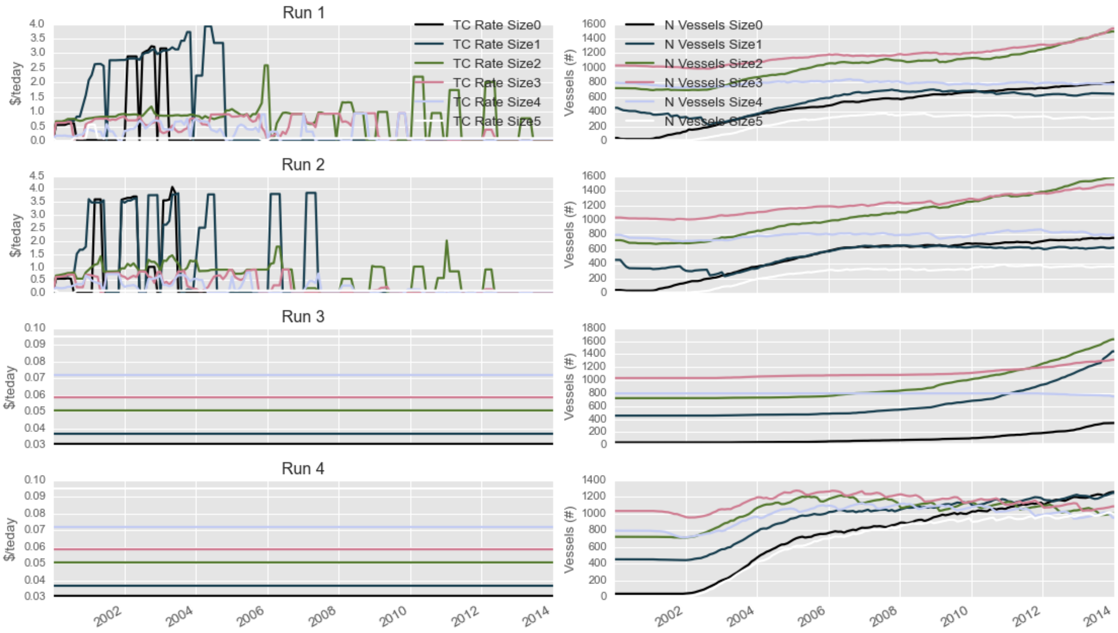


Figure 12.23. Model time series plot of mean time charter price for each size category

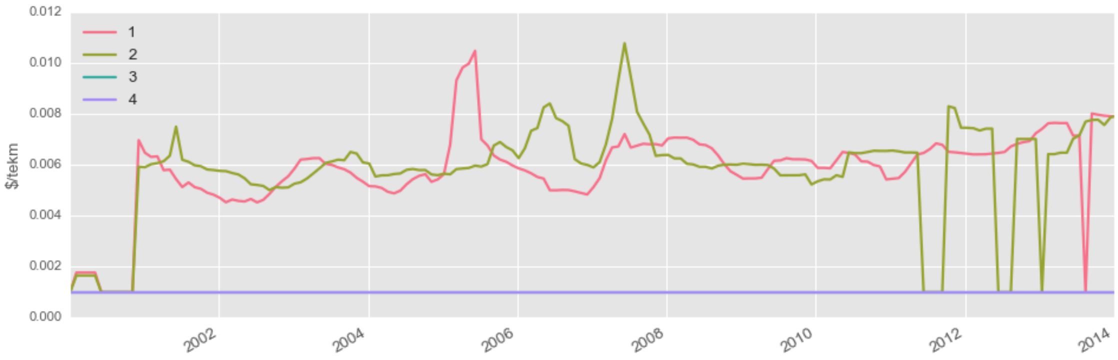


Figure 12.24. Model time series plot of mean CoA rate for each run

12.5 Summary

This chapter highlights the difficulty in validating ABMs, particular *GooFy* as the model runs show a simulation run rather than representing results probabalistically from Monte Carlo simulations. Additionally, the lack of observed data, particularly at high granularity, compounds this difficultly in both validating but also in providing correct inputs to effectively simulate the real DBSS. Moreover, a significant amount of the validation data is itself the result of modelling the real DBSS and is thus uncertain, in most cases of unknown uncertainty (particularly fuel consumption and CO_2 emissions).

Notwithstanding these limitations, 4 scenarios were run: runs 1 and 2 with mix strategies, run 3 as a pure spot market and run 4 using only random shippers and shipowners.

There are good correlations in some statistics both on data points but also on system responses such as days at sea and operational speed. In other areas, such as fuel consumption, there are significant differences particularly for size 0 vessels. As noted in the text, this is due to a number of factors both endogeneous and exogeneous. The system is strongly dependent on the trade pattern and how that trade pattern is disaggregated in commodity flows and shipper schedules. The number of vessels available on the market initially and their locations appears significant in the evolution of the system. The initial supply-demand mismatch causes a number of vessels to be purchased and then scrapped not long after. It takes up to 5 years for a stable and robust market signal to develop.

Internally, the mapping of vessels to cargoes is strongly dependent on the shipper strategies and shipowner strategies. A shipper schedule that is marked as industrial shipping will likely have different cargoes sizes (and variance in the cargo sizes) than a shipper schedule that is on the spot market.

In general, the system is performing in an intuitively consistent way, particularly in runs 1 and 2 which contained mixed strategies. The pure spot market performed worst of all, significantly falling short of matching supply and demand. In some sections, the random scenario performed best (particularly on fuel consumption) but it doesn't represent the full range of shipping contracts (i.e. it doesn't include CoAs and industrial shipping). Runs 1 and 2, the mix strategies, are therefore used in the projection scenarios. These runs included random shippers and shipowners but also included learning agents.

Chapter 13

Scenario development

13.1 Introduction

This chapter introduces the scenarios that are run on *GooFy* for the projections to 2050. In addition to these two scenarios an additional scenario running from 2000 to 2010 is generated using the same data sources for backcasting and model validation which is described in **Chapter 12**.

13.2 Scenario Narratives

The basis for the scenarios is the work on representative control pathways (RCP), produced by Moss et al. (2010). This work identified climate impacts for several representative scenarios. The economic scenarios underlying these are the shared socioeconomic pathways with the two scenarios used in this study being SSP5 and SSP1, which are coupled with impact pathways discussed below.

13.2.1 High growth, high impact scenario

Economic scenario SSP5 is coupled with impact scenario RCP 8.5. The RCP 8.5 is characterized by increasing greenhouse gas emissions over time representative for scenarios in the literature leading to high greenhouse gas concentration levels.

13.2.2 Sustainable development scenario

This is consistent with scenario SSP1 and RCP 6. It is a stabilization scenario where total radiative forcing is stabilized after 2100 without overshoot by employment of a range of technologies and strategies for reducing greenhouse gas emissions.

13.3 Scenario Data

The following section outlines the supporting data required in the running of *GooFy* and its provenance. As discussed at length in **Chapter 10**, the granularity of *GooFy* is such that it requires a significant amount of disaggregated input data. This is discussed in the following sections.

13.3.1 Commodity Prices

It is assumed that commodity prices are consistent globally and applied uniformly (eg. there is no adjusted internal commodity price that a shipper will use), with the baseline price calculated as the global share of the constituent commodity, shown in **Figure 13.1**. The commodity prices are based on a normally distributed data generating process, estimated using the annual prices of the mapped commodity for the period 2007 to 2014. This results in a stable mean price for all commodities over the full period of the model run. For each of the different scenarios, the seed of the generating process is locked, resulting in the same commodity price scenario for all the scenarios. The resultant commodity prices are shown in **Figure 13.2**.

$$P_k \sim \mathcal{N}(E\left[P_k^{2007-2014}\right], var\left[P_k^{2007-2014}\right]) \tag{13.1}$$

Where

P_k = Price of commodity k used in *GooFy*(\$/t)

$P_k^{2007-2014}$ = Annual commodity prices for commodity, k over the period 2007 to 2014

Figure 13.1. Data generating process for commodity prices

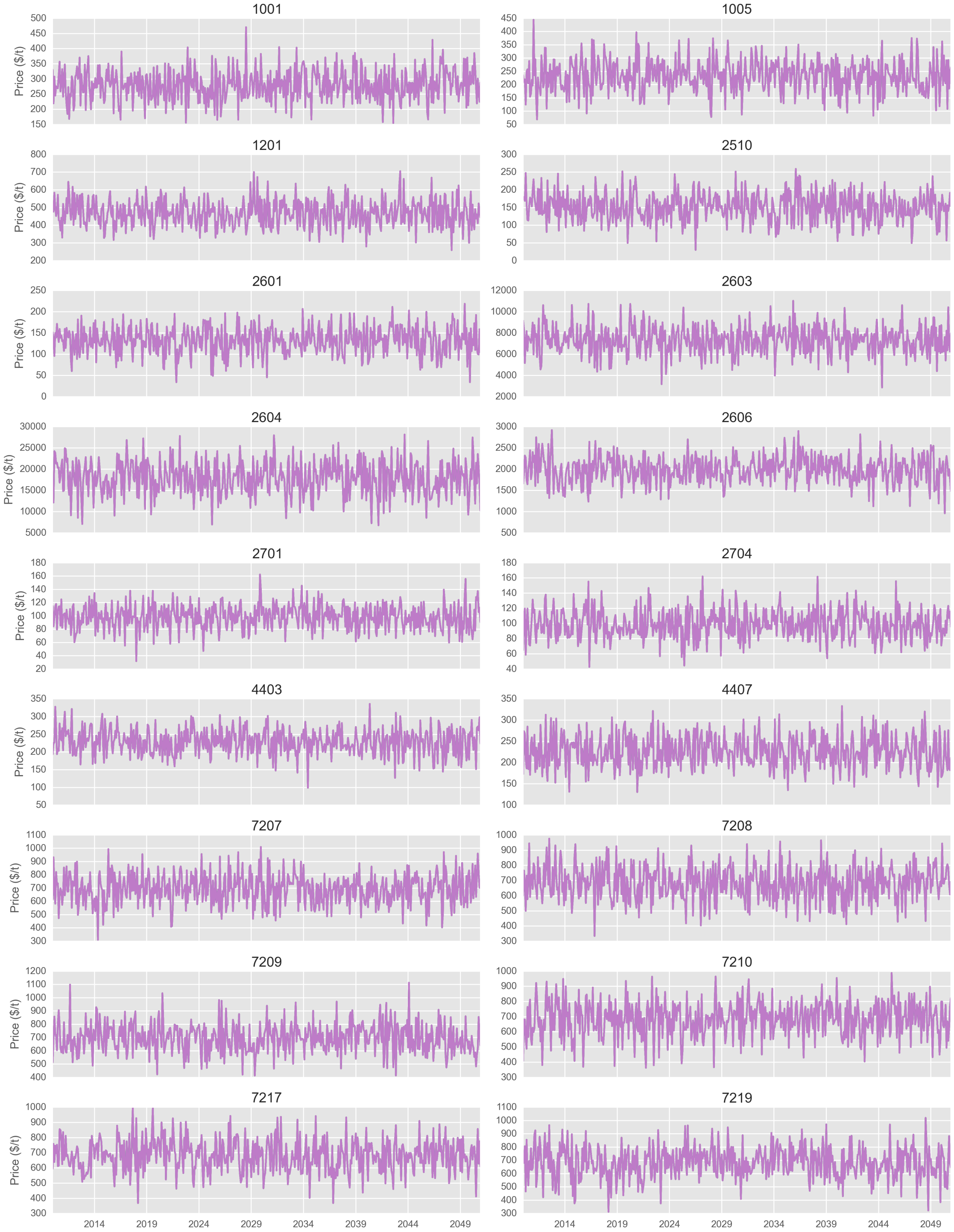


Figure 13.2. Commodity price, by row, in each scenario. Although each scenario is represented by a different colour, the commodity price was generated once for all scenarios resulting in all scenario prices overlapping.)

13.3.2 Countries

The top 100 countries for trade flows are selected, capturing over 90% of most trades as shown in **Figure 13.3**.

Figure 13.3. The effect of truncating the trade to a selected number of countries for selected commodities: The raw data (COMTRADE 2018) is shown in red and the effect of reducing to the selected countries is shown in in green. This was removed in the analysis in ***Chapter 9 Section 9.3***

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13.3.3 Generating port to port distances

Distances between ports are generated using Dikstras algorithm (Dijkstra 1959) as deployed in NetworkX (Hagberg et al. 2017). The path edges are generated using a bespoke algorithm developed in this thesis, which adopts a similar approach to Kaluza et al. (2010), where the coastline of all countries is reduced to a series of nodes. All nodes, where the edges do not cross land, are joined to form the edges for the algorithm. There is a different template generated for different paths that a vessel can use. These are:

- Cape routes: No edges are allowed to cross at Suez or Panama and is applied to vessels size 0. This template is shown in **Figure 13.4**.
- Suez routes: Edges are created at Suez to allow crossing of the canal but Panama routes are excluded. This is applied to vessels between size 2 and size 1.
- Suez and Panama routes: Same as Suez but also includes the edges facilitating use of Panama canal. This is applied to all vessels of size 2 to size 6. But the size cutoff increases from 2018 due to the expansion of Panama.
- The three routes above but includes Arctic routes: The generation of the templates above excluded all routes passing through the Arctic zone. This area is now assumed to be uncovered and edges that cross this zone are allowed. Depending on the scenario, these routes are applied to the same size ranges as outlined in the three route options above.

Before each scenario is run, all port to port distances are generated for each of the different size categories above. These distances may vary over time. In *GooFy*, when a distance is requested from the distance generating function, the vessel size and year is passed. Using these parameters, the associated shortest path distance is then returned. For example, for a capesize vessel in 2010, the distance from UK to Japan would return a path distance based on a route around the Cape of Good Hope. In a climate change impact scenario, from 2030 the returned distance would be using an Arctic route.

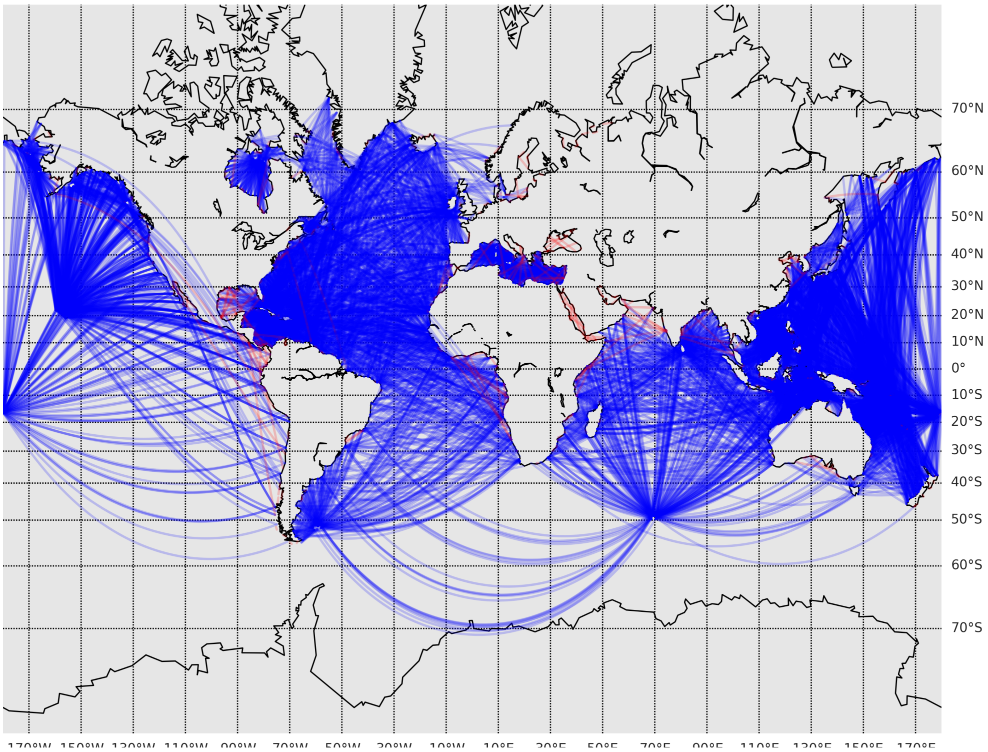

Figure 13.4. Template for generating shortest paths for capesize vessels. The edges between regions in blue and within regions in red for the cape template used in generating shortest path distances between ports. For clarity, the edges passing across the Pacific are removed and 1 in 5 of intra regional edges are shown.

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13.3.4 Policy and Regulation

Regulation can be broadly categorised into GHG and non-GHG. This work focusses on GHG related regulation and therefore does not include the Emission Control Areas (IMO 2017).The enacted regulation that is applied in *GooFy* is shown in **Table 13.1**.

	Size ('000s)	From Jan 2015	From Jan 2020	From Jan 2025
EEDI	10-20	0-10%	0-20%	0-30%
EEDI	20+	10%	20%	30%

Table 13.1. Scenario Regulation

In addition to the existing and expected regulation, the model also includes a carbon price scenario. Discussions at the IMO vary as to how a carbon price should manifest: ie cap on emissions or tax on emissions. Also, if a cap and trade option were selected then this could be an open scheme with other industries or a shipping scheme on its own.

Due to the uncertainty surrounding the carbon price, indeed if any solution is selected, the carbon price used for this model is assumed to be insensitive to the emissions. In other words, the carbon price is set exogeneously.

For *GooFy*, carbon price scenarios already used in other publications are deployed, specifically Argyros & Smith (2015). The scenarios are divided into status quo (SQ), global commons (GC) and competing nations (CN). These three scenarios represent a business as usual with a low carbon price, a global approach to reducing emissions resulting in a high carbon price and fragmentation and protectionism results in no carbon price respectively. The carbon price trajectories are shown in **Figure 13.5**.

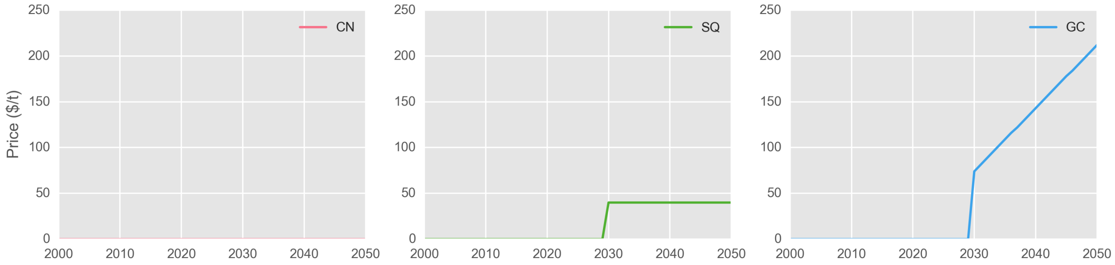

Figure 13.5. The three carbon price scenarios used in GooFy
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13.3.5 Fuel Prices

As was the case for carbon pricing, the fuel price scenarios are also taken from Argyros & Smith (2015), and show in **Figure 13.6**. GC offers lower fuel prices for the low in GHG fuels, while the competing nations scenario has high fuel prices in all scenarios.

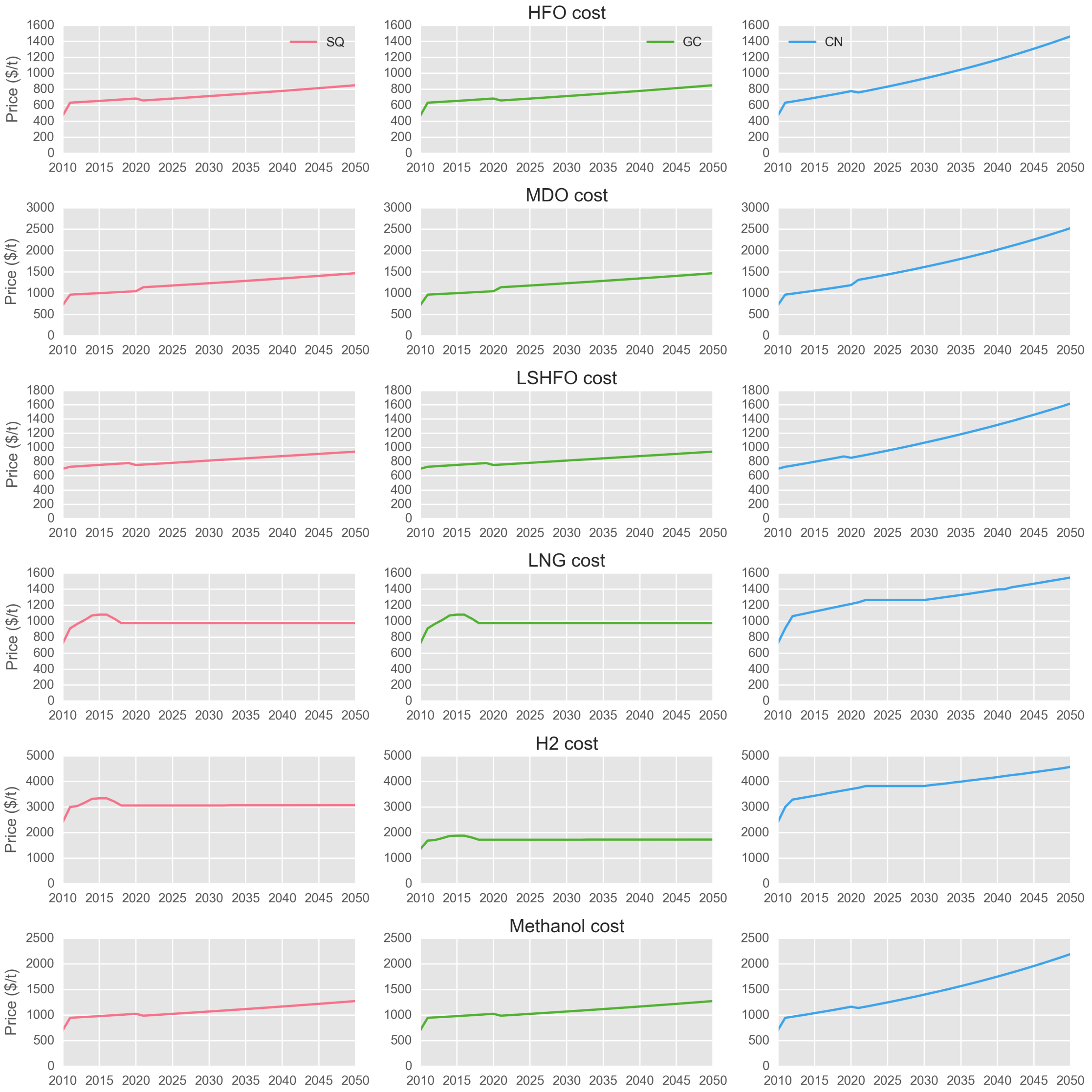

Figure 13.6. The three fuel price scenarios used in GooFy

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13.3.6 Trade

Before outlining the individual scenarios, it's important to discuss the individual processes that govern the production and consumption processes of the commodities. The equation governing the trade demand is shown in **Chapter 10 Figure 10.11**.

Considering global development, it's important to consider changes in trade openness. In the context of the environment, Grossman & Krueger (1991) provided the first framework for considering the impacts on the environment from trade liberalisation.

They consider the opening of trade in three effects:

- Scale Effect: In a liberalised situation, unemployed resources will reduce leading to increase production and economic activity and energy demand and thus an increase in emissions.
- Composition effect: How changes in relative prices and changes in comparative advantage will create shifts of focus of production in countries. A shift to low carbon intensive industries would cause a reduction in emissions and vice versa.
- Technique effect: This takes two forms: the first relates to the cheaper availability of low carbon technology and the second; the general expected rise in incomes will lead to an overall demand increase for low carbon goods.

Studies have found the scale effect to be strongly dominant resulting in increasing emissions (Tamiotti 2009). In terms of the impacts of climate change on trade, few studies have considered this (Tamiotti 2009). Impacts may effect countries comparative advantage, particularly those who rely on comparative advantage from geophysical or climate reasons (Tamiotti 2009) such as agriculture or tourism sectors. Secondly and most importantly for this study, Tamiotti (2009) suggest *'climate change may increase the vulnerability of the supply, transport and distribution chains upon which international trade depends'*.

Hummels considers transport costs in three ways:

- Changes in ad valorem cost, which is the change in transport cost as percentage of value of goods.
- Changes in transport costs as percentage of trade costs. Anderson & Van Wincoop (2004) estimated that the tariff equivalent of trade costs for industrialised countries at that time was on average 170%.
- The extent to which transport costs alter relative prices of commodities.

Although the first item can be estimated from modelling with *GooFy* the second two item cannot, as only primary sources are modelled.

To generate the parameters identified in the production and consumption models overall trends and volatility must be generated for the individual commodities for each origin and destination pair. The exports for each commodity and each country is decomposed in trend and seasonality factors. The example of USA grain exports is shown in **Figure 13.7**. Once the production process is generated for each origin-destination pair as discussed below, this seasonality (applied as a % of annual trade) is applied allowing the annual trade to be disaggregated into monthly flows.

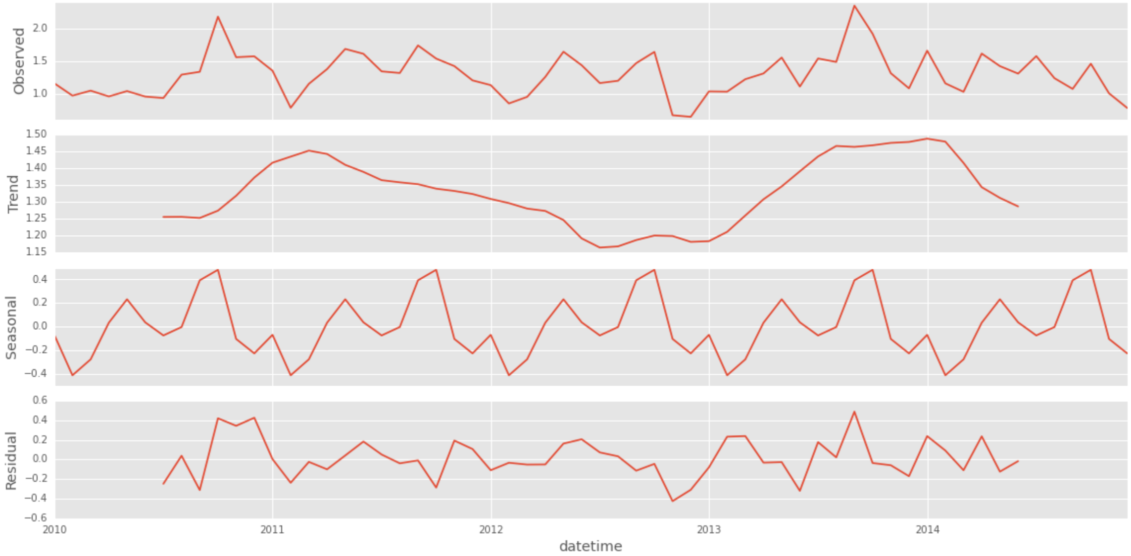

Figure 13.7. Reported monthly grain exports (top plot) from the USA decomposed into trend, seasonality and residual respectively.

The commodities are then split into three different categories so that annual growth rates can be applied. These are shown in **Table 13.2**.

Type	**Commodity Codes**
GDP growth rates	1005, 1001, 1201, 2601, 2704, 2510, 2606, 2604, 7207, 7208, 7209, 7210, 7217, 7219, 4407, 2603
Coal energy growth rates	2701
Biomass energy growth rates	4401, 4402, 4403

Table 13.2. Growth rate categories for each commodity

The growth rates for these category groups are shown in **Figure 13.8**.

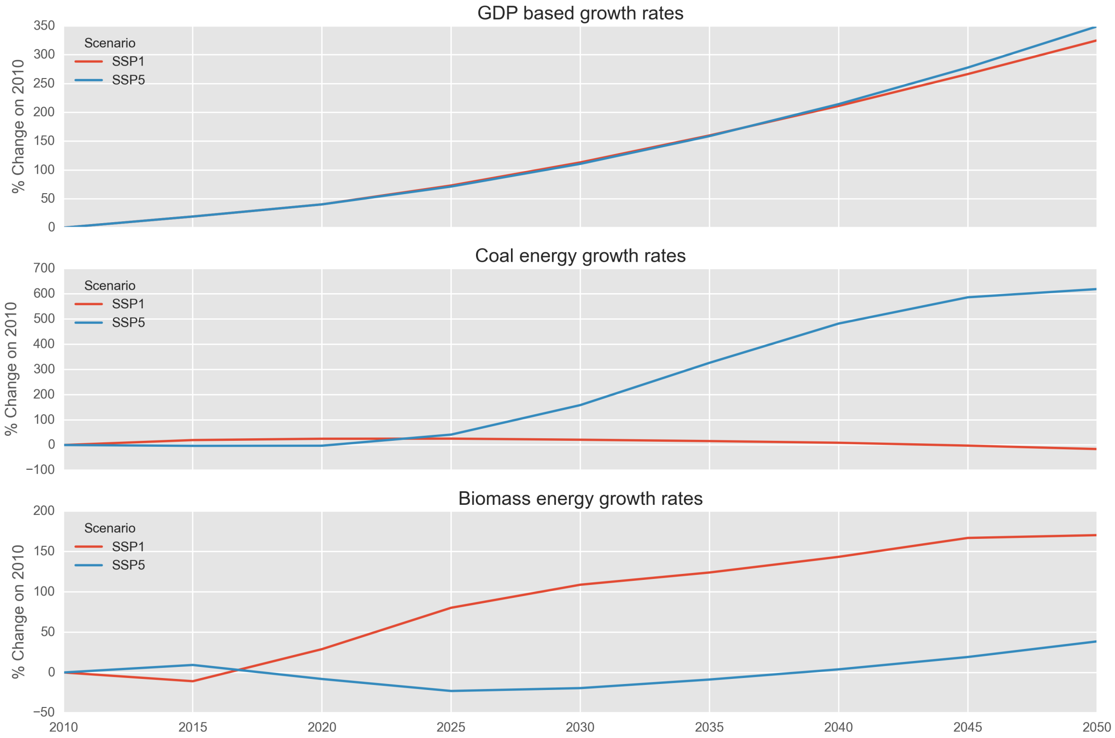

*Figure 13.8. GDP, coal energy and biomasss energy growth rates used in GooFy Source: Kriegler et al. (2014). The scenarios have been updated recently (Riahi et al. 2017*a,b*) but this study uses those growth published in the 2014 study.*

13.3.7 Country flows disaggregation

Country to country flows must be disaggregated between their respective port to port flows. For this, the trade is assumed to split by vessel class. Using the port calls generated in the network analysis for each country, the port flows are split between this traffic.

$$(P)(p|c,k) \quad = \quad \frac{n_v^p}{n_v^c}, v \in \begin{cases} V_k & \forall V_k \neq \varnothing \\ V & \forall V_k = \varnothing \end{cases}$$

where

c = country c, can be origin or destination country in a trade flow
p = port, p in country c
k = Commodity k
V_k = Vessels allocated to the commodity k, eg capesize for iron ore

Commodity Code	Typical vessel type
1001	Handymax, supramax and panamax
1005	Handymax, supramax and panamax
1201	Handymax, supramax and panamax
2510	Handysize
2601	Capesize
2603	Feeder and Handysize
2604	Feeder and Handysize
2606	Handysize
2701	Suezmax and Capesize
2704	Suezmax and capesize
4403	Feeder and handysize
4407	Feeder and handysize
7207	Feeder and handysize
7208	Feeder and handysize
7209	Feeder and handysize
7210	Feeder and handysize
7217	Feeder and handysize
7219	Feeder and handysize

Table 13.3. Cargo parcel size categories

Market factors

Demurrage rates are an important part of the model as cargoes not matched to vessels may incur late fees for the shipper. Published rates are not available, but (Handybulk 2018) uses an example of 30,000 per day. Depending on the size of the vessel and commodity this could be less than 1% of commodity value or up to 30%. To ensure delivery of cargo, the late fees are assumed to be an annualised rate of 30% of the value of the cargo compounded daily. As well as the difficulty involved in calculating demurrage rate, there is further difficult in calculating port costs and canal costs. However, (Stopford 2009) provides some guideline figures that have been used in this analysis, shown in **Table 13.4**.

item	**Approx cost**
Ports and Canals	
Cargo handling costs	$1.4te
Canal dues	$1te
Broker commision	1.5%
Maintenance	
Age 0-5 years	$1teyr
Age 6-10 years	$1.5teyr
Age 11+ years	$2.7teyr

Table 13.4. Typical additional vessel costs. Source: Stopford (2009)

However, given the uncertainty surrounding these, they are excluded from *GooFy*.

13.3.8 Vessels and Technology

The baseline fleet was based on Clarksons (2011). New technologies and their technical impact is taken from the GloTraM (Smith et al. 2010). Each scenario has the same technology options, shown in **Table 13.9**.

Source	Measure
MEPC59/10	Superstructure streamlining 1
MEPC61/18	Wing pods
MEPC61/18	Pulling pods
Both	Contra-rotating props
MEPC61/18	Prop section optimisation
MEPC59/10	Ducted Propeller
MEPC59/10	pre-swirl duct
MEPC61/18	Propeller upgrade
Both	Propeller boss cap fin
MEPC59/10	Asymmettric Rudder
Both	Propeller rudder bulb
MEPC59/10	waste heat recovery gas fuel
MEPC61/18	Waste Heat Recovery slow speed (propulsion)
MEPC61/18	Air lubrication (bubbles)
MEPC61/18	Air lubrication (cavity)
MEPC61/18	Hull coating 1 (biocidal)
MEPC61/18	Hull coating 2 (foul release)
MEPC61/18	Hull cleaning
both	Propeller polishing
MEPC59/10	Sails
MEPC61/18	Wind engine
MEPC61/18	Wind kite
MEPC61/18	Covering hull openings
MEPC61/18	Speed control pumps and fans
MEPC61/18	Energy saving lighting
MEPC61/18	Autopilot upgrade/adjustment
MEPC61/18	Trim and ballast optimisation
MEPC61/18	Main Engine Tuning Phase 1
MEPC61/18	Prop Hull optimisation
MEPC61/18	Skeg optimisation
Other	Improved Rudder
Other	Stator fins
MEPC59/10	Superstructure streamlining 2
MEPC61/18	Main Engine Tuning Phase 2
MEPC59/10	Solar Power (Hotel dry and wetbulk)
MEPC61/18	Optimisation of dimensions (slow)

Figure 13.9. Technology options with associated MEPC reference. Source: Smith et al. (2010)

13.4 Agent Strategies

Strategies are assigned according to the conditions set out in **Table 13.5** and **Table 13.6**.

flow_size	vessel_count	s_t1	s_t2	s_t4	s_t5	s_t6
0	0	1	1	1	1	1
10000000	0	1	1	1	1	1
10000000	1	0	0	1	1	0

Table 13.5. Criteria for mix scenarios for shipper agent. The flow_size shows the volume ranges which the strategy can be assigned to a shipper for. Equally, the vessel_count shows the vessel ranges over which the strategy can be applied to a shipper. 1 (0) indicates that a shipper categorised in this row can(not) be assigned this strategy. For example, if a shipper has only commodity flows below 1m tonnes, it can s_t1, s_t2, s_t4, s_t5 or s_t6

vessels_count	so_t7	so_t8	so_t9
30	1	0	0
20	1	0	1
10	0	0	1
0	0	1	1

Table 13.6. Criteria for mix scenarios for shipowner agent. The vessels_count indicates the ranges for which a particular strategy can be applied to the shipowner. The criteria is based on the initial fleet of each shipowner.

13.5 Scenario Descriptions

The scenarios are developed based on combinations of trade scenarios, price scenarios and impact scenarios. In a full probabilistic analysis, a monte carlo simulation would be run to capture the uncertainty in each scenario combination. However, due to computational limitations, the variation was limited to running each scenario with two different random seeds. The final scenarios run are shown in **Table 13.10**.

Scenario	Trade	Climate Impacts	Price	Seed
scenario_mix_mix_SSP1_seed_10_NWP_False_CP_CN	SSP1	False	CN	10
scenario_mix_mix_SSP1_seed_10_NWP_False_CP_GC	SSP1	False	GC	10
scenario_mix_mix_SSP1_seed_10_NWP_False_CP_SQ	SSP1	False	SQ	10
scenario_mix_mix_SSP1_seed_10_NWP_True_CP_CN	SSP1	True	CN	10
scenario_mix_mix_SSP1_seed_10_NWP_True_CP_GC	SSP1	True	GC	10
scenario_mix_mix_SSP1_seed_10_NWP_True_CP_SQ	SSP1	True	SQ	10
scenario_mix_mix_SSP1_seed_20_NWP_False_CP_CN	SSP1	False	CN	20
scenario_mix_mix_SSP1_seed_20_NWP_False_CP_GC	SSP1	False	GC	20
scenario_mix_mix_SSP1_seed_20_NWP_False_CP_SQ	SSP1	False	SQ	20
scenario_mix_mix_SSP1_seed_20_NWP_True_CP_CN	SSP1	True	CN	20
scenario_mix_mix_SSP1_seed_20_NWP_True_CP_GC	SSP1	True	GC	20
scenario_mix_mix_SSP1_seed_20_NWP_True_CP_SQ	SSP1	True	SQ	20
scenario_mix_mix_SSP5_seed_10_NWP_False_CP_CN	SSP5	False	CN	10
scenario_mix_mix_SSP5_seed_10_NWP_False_CP_GC	SSP5	False	GC	10
scenario_mix_mix_SSP5_seed_10_NWP_False_CP_SQ	SSP5	False	SQ	10
scenario_mix_mix_SSP5_seed_10_NWP_True_CP_CN	SSP5	True	CN	10
scenario_mix_mix_SSP5_seed_10_NWP_True_CP_GC	SSP5	True	GC	10
scenario_mix_mix_SSP5_seed_10_NWP_True_CP_SQ	SSP5	True	SQ	10
scenario_mix_mix_SSP5_seed_20_NWP_False_CP_CN	SSP5	False	CN	20
scenario_mix_mix_SSP5_seed_20_NWP_False_CP_GC	SSP5	False	GC	20
scenario_mix_mix_SSP5_seed_20_NWP_False_CP_SQ	SSP5	False	SQ	20
scenario_mix_mix_SSP5_seed_20_NWP_True_CP_CN	SSP5	True	CN	20
scenario_mix_mix_SSP5_seed_20_NWP_True_CP_GC	SSP5	True	GC	20
scenario_mix_mix_SSP5_seed_20_NWP_True_CP_SQ	SSP5	True	SQ	20

Figure 13.10. List of scenarios that are run in GooFy

13.6 Summary

Following the discussion of the shipping industry in **Chapter 9**, this chapter outlined the projection of that industry through to 2050 in terms of inputs required for *GooFy*. Specifically, scenarios are developed around the Integrated Assessment Models (IAMS) developed for the IPCC (Kriegler et al. 2014) for trade growth rates, the pricing scenarios developed through the joint UCL and Lloyds Register pricing scenarios (Argyros & Smith 2015) and climate change impacts manifested as the opening of Arctic routes. These are combined to form the 24 scenarios outlined in **Table 13.10**.

Chapter 14

Results and Discussion

14.1 Introduction

This chapter provides some overall results from the projection in each scenario before dealing with the hypotheses outlined in **Chapter 3**. In the initial analysis on overall results, there is less focus on individual scenarios, preferring instead to display all scenarios in figures, but not naming them for the purpose of displaying the range of results.

14.2 Overall Results

Total cargo transported annually is provided in **Figure 14.1**. As discussed previously, the actual transported cargo does not necessarily match that produced due to a number of reasons, most significantly constrained supply and transport cost. As was the case for the validation scenarios, there are significant spikes in cargo transported, seeming to exceed the actual produced within *GooFy*. This divergence is allowed and assumed to be supported by stocks. Although the produced commodity for each scenario is within a 10% range, the range in actual cargo transported is approximately 30% within a year.

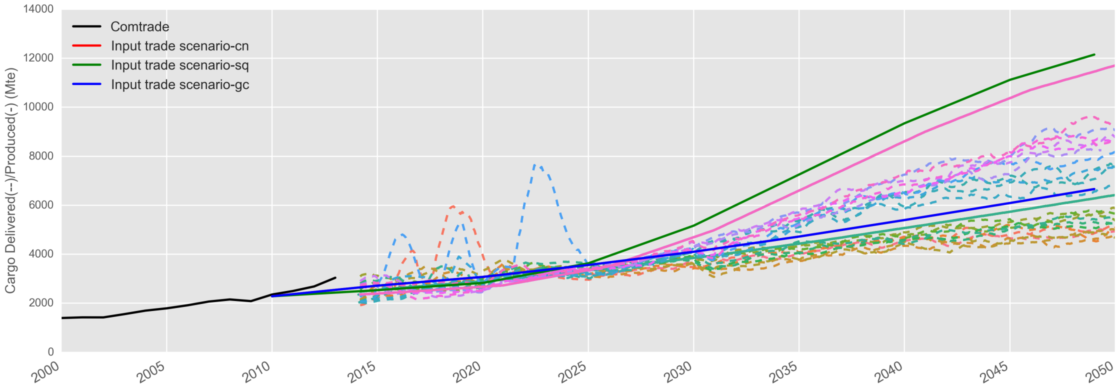

Figure 14.1. Annual cargo delivered in each scenario. The broken lines indicate the annual cargo delivered in each scenario, with the colour matched unbroken line representing the volume produced for that same scenario. The black line is the trade demand as reported by UN Comtrade (COMTRADE 2018) to show the curent trade trajectory. The projections are run from 2010, hence the trade in that year is 0 as shown.

The emissions trajectory is shown for all size categories in **Figure 14.4** with the corresponding size ranges shown in **Table 14.1**.

Table 14.1. Vessel size ranges

Min. Deadweight (t)	Max. Deadweight (t)	id	Name
200000	450000	0	Capesize
100000	200000	1	Suezmax
60000	100000	2	Panamax
35000	60000	3	Supramax
10000	35000	4	Handy
1000	10000	5	Feeder

The number of vessels in the fleet increases significantly from a baseline total of approximately 3000. This is largely driven by the largest size category (size 0) which in some scenarios increases to over 6000. Following the initial rapid increase, there is a significant reduction in the fleet, in some cases halving it by 2022. At this point, the total fleet supply remains stable before increasing again from 2030 onwards particularly in the SSP5 scenarios where demand for transport of coal increases. Vessels below 100,000dwt reduce in number from 2040 as more trade is diverted to the larger sizes.

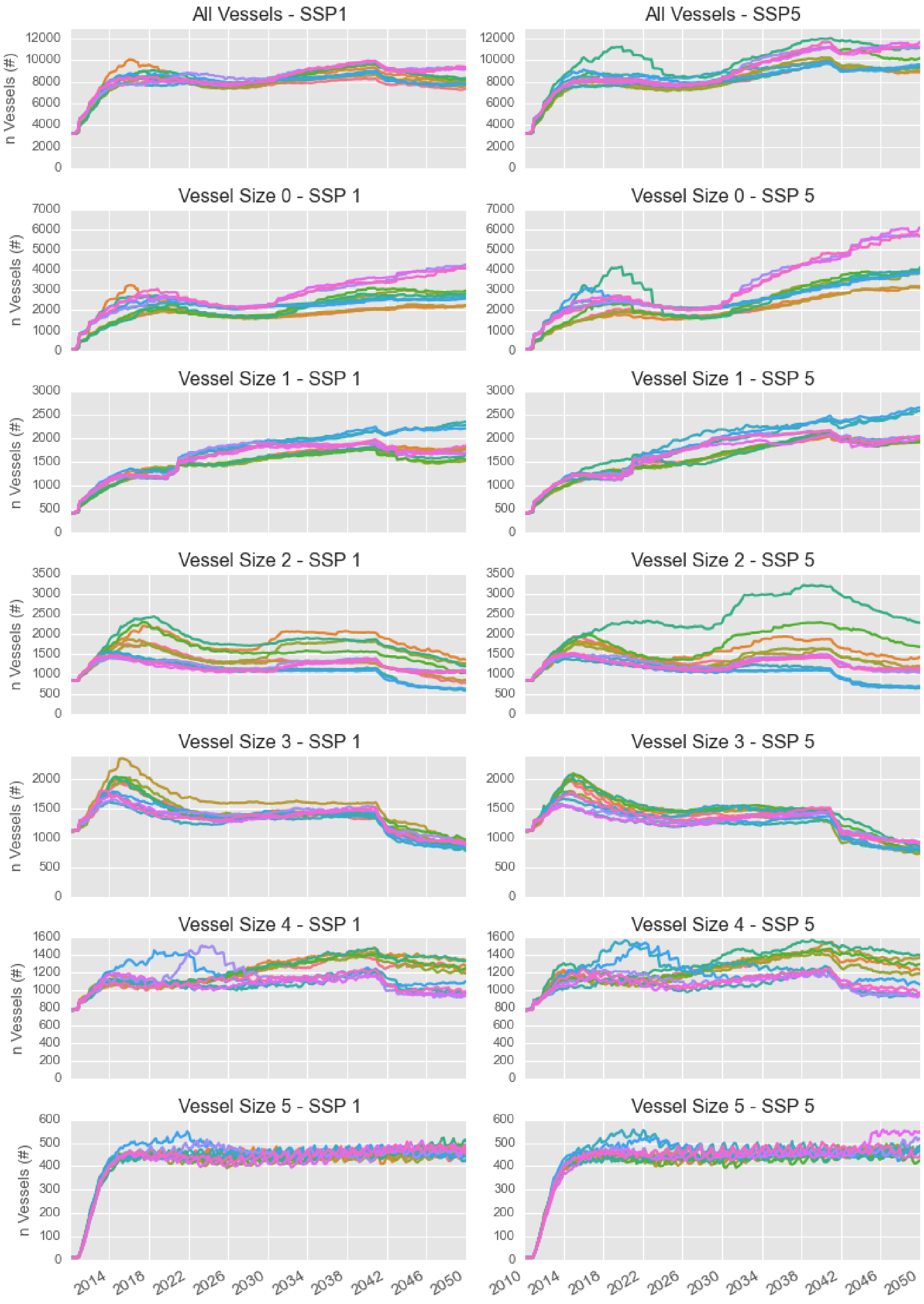

Figure 14.2. Time series of number of vessels in each size category with each scenario represented by a different colour

The rapid initial increase in vessels on the market is driven by the demand for transport reflected in the spot rate shown in **Figure 14.3**. For size 0 and 1 the price, following the initial rapid increase and decrease, is steadily increasing in most scenarios. However, for other sizes and with increasing magnitude as the sizes decrease, there are significant rapid short term price changes. There exists a price inflation in all size categories, although the spot price appears to be mean reverting in the short term, as is the case in the real DBSS (discussed in **Chapter 9 Section 9.2**).

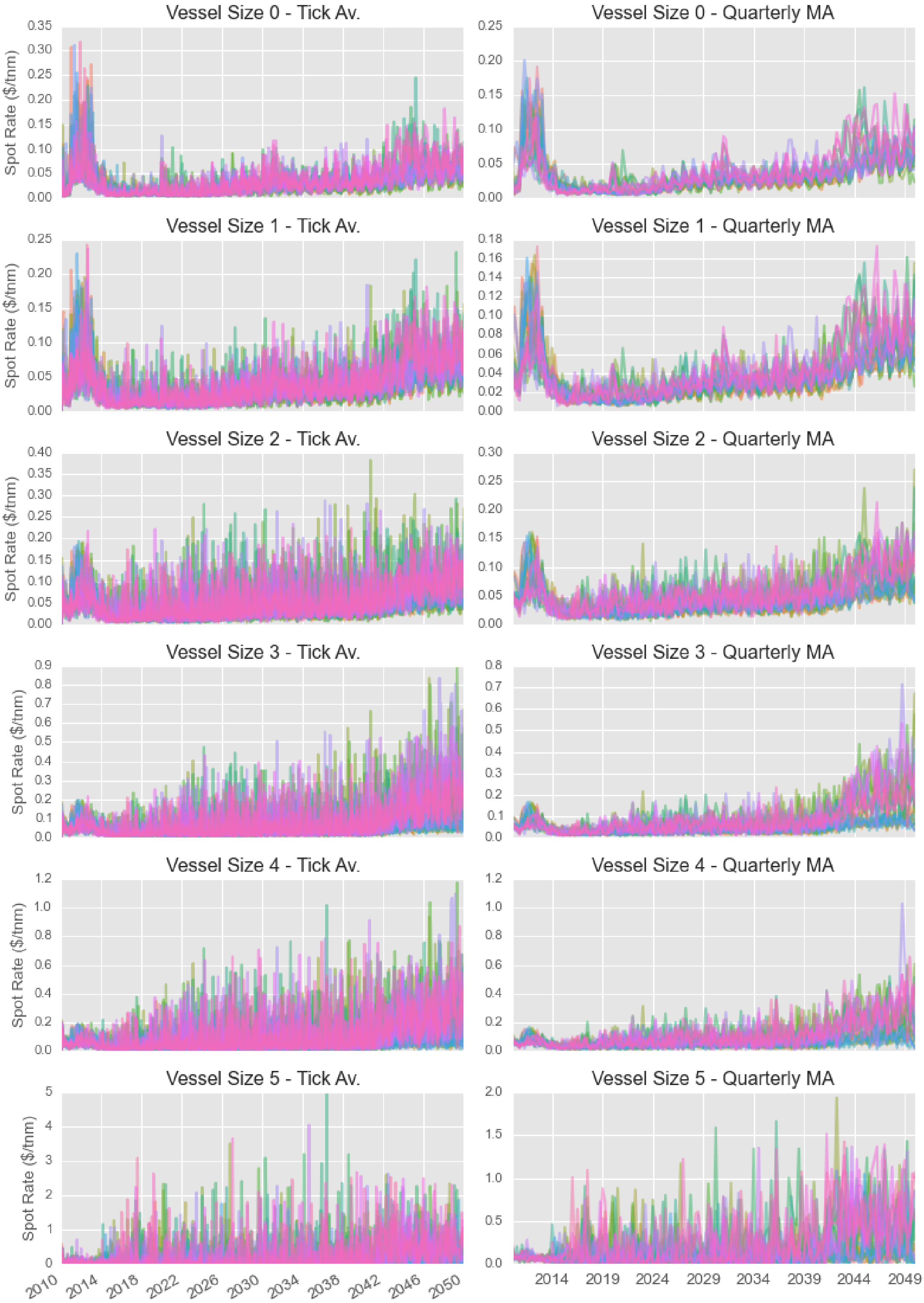

Figure 14.3. Time series of spot market price in each size category as a tick average (left column) and as a quarterly average (right column) with each scenario represented by a different colour

For all size categories, there is an initial significant increase in emissions but by 2020 emissions either level off or begin to reduce. From about 2030 onwards, the emissions increase for larger vessel sizes but reduce for vessels below 100,000dwt. In general, the emissions for each size category are strongly correlated with the number of vessels in that size category, so there remains a strong coupling of emissions and transport supply. For example, vessel size 3 in the SSP1 scenarios shows a sudden reduction in emissions in 2040. There is a concommitant change in vessel numbers as shown in **Figure 14.2**. The variance in emissions for SSP5 is significantly greater than for SSP1 across all size categories.

This variance in emissions is reflected in the fuel consumption for each of the scenarios, shown in **Figure 14.12**. Fuel demand for LNG and MDO increases throughout all scenarios but the main fuel for the vessel remains HFO. There is very limited shift to hydrogen fuel cells or methanol.

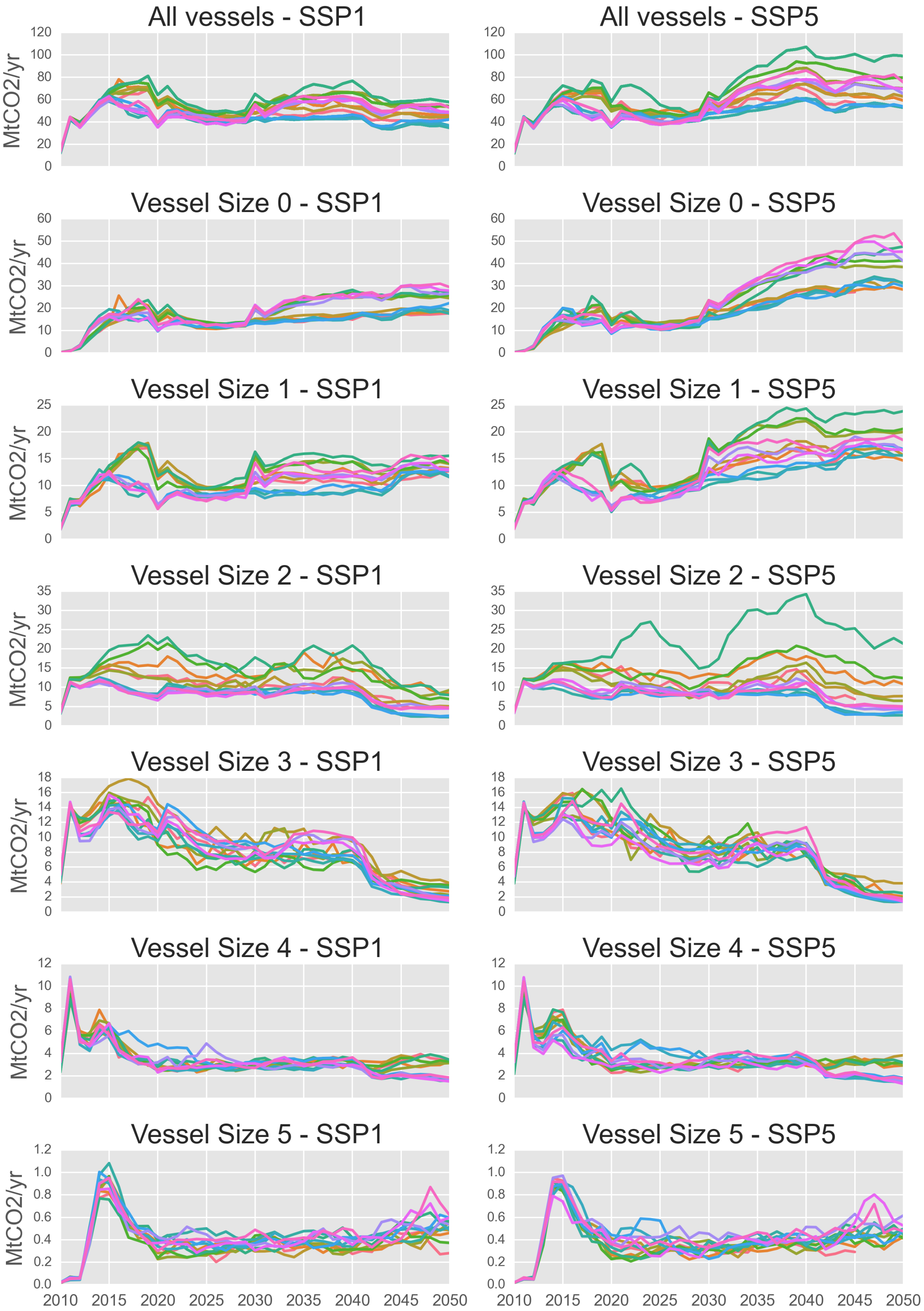

Figure 14.4. Annual emissions of CO_2 for all vessels in the top row and for all size categories in decreasing size range.

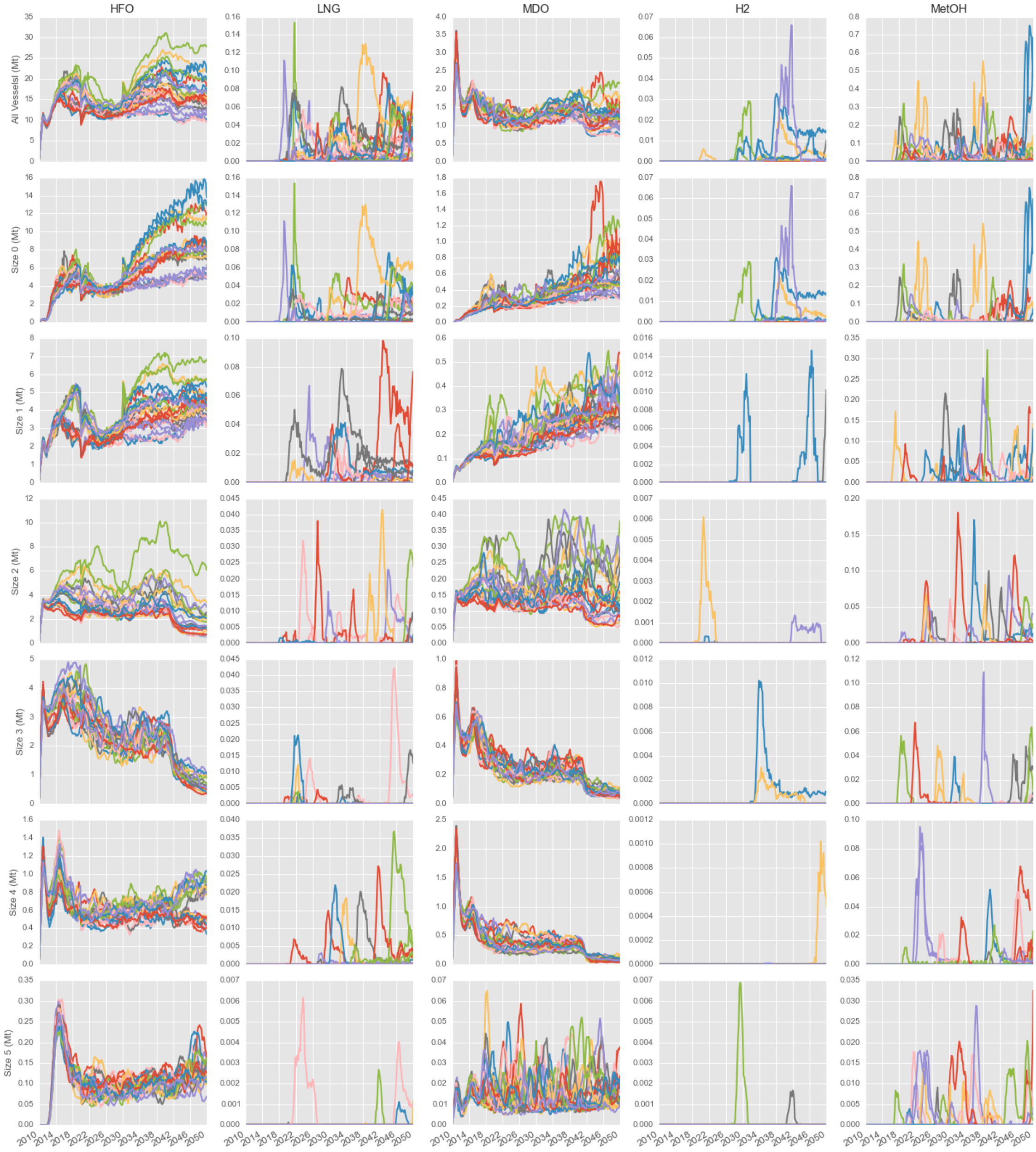

Figure 14.5. Fuel consumption in each scenario.

Vessels scrapped and built are shown in **Figure 14.6**. For both scrappage and newbuild the rate is stable, in general, between 2020 and 2040. The sudden increase in both newbuild and scrappage at 2040 occurs in almost all scenarios, although the magnitude varies.

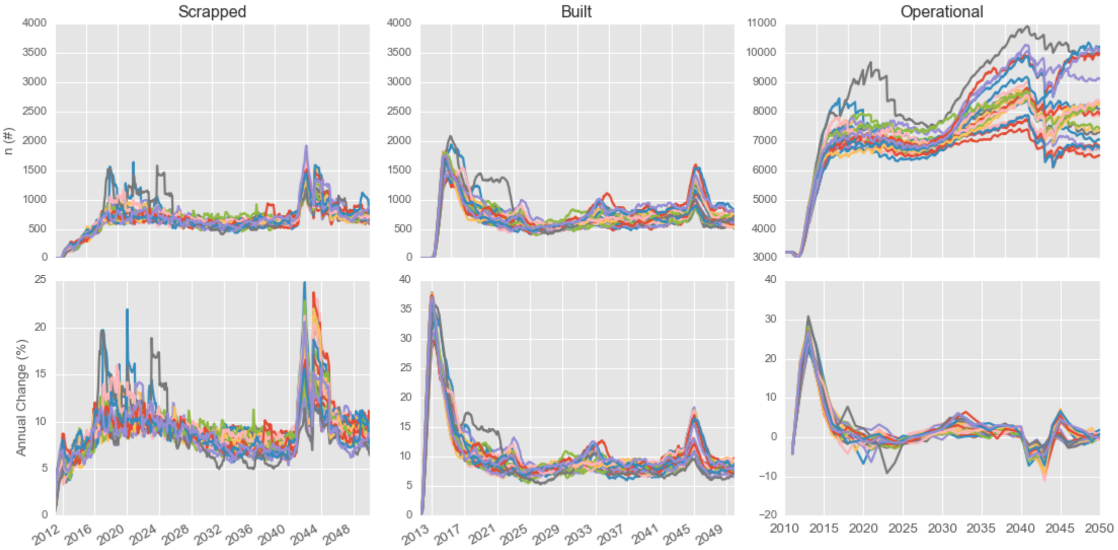

Figure 14.6. Time series of number of vessels scrapped (top left), built (top center) and total live vessels (top right) and as a proportion of the total fleet for scrapped (bottom left) and built (bottom center). The bottom right plot shows the percentage fleet change on the previous year.

There is a trending improvement in technical efficiency in all scenarios, punctuated by a rapid improvement with the deployment of a newbuild fleet at around 2015 and additionally at around 2040 for most sizes. The technologies installed varies between scenarios as shown by the large number of ”other” technologies installed for both 2050 and 2020 technology uptake shown in **Figures 14.8, 14.9, 14.10** and **14.11**. But for the most part the technologies installed are those that provide marginal improvements such as propellor polishing and hull cleaning. As was shown in **Figure 14.12**, there is not a significant shift to new fuels, so the improvements in technical efficiency are not radical enough to create rapid decarbonisation.

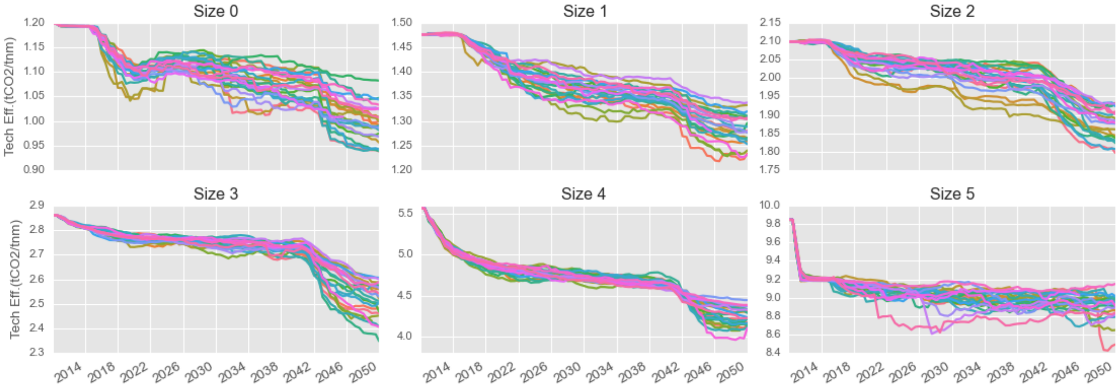

Figure 14.7. Technical Efficiency across all runs (identified by colour). Each vessel size category is on a different plot in descreasing size from top left to bottom right

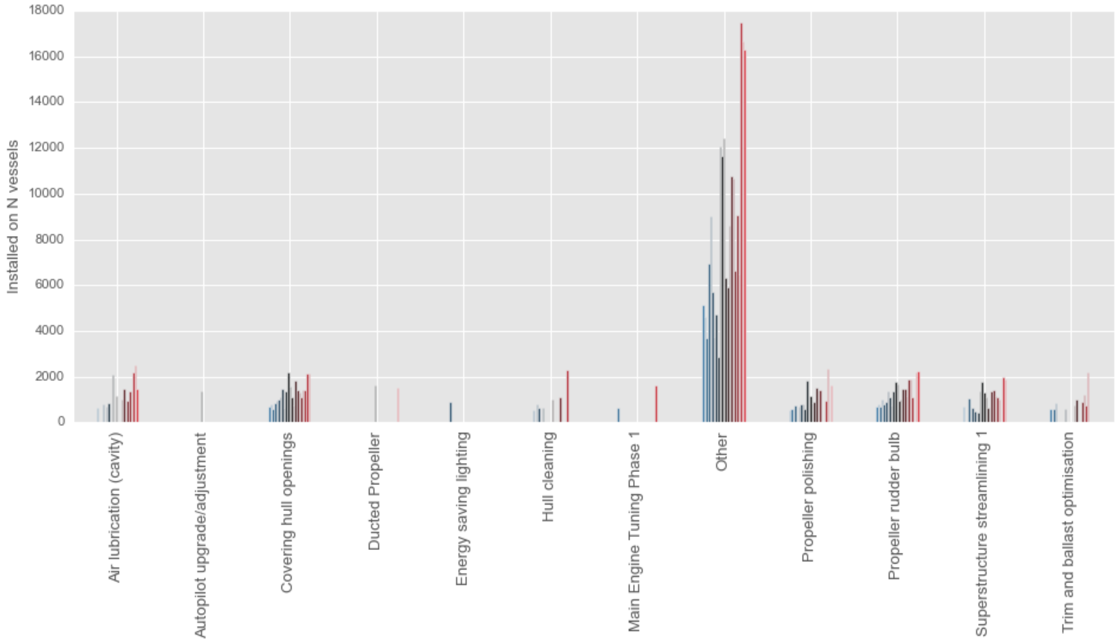

Figure 14.8. Top 5 technologies installed in size 0 for each run in 2050. Additionally, there is an "other" which captures the remaining technologies installed.

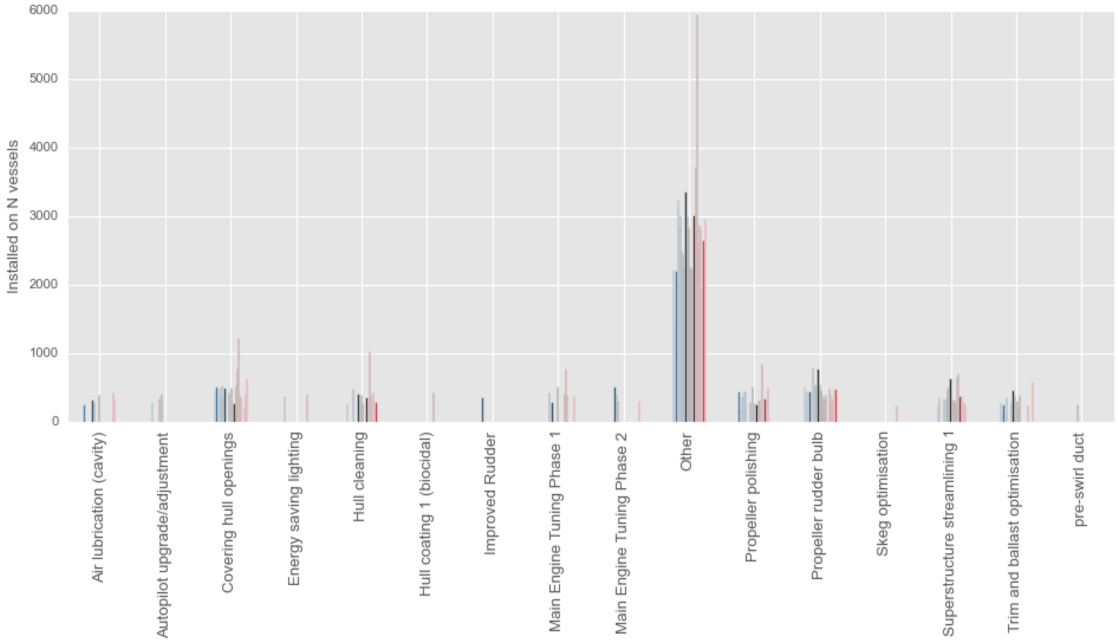

Figure 14.9. Top 5 technologies installed in size 0 for each run in 2020. Additionally, there is an "other" which captures the remaining technologies installed.

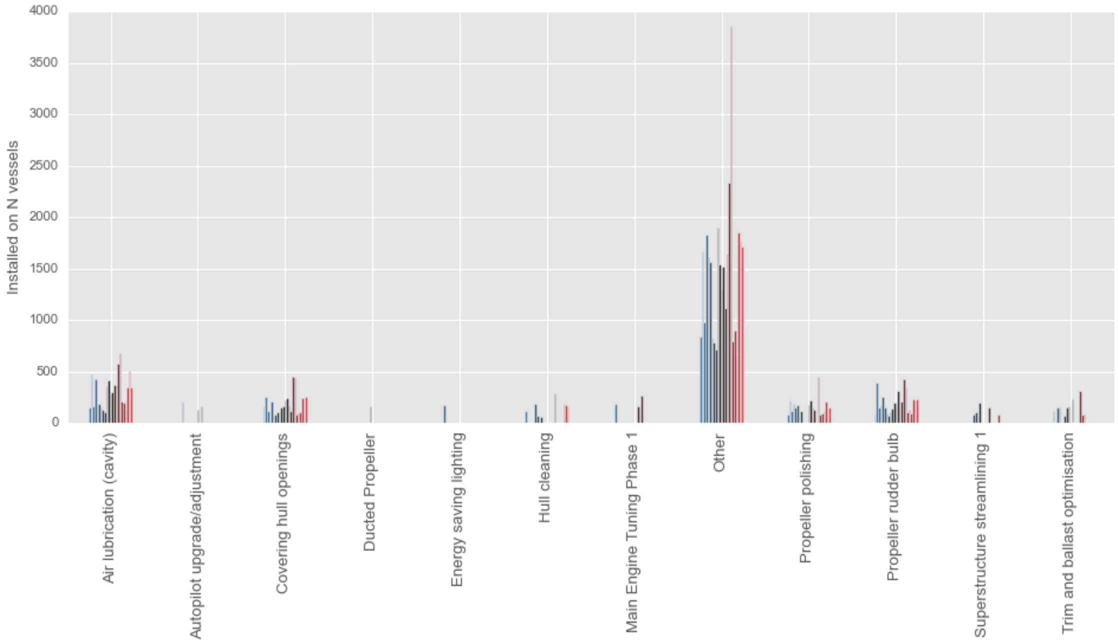

Figure 14.10. Top 5 technologies installed in size 2 for each run in 2050. Additionally, there is an "other" which captures the remaining technologies installed.

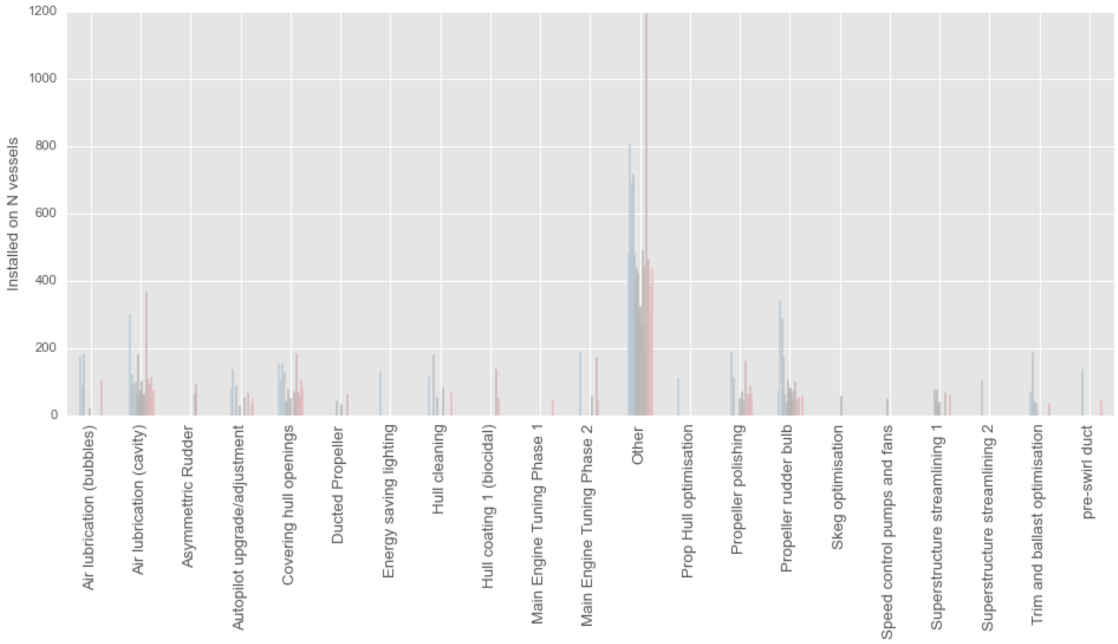

Figure 14.11. Top 5 technologies installed in size 2 for each run in 2020. Additionally, there is an "other" which captures the remaining technologies installed.

The vessel operational efficiency shows considerably more variation particularly for size ranges less than 100,000t. For size 0 and 1, the demand for transport is more constant while the smaller sizes have lower capacity utilisation (and more variability within this).

Figure 14.12. Operational efficiency index across all runs (identified by colour). Each vessel size category is on a different plot in decreasing size from top left to bottom right. Some plots are truncated for clarity and restricted to vessels that have carried more than 10,000t cargo within the year.

14.3 Research Questions Discussion

This section addresses directly the research questions outlined in **Chapter 3**. Typically, in this section, the scenarios are divided into two groups, SSP1 and SSP5, which are the two main trade scenarios. Depending on the research question being dealt with, the groups may then be further disaggregated. For example, in **Section 14.3**, each group is split into those scenarios that include climate change impacts and those that do not.

Research Question 1 *Will climate change impacts be similar across the route network, as the opening of new northern routes only affects certain commodities and trades?*

Table 14.2 shows the commodities used in the scenarios and their associated codes, with the time series of the evolution of transport work in each of the SSP1 (**Figure 14.13**) and SSP5 (**Figure 14.14**) scenarios. In this case the transport work is the distance the commodity was transported factored by the cargo volume. Therefore, although a commodity itself may not be directly transported using Arctic routes, the vessel that is transporting the cargo may be different and hence use a shorter or longer route depending on capacity constraints. In other words, the opening of the Arctic routes may shift some vessels to serve a commodity on this route that would have otherwise been deployed elsewhere. Additionally, it could also be a factor of the amount of cargo transported.

Table 14.2. Global commodities used in the projection scenarios

HS Code	Descriptions
1001	Wheat and meslin
1005	Maize (corn)
1201	Soya beans
2510	Natural calcium phosphates
2601	Iron ores and concentrates
2603	Copper ores and concentrates
2604	Nickel ores and concentrates
2606	Aluminium ores and concentrates
2701	Coal, briquettes, ovoids etc, made from coal
2704	Coke and semi-coke of coal, of lignite or of peat
4403	Wood in the rough or roughly squared
4407	Wood sawn or chipped lengthwise, sliced or peeled
7207	Semi-finished products of iron or non-alloy steel
7208	Flat-rolled products of iron or non-alloy steel
7209	Flat-rolled products of iron or non-alloy steel
7210	Flat-rolled products of iron or non-alloy steel
7217	Wire of iron or non-alloy steel
7219	Rolled stainless steel sheet, width > 600mm

Figure 14.13. Transport work in scenarios for SSP1 showing all the scenarios with climate change impacts in green and those without climate change impacts in red.

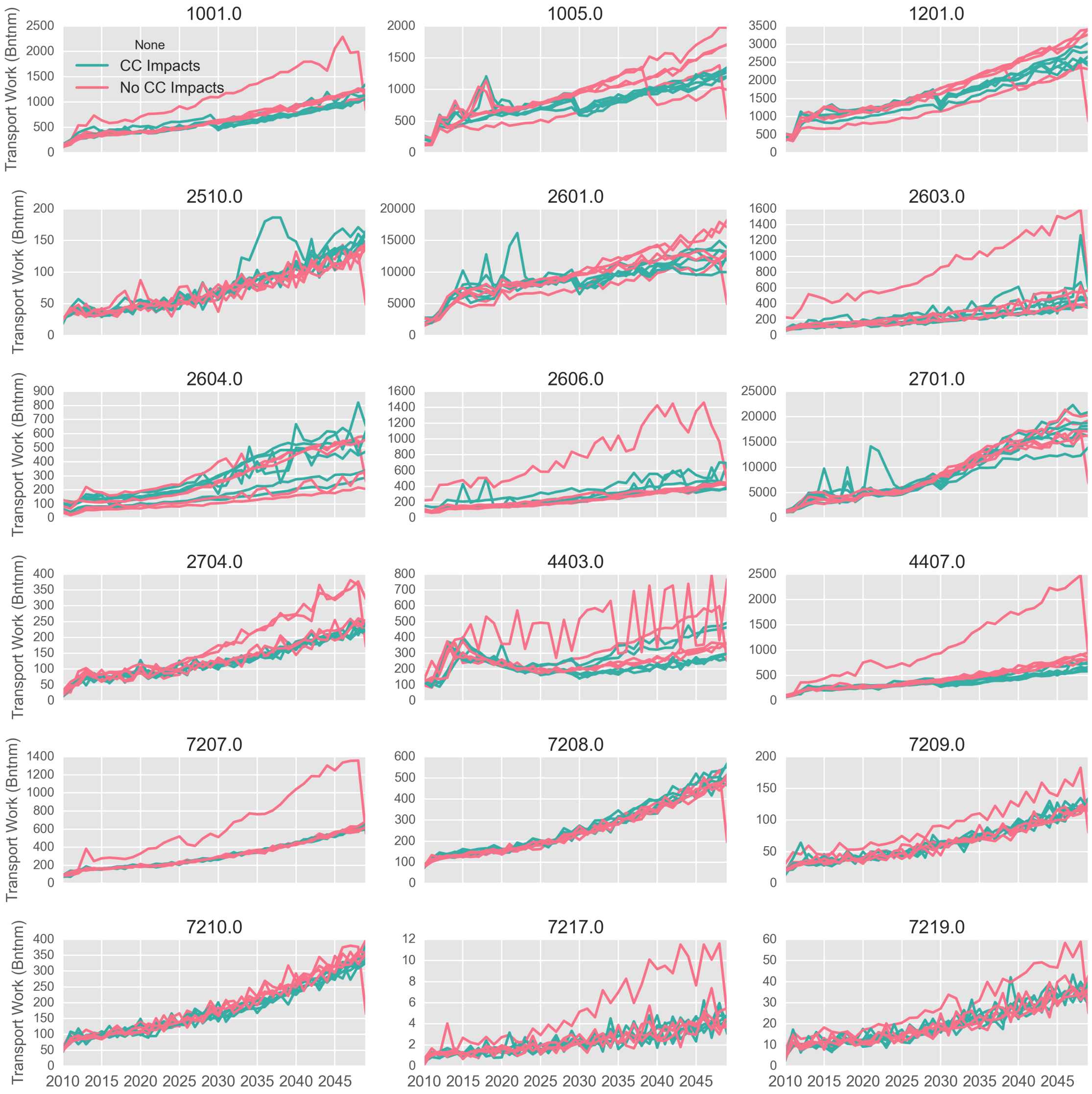

Figure 14.14. Transport work in scenarios for SSP5 showing all the scenarios with climate change impacts in green and those without climate change impacts in red.

Focussing on the final year of each scenario (as we would expect the differences to be greatest at this point), and plotting as frequency plots, a significant difference between transport work becomes evident for commodities 1005, 1201, 2601 and 4403 in the SSP1 scenario (**Figure 14.15**). There are similar differences in the mean for SSP5 but there is overlapping in the different scenarios so the differences are not as prominent (**Figure 14.16**). Significant difference is defined here as those histograms where there is no or very little overlap. For the remaining commodities, the differences between the climate impact versus non-climate impact scenarios show either no difference or are strongly overlapping, suggesting that either the opening of new routes has no effect or is not significant.

Figure 14.15. Final year transport work in each commodity for SSP1 scenarios where green bars show scenarios with climate change impacts and red bars are for scenarios without climate change impacts. The x-axis shows the number of scenarios within that bin, and the y-axis indicates the transport work (10^{12}tnm)

Figure 14.16. Final year transport work in each commodity for SSP5 scenarios where green bars show scenarios with climate change impacts and red bars are for scenarios without climate change impacts. The x-axis shows the number of scenarios within that bin, and the y-axis indicates the transport work (10^{12}tnm)

In summary, the opening of new routes appears to show a significant effect on transport work for some commodities, albeit less significant in some scenarios. Therefore, the effect of opening up of new routes is likely to cascade through the full DBSS, and potentially effect some commodities more than others (and not identically). However, those commodities that are materially effected are not necessarily those commodities that will use these new routes, or indeed be limited to those commodities, and therefore isolating those ”certain commodities and trades” is not trivial.

Research Question 2 *Will relative changes in demand for dry bulk commodities, potentially as a result of climate mitigation policy in other sectors, lead to significant changes in the world shipping system such as arrangement of the world fleet structure?*

The changes in demand are reflected in the SSP1 and SSP5 scenarios. But for comparison, the plots are also disagregated by the pricing scenarios CN, GC and SQ. The variation in number of vessels for each size category varies more significantly within each demand scenario that between the demand scenarios except for the first size category (see **Figure 14.17**). The vessel count range is between 2000 and 4000 for SSP1 and between 3000 and 6000 for SSP5. As discussed in **Chapter 9 Section 9.3**, the main difference between these scenarios is the demand for coal in SSP5 which, it is clear from these plots, is largely transported by vessel size 0.

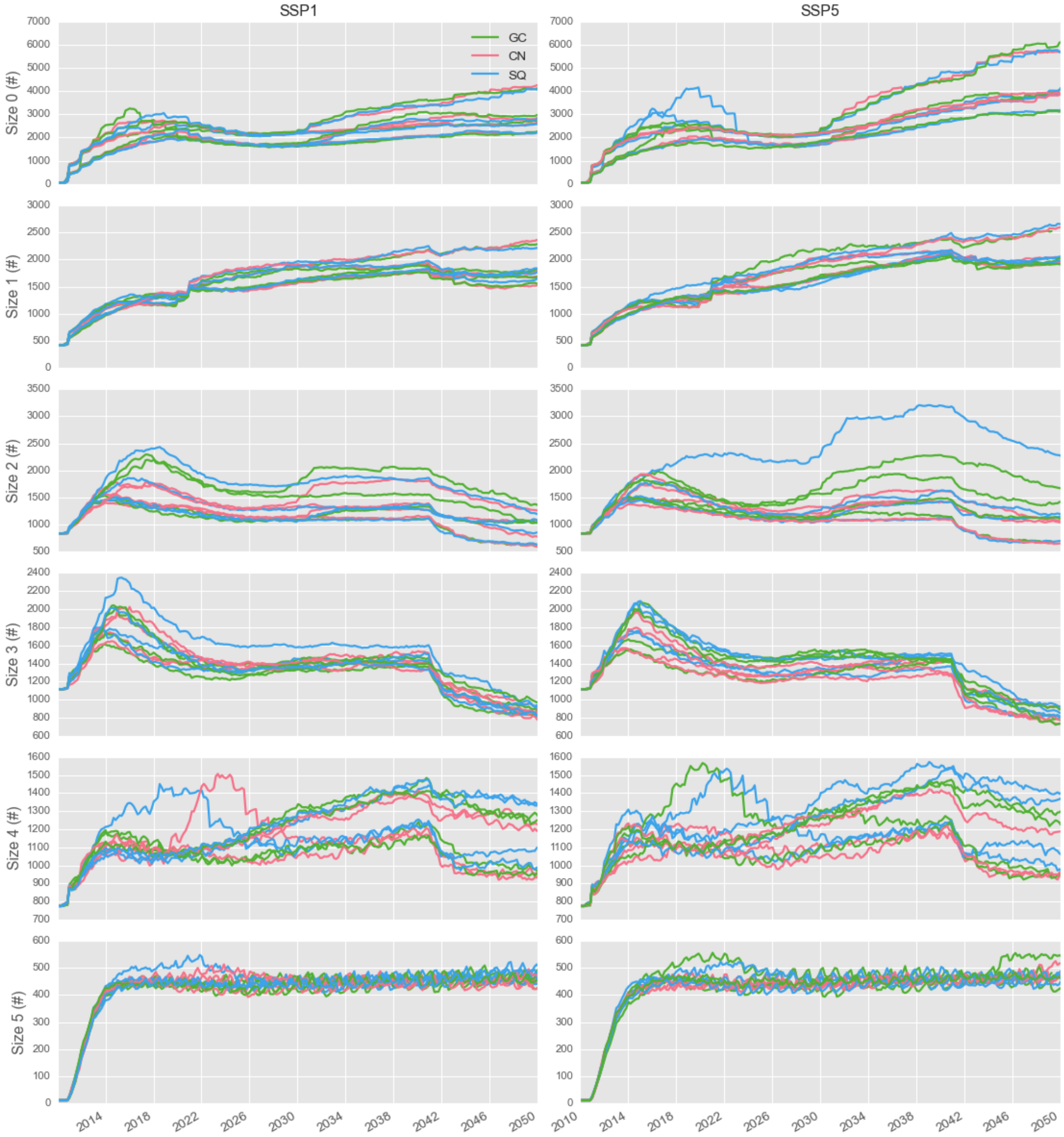

Figure 14.17. The plot shows the number of vessels in each size category for each of the policy scenarios and trade scenarios. Each policy scenario has multiple manifestations represented by two randoms runs and runs with and without climate change impacts.

The next metric of comparison is the port degree shown in **Figure 14.18**. In this case, the time evolution is very similar throughout the full period.

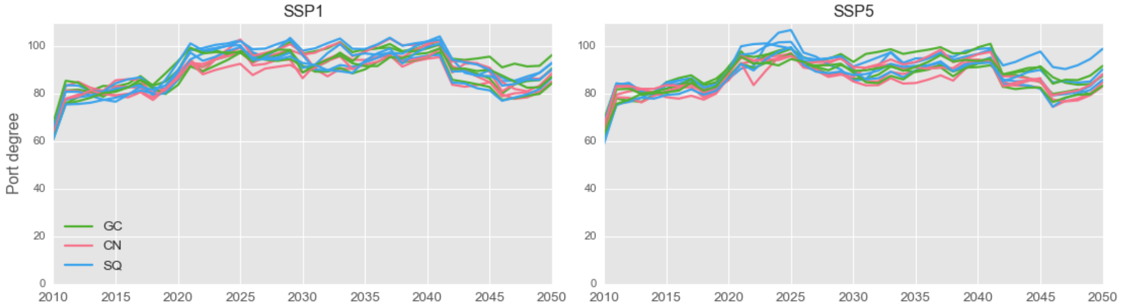

Figure 14.18. Port degree.

Finally, the average speed by vessel size is compared in each scenario group in **Figure 14.19**. Comparing left and right columns, it is clear that the trajectories are broadly similar between the two trade groups, with variation due to other factors greater than that between SSP1 and SSP5.

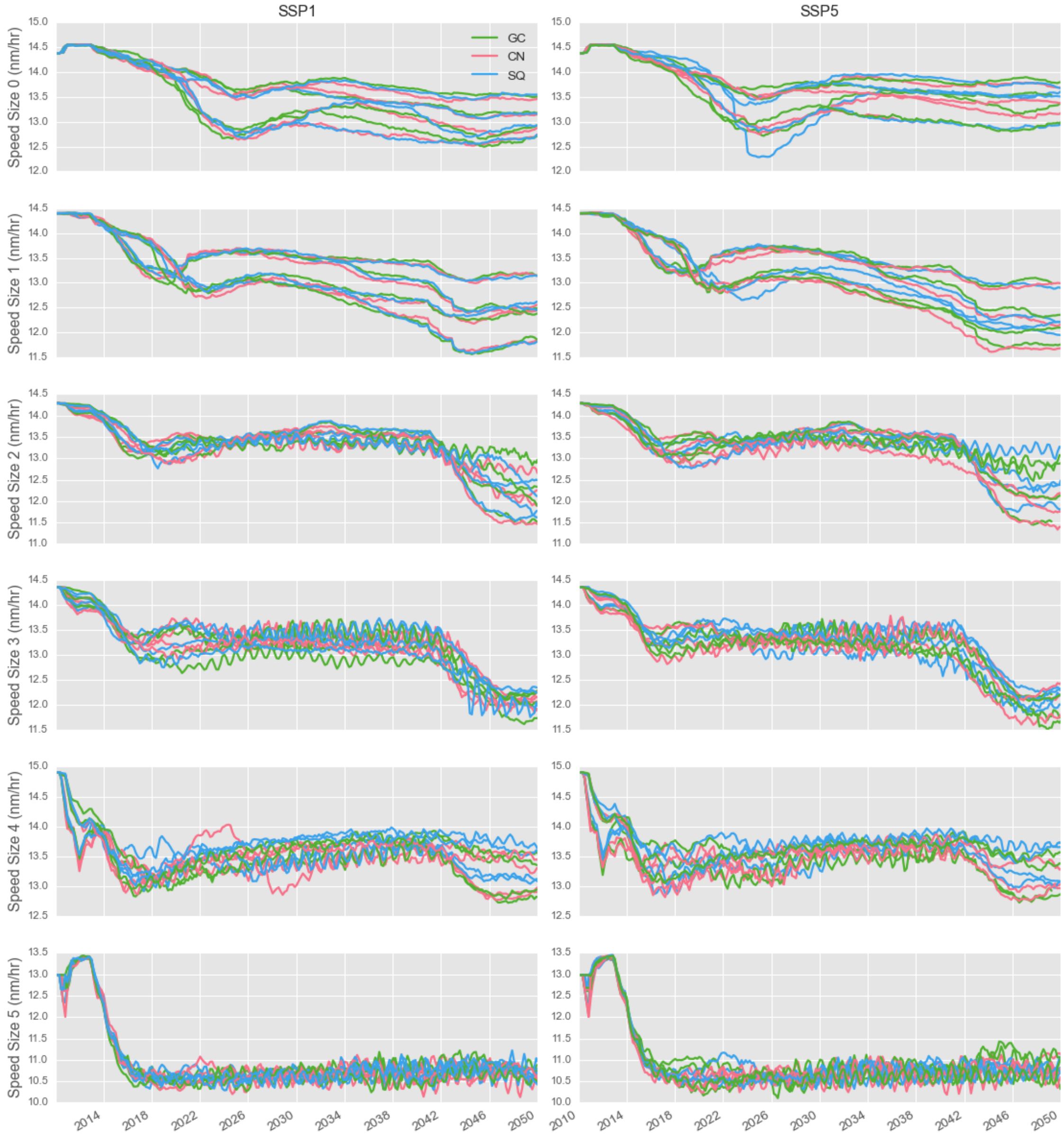

Figure 14.19. The plot shows the mean operational speed of vessels in each size category for each of the policy scenarios and trade scenarios.

This analysis has shown that the impacts of trade changes, as set out in the SSP scenarios, results in changes in the number of vessels required to service the difference in transport demand. However, these vessel changes are limited to the those vessels that serve this additional demand. There does not appear to be wider operational changes, such as changes in operational speed. Therefore, within the limitations of the demand scenarios used, it is suggested that impacts are restricted to those vessels that are required to service the trade with no discernible cascading effects.

Research Question 3 *Will the impact of climate change mitigation regulations cause a change in the provision of transport thus reducing the uptake of carbon emission reducing technologies?*

The climate change mitigation scenarios are represented by the CN, GC and SQ pricing scenarios, shown below in **Figure 14.20**, where GC is the high carbon price scenario.

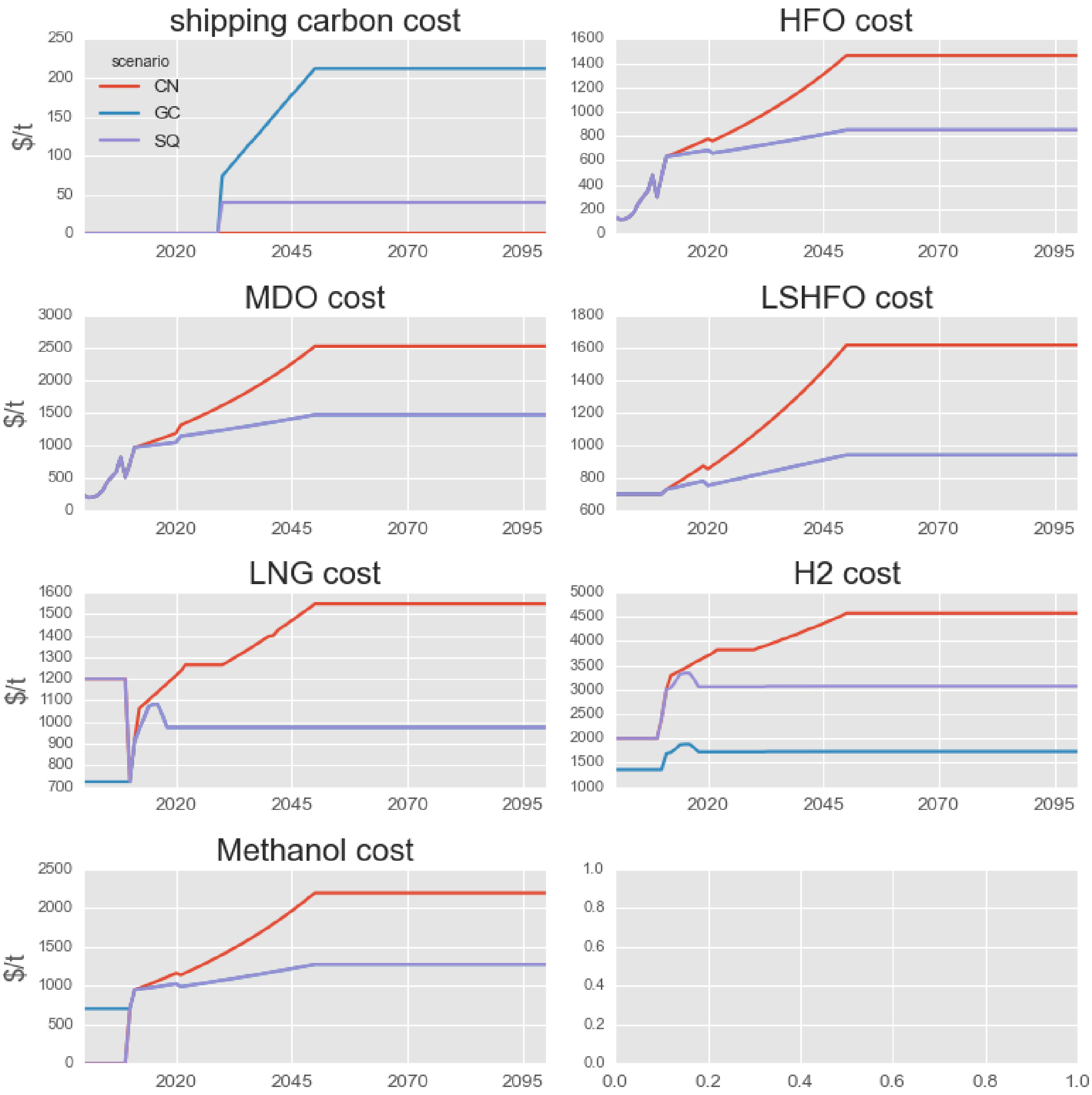

Figure 14.20. Fuel and carbon price scenarios. GC and SQ overlap in most plots, thus hiding GC from view.

Figure 14.21 shows the mean number of technologies installed on each vessel in each size category. There is no clear distinction between the evolution of uptake of the number of technologies between each of GC, SQ and CN. The uptake of technology is driven by the combined effect of increasing fuel price (particularly HFO/MDO), carbon price and fleet turnover. GC has low fuel prices but the effect of the carbon price is that it effectively inflates the fossil fuel prices so the fuel price in effect approaches the CN scenario. This is similarly the case for SQ, albeit not to the same extent.

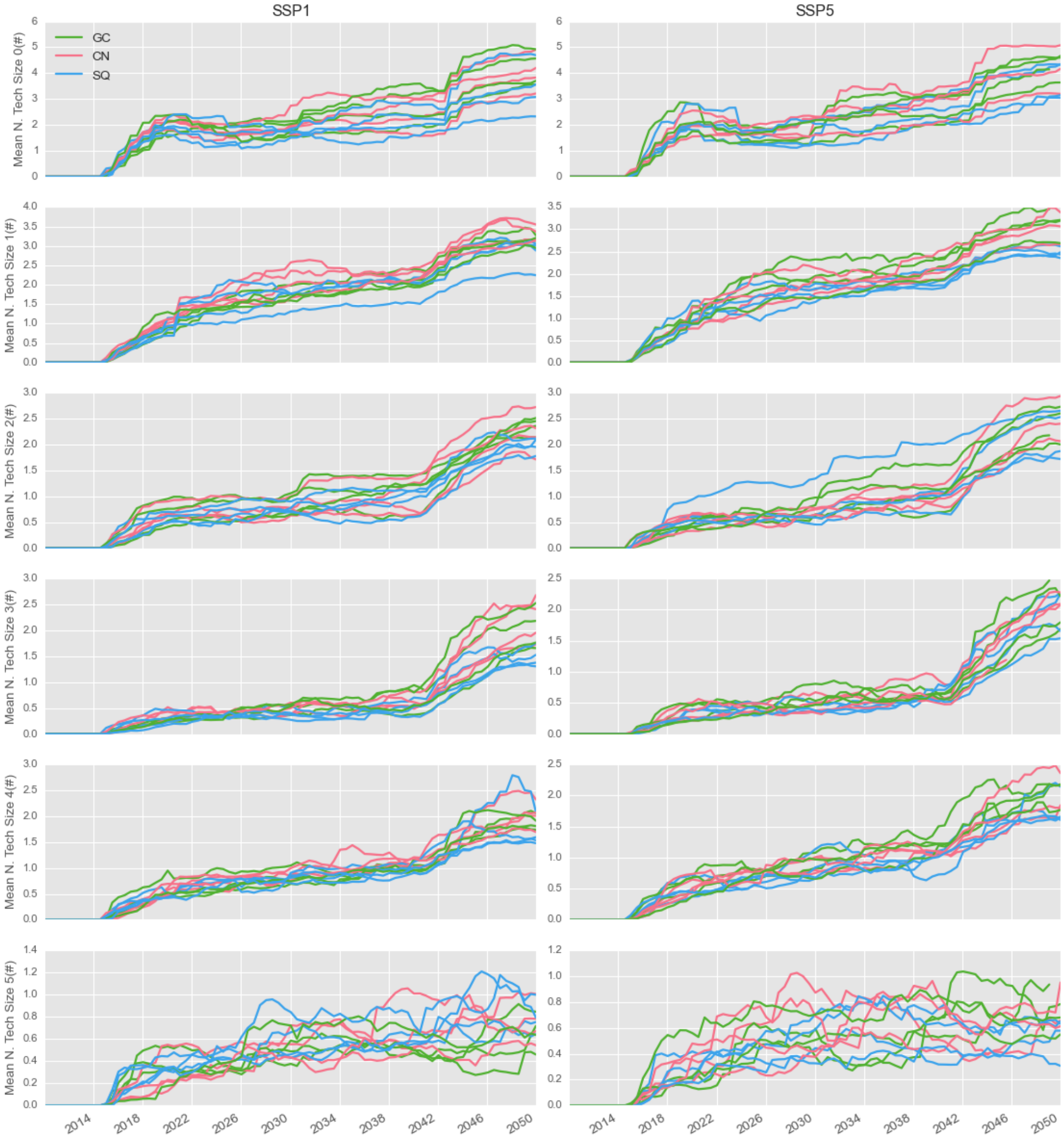

Figure 14.21. Mean number of technologies installed on each vessel in each size category for SSP1 (left column) and SSP5 (right column) scenarios. The different fuel price and regulation scenarios are indicated by colour where SQ scenarios are blue, GC scenarios are green and CN scenarios are red.

This is echoed in the vessel technical efficiency results, shown in **Figure 14.22**, where there is no clear distinction between the three price scenarios. The EEOI shows considerable variance between the scenarios with none of the scenarios resulting in greater operational efficiency than the other scenarios (see **Figure 14.23**).

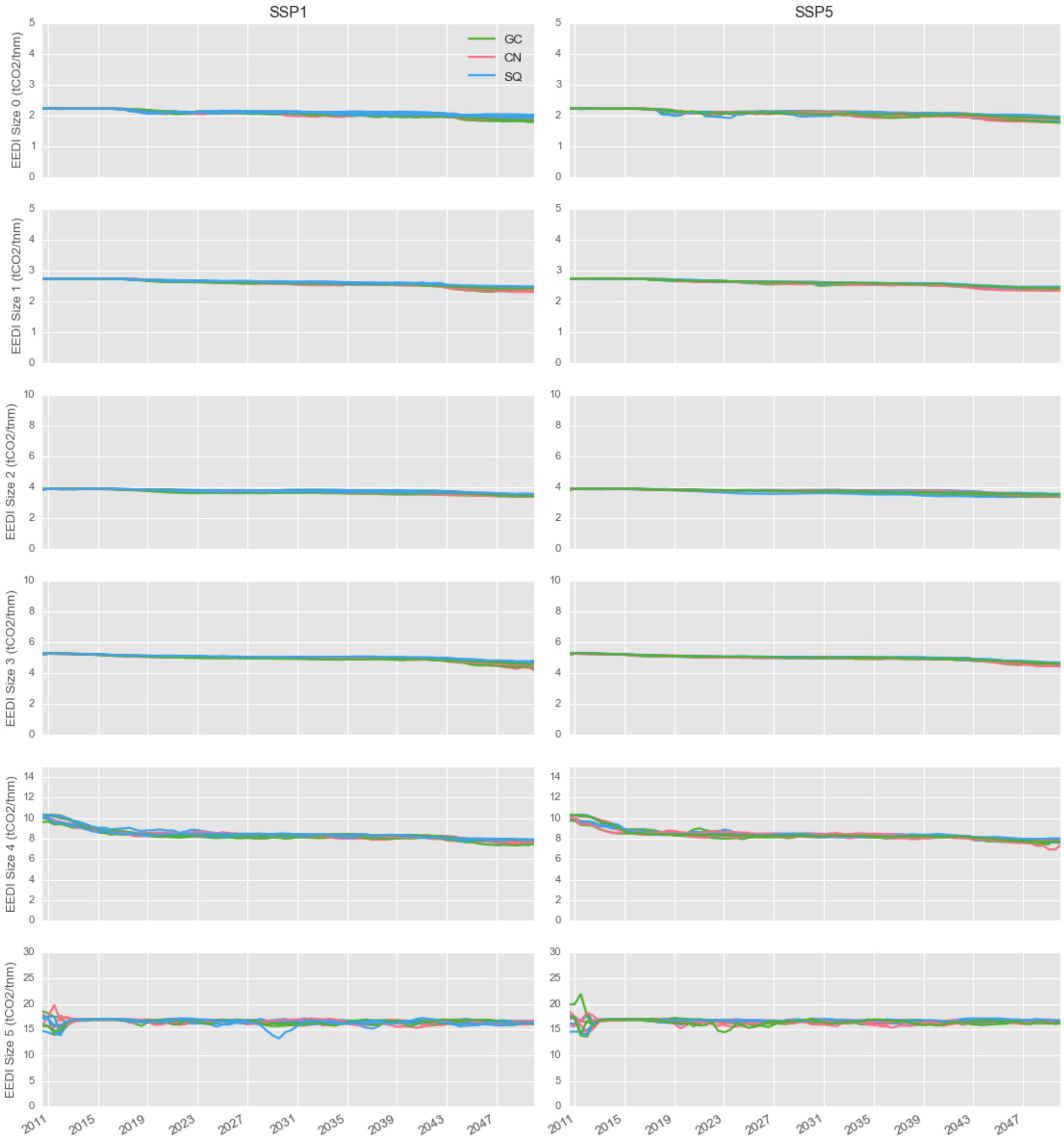

Figure 14.22. Mean technical efficiency for each vessel size category for SSP1 (left column) and SSP5 (right column) scenarios. The different fuel price and regulation scenarios are indicated by colour where SQ scenarios are blue, GC scenarios are green and CN scenarios are red.

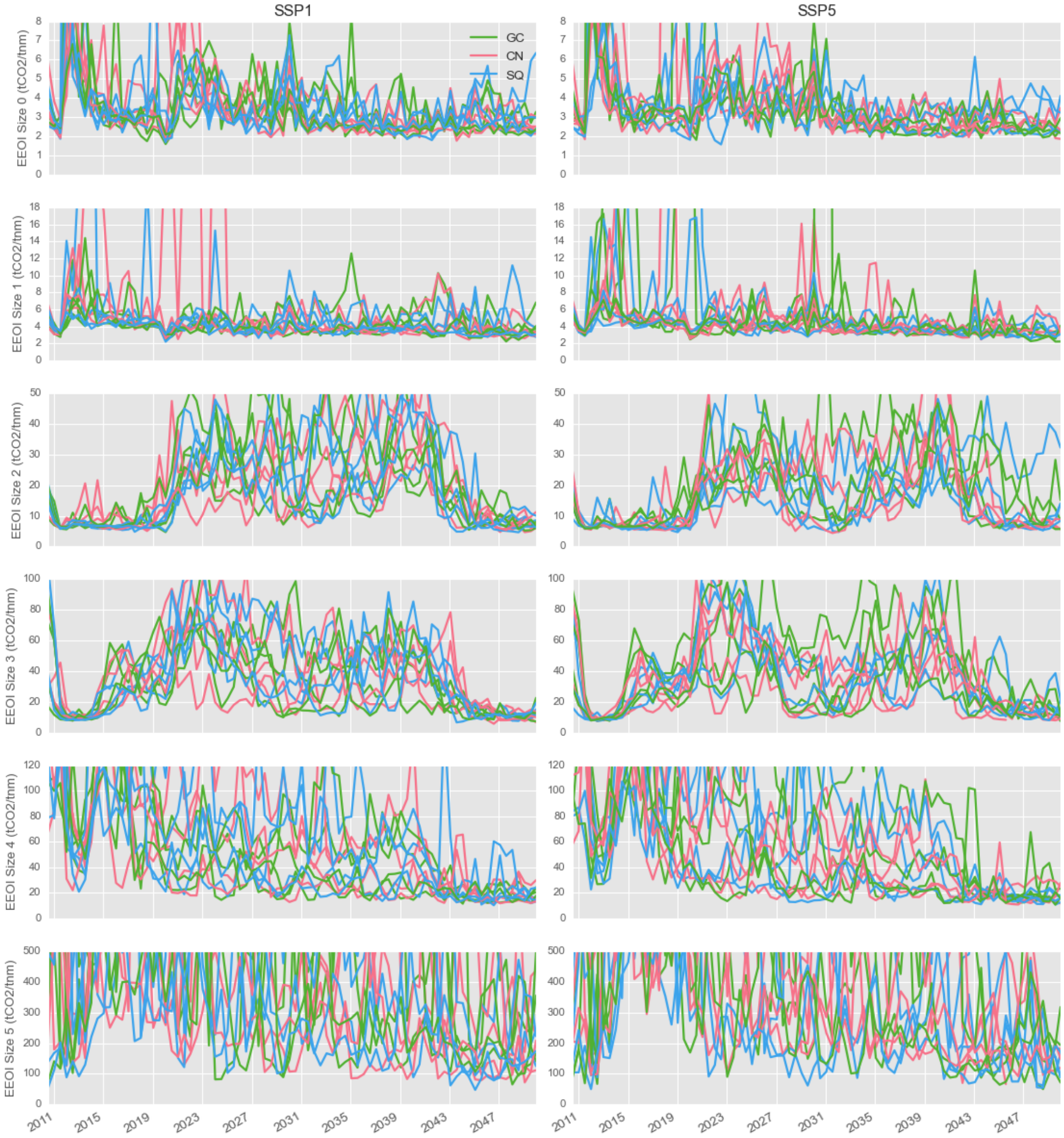

Figure 14.23. Mean operational efficiency for each vessel size category for SSP1 (left column) and SSP5 (right column) scenarios. The different fuel price and regulation scenarios are indicated by colour where SQ scenarios are blue, GC scenarios are green and CN scenarios are red.

Finally, the market structure is investigated, particularly looking at the types of contracts that are used to transport the cargo. Consistent with the above, the fuel/carbon price scenarios do not appear to significantly affect these contractual arrangements. The cargo volume transported on the spot market against industrial shipping follows two distinct paths. However, these paths are not driven by pricing scenarios which span both pathways. Instead, the system appears to show lock-in of a particular strategic planning option which is agnostic of the input scenario. This suggests that the main drivers of strategy options are predominantly an endogeneously generated emergent property and less forced by external factors to the DBSS, at least for the scenarios investigated here.

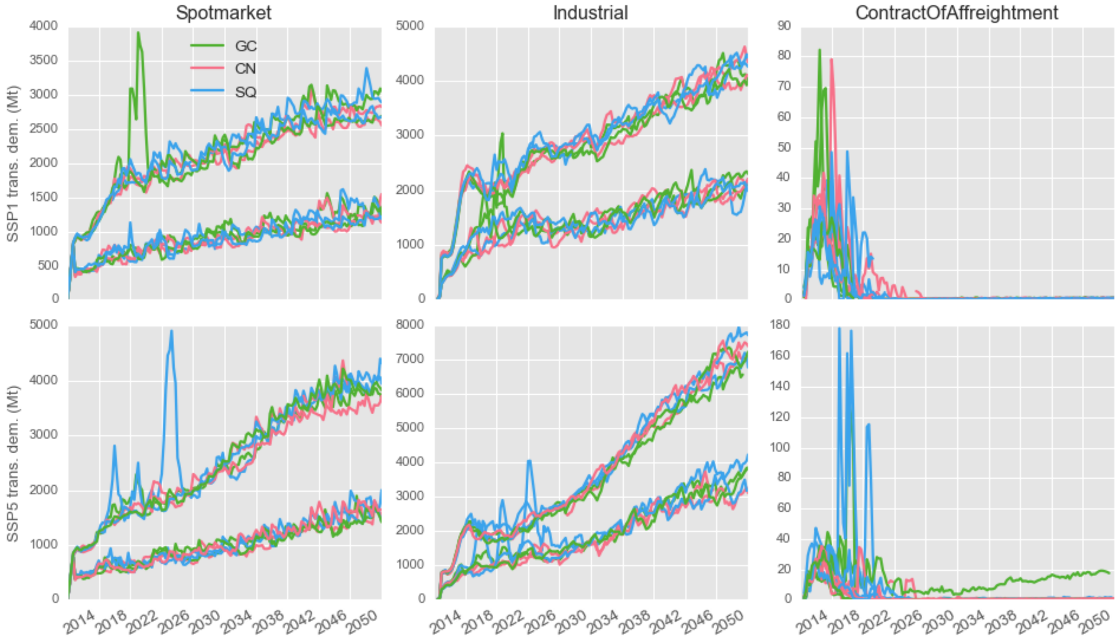

Figure 14.24. The amount of trade carried by each schedule type in each scenario

14.4 Hypotheses

Hypothesis 1 *The treatment of the dry bulk shipping sector as a system of heterogeneous agents allows modelling of complex behaviour not captured with existing approaches in the field.*

As compared with equation based approaches, the amount of cargo transported annually and the fleet change over time emerges from the interactions of the agents. An equilibrium based approach would see supply matched to demand annually and not see the significant system response such as undersupply and oversupply in the first 10 years of the model.

As an example, **Figure 14.25** shows a Lomb-Scargle periodogram. The Lomb-Scargle algorithm estimates the frequency spectrum to identify cycles in data. An approximate 10 (varies between 8 and 12 years depending on the scenario) year cycle seems to emerge for vessel size 0 in most scenarios. This is interesting as there are no external drivers (eg. trade) that is driving this cycle frequency. The emergence of cycles in prices and their amplification is a typical emergent property of ABM (see for example Perc (2018)).

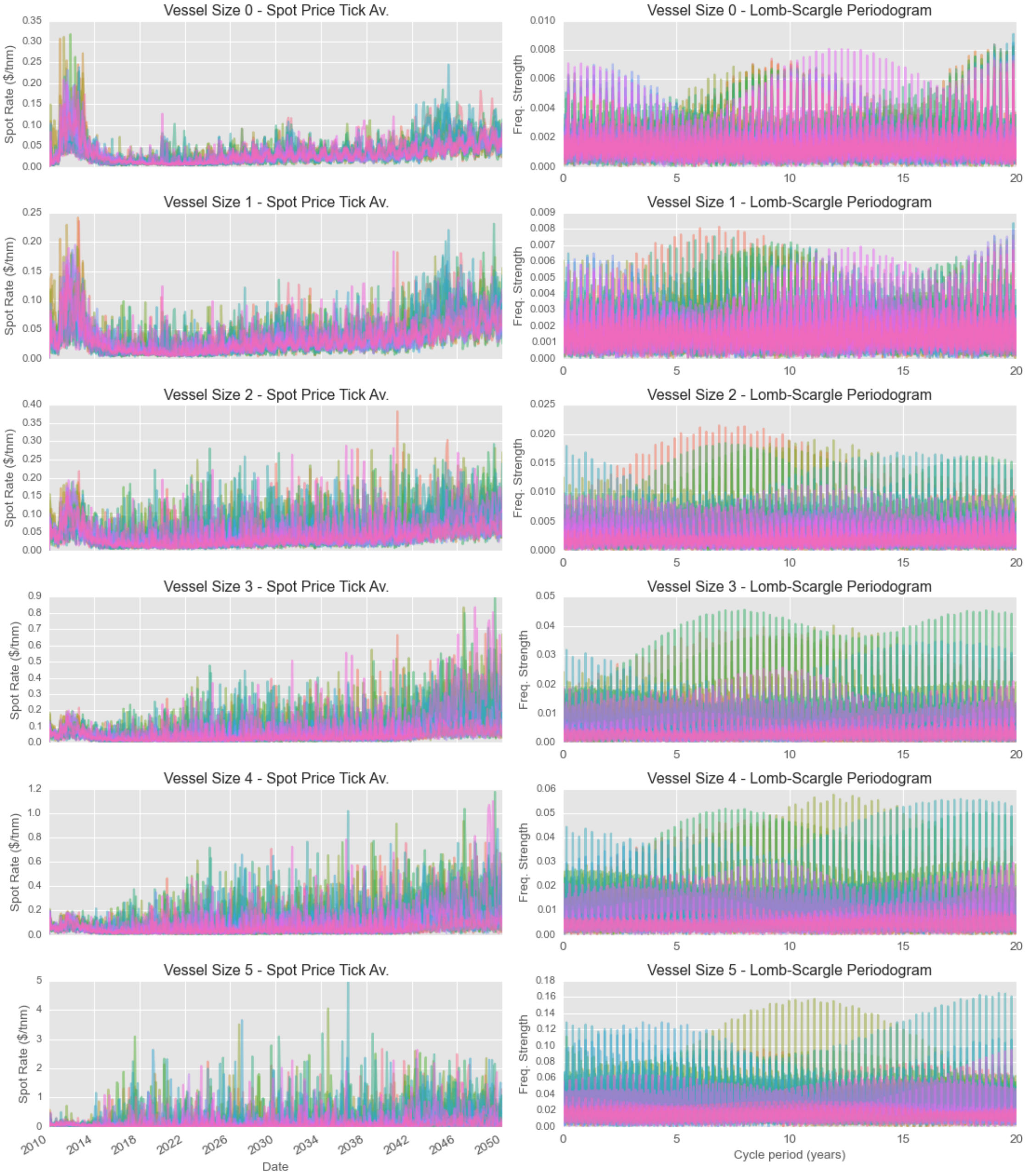

Figure 14.25. Spot prices (left column) and Lomb-Scargle Periodogram for these spot prices (right column) for the spot market in each size range and scenario

Similarly, there is evidence of an emergent cycle at approximate 7 and 16 year periods in vessels built (all sizes) in all scenarios, albeit of different strength. For vessels scrapped the signal is less consistent across sizes.

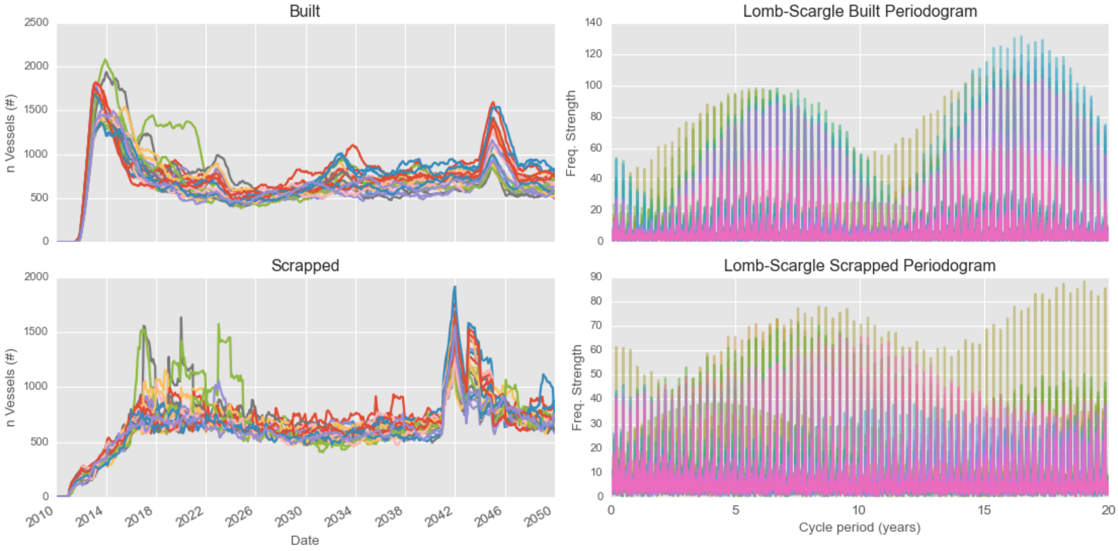

Figure 14.26. Vessels built and scrapped (left column) and Lomb-Scargle Periodogram for these values (right column) in each size range and scenario

A natural result of the description of the system as has been done in *GooFy* is the extremely granular view of the behaviour of individual vessels. As their movements are effectively a markov chain process from port to port, it is not possible to describe this behaviour using equation based approaches. An example of this granularity is shown in **Figure 14.27** for a vessel during its first two and last two years of operation.

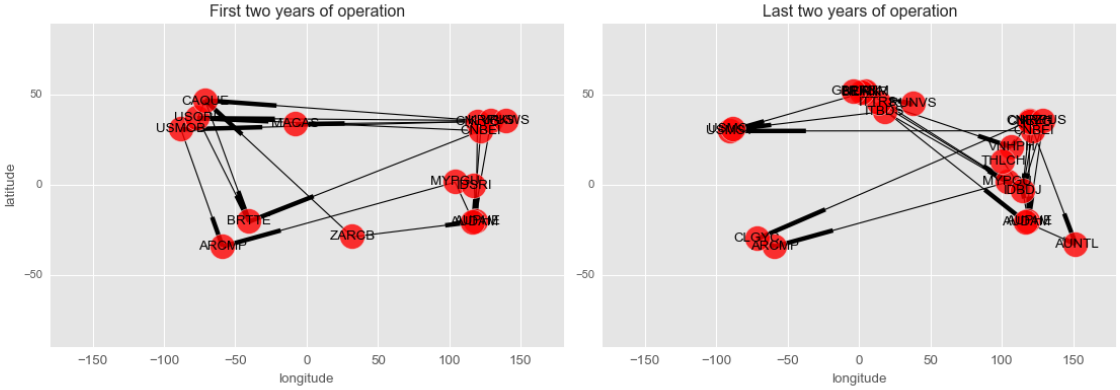

Figure 14.27. Example vessel network for a random vessel for its first two years of operation (left) and last two years of operation (right). The nodes are ports with ISO port labels.

This granularity allows for the evolution of system properties that are internally generated rather than forced on the system. More concretely, the setting of cargo size and capacity factors and vessel utilisation are endogeneous to *GooFy* rather than in an equilibrium based model where these factors are assumed, albeit disaggregated between ship sizes. In an equation based model sensitivity analysis can be performed that adjusts these factors, however, it would not be known a priori under what conditions they develop.

Hypothesis 2 *Setting shipowners and shippers as learning agents creates different take up of vessels and technology as compared with treatment of these entities as having consistent homogeneous market preferences.*

The purpose of this section is to show that a learning agent effectively commands a different fleet to a random agent under approximately the same conditions. The results are shown for the fleet size for each of these strategy types in **Figure 14.28**. As outlined in **Chapter 13 Table 13.6**, assigning of strategies is not based on the same criteria for the different strategies. Notwithstanding these differences, it is clear that the construction and scrappage as a result of each strategy type follow a significantly different trajectory.

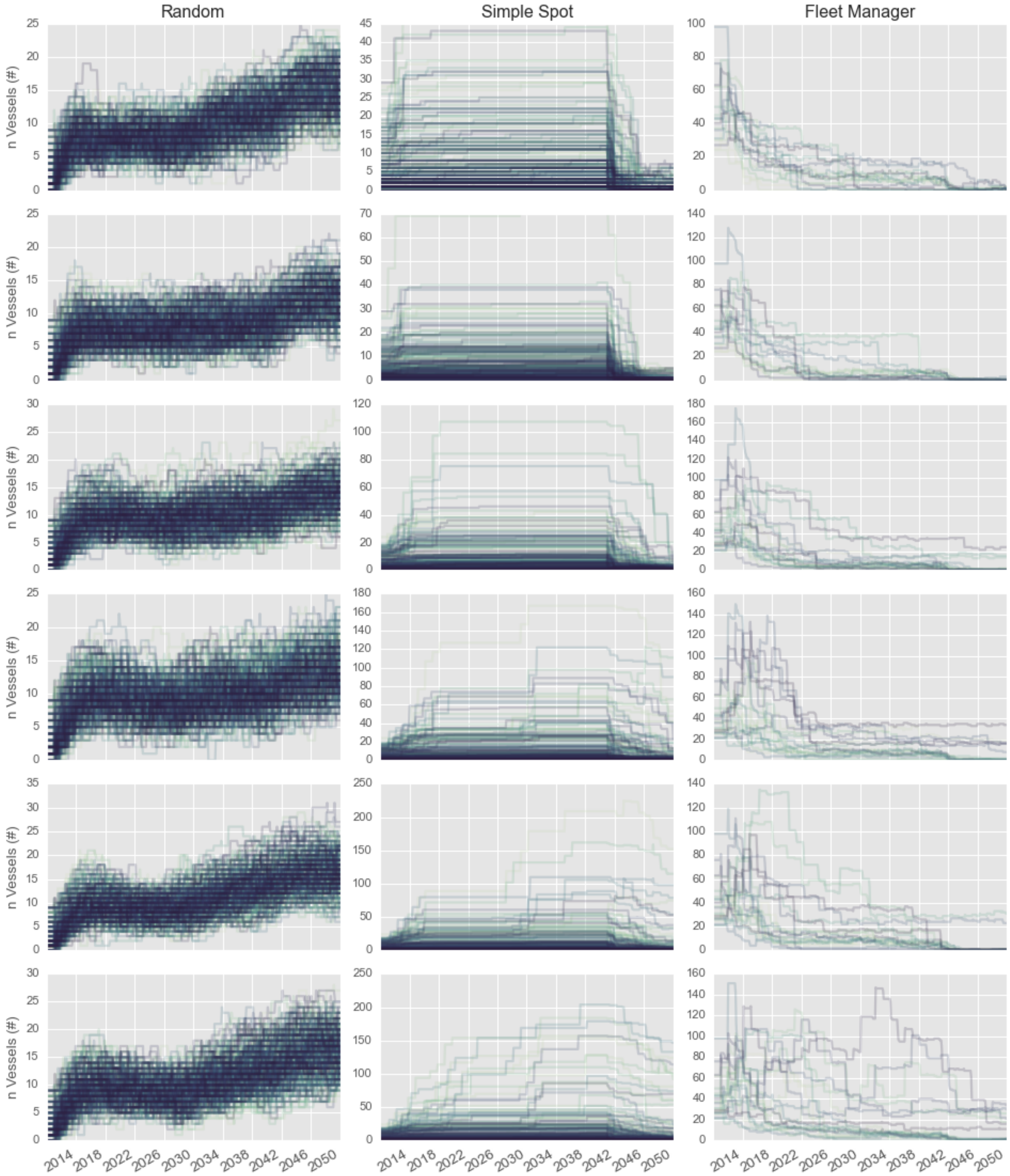

Figure 14.28. Comparison of fleet size per shipowner with random shipowner, pure spot shipowner and a fleet manager. Each line in the plots represents an individual shipowner with each row representing a different scenario.

In an equilibrium based approach, the variation in agent strategies can be modelled using probability distributions that reflect the range of preferences. However, the variation remains similar in how it is defined (ie. all are drawn from the same distribution). In *GooFy* and ABM more generally, the variations in agent strategies can and are represented radically differently within the same model allowing greater flexibility (and likely higher fidelity to the actual DBSS).

This work shows that the mix of strategies that an agent has can lead to significantly different outcomes. Therefore, being able to represent these different preferences is important in the first instance to understand how the system can evolve, but most significantly in understanding how and when to intervene to affect these agents and their decision making.

14.5 Model limitations

The modelling framework of ABM, as discussed previously, allows the user define the DBSS in a natural way. Particularly, its ability to incorporate the high granularity of individual vessel voyages and higher level strategic decisions of vessel stock adjustments. This complete system description, in this authors opinion, sets the ABM framework as an appropriate tool for answering the research questions and hypothesis that this thesis is investigating. However, with the power of this tool comes a demanding requirement for data both to define the agents and their interactions but also to validate the results. As discussed, there is a lack of high fidelity data available to fully support such an approach. In particular, it was evident throughout model development and indeed in the calibration and validation results that the system (as defined in *GooFy*) contains many feedback mechanisms. There are likely many constraining forces in the real system (for example, rules of thumb for constraining parcel size on a route) that are not included here. This is not suggesting that this work is not worthwhile. On the contrary, this work can be used to target what further supporting data is required to bring greater support to this approach.

Further to the application of ABM to the DBSS, there are issues related to *GooFy* as a specific implementation. A key limitation is the extent to which fuel stops are merged with the existing voyages of vessels. For example, would a vessel divert to another port that was not en route to bunker? No account for this is taken in *GooFy*, indeed no additional time is allocated for refuelling. Moreover, congestion at ports is not endogeneously modelled as this is dependent both on dry bulk vessel volume but also other factors such as non-dry bulk traffic and also land-side constraints.

Due to the high runtime of *GooFy*, the number of scenarios simulated was very limited and thus a Monte Carlo simulation could not be run. More concretely, a sensitive analysis was not constructed which would have been crucial for identifying the key variables that affect energy efficiency, in particular those related to network features. As has been highlighted through this thesis, there has been a lack of good quality data for both inputs and validation. However, one dataset bucks this trend; AIS data is a high quality, highly disaggregated dataset that can be used to generate network features. Therefore, by relating emissions (or some other emergent property of interest) to network features would provide sensitivities that could immediately be used in studies using AIS data.

Layup and retrofit is assumed to be at a local port and therefore not strategic in terms of vessel placement or subject to availability of support services. A vessel is not re-routed to another location for this to occur. The effect of this is that there would be an additional cost (i.e. the rerouting cost) to account for in these decisions.

No constraints are placed on the availability of capital; although these are indirectly accounted for in the cost of capital, they are not explicitly modelled. Further to this, the number of firms is controlled. In other words, exits and new entrants to the system are not allowed. This is contrary to Schumpeters theory of creative destruction (Schumpeter 1942) particularly for shipowners. For shippers, their core business is likely to be in the production and sale of the commodity, rather than the shipping cost, and therefore modelling the performance of the company cannot be complete within *GooFy* because it does not explicitly model the commodity markets. This same point does extend to shipowners, many of whom deploy vessels in both the tanker and dry bulk markets. In addition to the lack of capital constraints, *GooFy* did not include the second hand market for sale and purchase of vessels. The inclusion of this market would have allowed shipowners an additional hedging strategy when buying or selling vessels and therefore would have moderated the extreme changes in transport supply.

A key finding was the difficulty of matching supply to demand. It is not possible to force a trade output on the system, only a production rate and consumption rate. This in itself is not a new result and indeed, we see this occurring in shipping (Ole Andersen 2017).

Related to the trade disequilibrium is the difficulty in defining a baseline. As discussed at length throughout this work, the availability of granular data at the ship level is not available, therefore knowing exactly how the current DBSS functions, for example in terms of what is currently shipped through industrial shipping versus voyage charter is not known. However, the initial conditions are crucial for determining the path of evolution. As the system begins in a state of flux, methods such as reinforcement learning, that were initially deployed as potential strategies, were ineffective as the system was changing so rapidly and thus these did not lead to the development of an efficient system, rather increased the instability.

Perhaps the most significant limitation has been the scenarios that were simulated. As has been discussed already these were conservative, both in terms of transport demand but also regulation options and abatement technologies included. To have included an extreme decarbonisation scenario would have provided insight into how the endogeneously generated variability compared with that generated from external inputs. For example, would the range in total emissions for SSP5 in 2050 be the same if a scenario with a $1000 per tonne carbon price were included?

14.6 Summary

This chapter shows the results of the projection scenarios, specifically in relation to the research questions and hypotheses outlined in **Chapter 3**. Climate change impacts were found not to be identical across the route network, but largely limited to selected commodities. Comparing two competing scenarios of trade, no significant differences in vessel operations were found, with impacts limited to the number of vessels required in a particular size range that is used to service that trade. Finally, the various fuel and carbon price scenarios did not result in significant differences in the uptake of climate change reducing technologies.

On the broader question of the hypotheses outlined, particularly the capability of ABMs to capture complex behaviour, *GooFy* showed both emergent properties and the granularity that allows a full system understanding captured to a greater fidelity than with equilibrium based approaches.

Chapter 15

Conclusion

15.1 Introduction

As discussed at length in this thesis, the DBSS is a complex system that can be modelled in multiple ways. This thesis focussed on using a complexity science approach, agent based modelling. The thesis therefore has largely focussed around supporting this approach as a valid method to model the DBSS. To that end, it was compared against traditional four stage models which use equation based modelling approaches assuming annual linear equilibrium.

15.2 Main Findings

A notable output was the range of system responses over a small number of scenarios. It was found that interactions within the shipping system itself, driven by endogeneous factors, can in some cases contribute more to how the system will evolve than those derived from external factors. Projected changes in demand for goods do not vary to the extent that they will cause radical changes within the shipping system. More likely, it is the evolution of shipper and shipowner preferences that will alter the system. Notwithstanding this, the scenarios were limited in their scope and it is this author's opinion that projection scenarios are extremely conservative. The reason is likely the perceived 'realism' of these changes coupled with most models treating transport demand in an aggregated way. In this authors opinion, this 'realism' is rooted in a misplaced belief that the status quo is static and long running. The benefit of *GooFy* or indeed any highly granular model is that total demand could remain constant while radically altering the pattern of trade. As was shown in **Chapter 14 Section 14.3**, the opening of the Northwest passage appeared to have a significant effect on several commodities.

As was discussed at length in preceeding chapters, the system itself is highly complex both in its description and its interactions, and it is this that must be paid attention to. In this thesis, several narratives were developed for the shippers and shipowners, but these were very conservative. Despite this, they generate highly variable results. How these stakeholders make decisions and how affected they are by current market conditions is vital to understand.

It is notable that despite the obvious potential of ABM for modelling the shipping sector, it has rarely being attempted. Certainly not to the granularity and scale that has been carried out in this thesis, to this author's knowledge. There are a number of reasons for this, not least opportunity and interest, but most notably is the difficulty of reducing the degrees of freedom. The scope of this work was already limited by only focussing on the DBSS and not including several markets, including the second hand market, but there remained significant complexity and scale. In this author's opinion, and as found in this work, in order to recreate the emergent properties of the system to high fidelity it was not possible to limit the scope any further. For example, the physical transport of the cargoes by vessels could have been parameterised so that vessel location was not explicity modelled by using capacity factors and utilisation rates. However, this would have resulted in an exogeneous spot rate as the spot rate is highly dependent on instantaneous vessel location, thus affecting demand for new vessels or scrappage rates. Another example would have been reducing the markets to only the spot market, thus reducing the required complexity for defining shippers and shipowners. However, this would then ignore a large part of the transport system, as there is a significant volume of cargo transported using industrial shipping and CoA. It would also have had a significant impact on the evolution of vessel sizes. It is this author's opinion, if the areas of interest are fleet size evolution, capacity utilisation rates, indeed all areas of operation of a vessel, then the level of granularity and scope that was used in this thesis is required, particularly if the user wishes to model deviations from current conditions, such as significant changes in trade or high carbon price scenarios.

15.2.1 Data requirements

This work has highlighted significant gaps in available data that is important for system modelling or indeed any modelling within the DBSS. As discussed at length in **Chapter 12** the results of the hindcasting were approximately consistent with the validation data from that period. However, that data was for the most part highly aggregated. Greater level of granular data, would facilitate any structural changes to the model and indeed the description of the agents used. This work would benefit greatly from more granular data in a number of areas, including:

- Cargo sizes on trade routes by commodity
- The amount of trade shipped through contracts of affreightment, industrial and on the spot market.

15.2.2 Climate change impacts

As highlighted throughout this thesis, there is large uncertainty surrounding the impacts of climate change. Some of the more obvious direct and indirect impacts have been investigated here:

- Physical impacts of climate change through the opening of Arctic sea routes.
- Changing demand for commodities due to climate change and external projected evolution of the global economy
- Changing fuel prices due to external projected changes in the shipping sector
- Effects of mitigation of climate through carbon pricing and minimum standards on vessel efficiency

This work was hindered by the limited knowledge surrounding how climate change will impact trades, particularly grain trades. Therefore, it is suggested that *GooFy* be deployed against scenarios on the extreme effects of climate change on trade, to gain a greater understanding of how these effects would impact the sector.

15.2.3 Natural description of the system

A significant benefit of *GooFy* is its natural description of the system. This facilitates development of analogues for the actual agents in the market. Due to the high dependence on interactions at a vessel movement scale, there are effectively two approaches to modelling the evolution of shipping: one based on strong assumptions about vessel operations, and; a highly disaggregated approach that models interactions at the vessel movement scale, as was the case for *GooFy*. The former approach resides more comfortably with most practitioners as it satisfies the FSM paradigm and the natural tendency to be conservative in system alterations (and indeed does not have the validation challenges of the latter). However, it is driven by key assumptions on issues such as cost pass through and capacity utilitisation which are key drivers in the uptake of technology. The model described in this work suffers from an overload in complexity and data generation resulting in a model limited by computational challenges. However, these computational challenges are reducing all the time with greater computing power becoming available as well as sophisticated platforms to build on (e.g. Improbable (2017)).

Validation has long been an issue with ABMs, and this model has been no different. *GooFy* was approximately consistent with the limited aggregate level data that was available, but certainly not to the extent that it could be considered validated. Moreover, *GooFy* is very dependent on initial conditions, particularly over a short run of 10 years, given a two year inertia within the system, due to build periods. Therefore, what use is it? If it can't predict accurately the emissions in 2050, then is it of any use. It is very little use if that is the question, but then no model is able to do that, so that question is moot. What *GooFy* can do is elucidate system responses to interventions or projected impacts such as:

- How will the system respond to a carbon price of $500/t?
- Are there any negative feedbacks that result from enforced efficiency standards?

However, if the model is itself unvalidated, can you trust the answer? Due to the model structure based on a natural description of the system, the model results are naturally intuitive, and thus validated in that respect (but not necessarily exhaustive). Due to the description of equation based models in a parameterised way, the burden of validation is greater on them because they are not explicit in how they define a system. The onus is on them to show that they are not simply status quo models that can model minor perturbations well but cannot represent significant system changes.

15.3 Further Work

A significant output from this work has been the framework to extend what has been done previously. Below are described some key improvements that would greatly benefit this framework.

15.3.1 Scalability

A significant limitation to this work has been the scaling problems from theoretical or regional systems to the global DBSS. Parallelisation was investigated but it was not clear where this parallelisation could bring dramatic improvements. For example, regional trades could be parallelised but this limits all matching of cargoes to vessels to those regions and prevents matching to vessels outside of the current region, thus requiring a signalling process to broadcast cargo to vessel balances. This additional complexity would greatly offset any gains made through parallelisation because the parallelisation would be limited to under 10 separate regions. Multithreading has been incorporated in *GooFy* but this is all contained within a single process, so the overall capacity barrier remains.

A major advance however, would be the improvement of the solution algorithms for the mixed integer problems which typically occur at each planning stage. Improvements to this would not only greatly improve the overall runtime but also expose new opportunities for more sophisticated strategic, tactical and operational planning, which at the moment are highly parameterised.

15.3.2 Technology and Innovation

A natural extension of *GooFy*, is to include diffusion models of innovation (Kiesling et al. 2012) both for the uptake of technology on board vessels but also in the support infrastructure. In particular, it is cited that product adoption is dependent on the number of its users, as the value of the product to its users increases as the number of users increases (Bonabeau 2002) so the technology becomes 'locked-in' in a sub-optimal Nash equilibrium (Faber & Frenken 2009). This is commonly referred to as the network effect. Moreover, the value of the product may increase with increased use amongst the users' neighbours. This can be applied to the transition to new fuels, such as hydrogen fuel cells. It would require the alteration of ports from objects to agents with their own investment model.

15.3.3 Input data

There is required work both to collect data for inputs but also for validation, particularly trade flows disaggregated to a port to port level where there is little data on port to port flows (except that derived from AIS data, which is only a lower bound) and also port constraints.

15.3.4 Infrastructure interventions and system growth

Further to extending the port data, examination of the effect of new ports could be investigated with this model. As suggested by Barthelemy (2010), transportation networks evolve in time, allowing a network based approach such as that outlined in Barthelemy (2010) to potentially be adopted.

15.3.5 Coupling with trade model and production/consumption processes

As highlighted in **Chapter 9**, there have been recent developments in dynamic models of trade. The coupling of a system dynamics model of bulk trades has significant potential. Such a model would allow feedbacks of transport cost, transport delays and interruptions to influence an overall trade model. A system dynamics model of trade was developed in this thesis with the purpose of coupling with GooFy but was excluded due to runtime limitations, as discussed in **Chapter 6 Section 6.2**.

15.3.6 Agent extension

The agents within *GooFy* are limited to a single strategy profile during the simulation. However, significant work has been completed on agents learning to learn which could be deployed, such as Erev and Roths work (Erev & Roth 1998). In other words, they can adapt their strategy profile or choose from a range of profiles throughout the simulation, or the agents that Chen (2012) referred to as regime switching agents. This would develop into an an equilibrium state of strategies that are balanced. Indeed, agents could be supplied with incremental cognitive capacity, developing from entropy maximising (or random) agents to intelligent agents over time (Chen 2012).

Agent cooperation should be investigated further. For example, the development of alliances between operators to transport CoAs.

15.3.7 Strategy extension

The three planning phases in *GooFy* are coded as functions, with a consistent interface allowing plug and play of new planning functions. However, this does limit extension to new strategies to those users who can code functions in Java. Following the approach of MABS using belief-desire-intention (BDI) models, it would be sensible to develop a context-free grammar allowing users to define through a configuration file the strategies of agents. This would allow complete flexibility in the definition of new strategies. Indeed, it would allow shipowners and shippers to evolve their own strategies during runtime.

15.4 Summary

This thesis has been the culmination of thousands of hours of development of the agent based model, *GooFy*, that simulates the dry bulk shipping system (DBSS). Ostensibly it was developed to model the impact of climate change and climate change mitigation on the DBSS, but has evolved into a feasibility study for this approach on systems of this size. Due to computational limitations the sample size limits resulted in non significant results as to the impacts of climate change, notwithstanding some interesting effects due to the opening of the Arctic routes. This work found that there is great uncertainty in how the system will evolve due to agent evolution which is naturally impacted by the differences between the scenarios but for the most part there was a residual uncertainty due to the inherent uncertainty within the system. That being said, the scenarios were deliberately based on current literature and very conservative in their estimates of how significant external factors will change.

The result of this work, from a feasibility point of view, was that models of this type are very important for understanding how a system will evolve, and more importantly the uncertainty surrounding those estimates.

Appendix A

Data Sources and Treatment

A.1 Data Sources

The following data sources were used in this research:

- COMTRADE International trade statistics data: Trade volumes were available for the bulk commodities at the HS4 level (COMTRADE 2018).
- United Nations Code for Trade and Transport Locations (UNECE 2016)
- Eurostat Vessels in main ports by type and size of vessels (EU 2017)
- World Port Source (Source 2012)
- Clarksons fixture database (Clarksons 2013)
- World Fleet Register (Clarksons 2011)
- IMF Commodity Prices (IMF 2017)
- IndexMundi Commodity Prices (IndexMundi 2017)
- Glotram scenarios for Fuel Prices and Carbon Prices (Smith, TWP, Day, S. Bucknall, R. Mangan, J. Dinwoodie. J. Landamore, M. Turan, O. Wrobel 2014)
- Vessel Owner list from World Fleet Register Clarksons (2011)
- Vessel abatement technologies and engine specifications (Smith, TWP, Day, S. Bucknall, R. Mangan, J. Dinwoodie. J. Landamore, M. Turan, O. Wrobel 2014)

A.2 Data Treatment where applicable

A.2.1 COMTRADE International trade statistics data

The data was collected using a bespoke algorithm created for this thesis (O'Keeffe 2018) that collated the required datasets for creating the baseline country to country trade volumes, both on a monthly basis and annual trade volumes. As highlighted in **Chapter 9 Section 9.3**, this data contain significant spurious data that were removed or infilled (based on moving average).

A.2.2 Port database generation

This is provided in detail in **Chapter 9 Section 9.4.1**.

A.2.3 Vessels database

This was extracted from the World Fleet Register, including only those in the bulk carrier category and excluding those below 5000dwt.

A.2.4 Commodity price data

The various sources were merged and mapped to the relevant HS4 code level.

Appendix B

Author publication listing

B.1 Relevant Publication listing

- Simpson et al. (2010)
- Smith et al. (2010)
- Smith & O'Keeffe (2012)
- Haji et al. (2013)
- Smith, O'Keeffe, Aldous & Agnolucci (2013)
- O'Keeffe (2013)
- Smith, O'Keeffe & Haji (2013*a*)
- Smith, O'Keeffe & Haji (2013*b*)
- Smith et al. (2014)
- O'Keeffe et al. (2017)
- Scarbrough et al. (2017)
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