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Systems Modelling of the South African Offshore Demersal Hake Trawl Fishery: An Economic Perspective

Rachel Cooper

Supervisors:
Prof. Astrid Jarre
Prof. Anthony Leiman

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Declaration

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Rachel Cooper

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ABSTRACT

Systems Modelling of the South African Demersal Hake Trawl Fishery: An Economic Perspective

Rachel Cooper – February 2015

The offshore demersal hake trawl is the largest sector of the South African hake fishery, which targets shallow-water (*Merluccius capensis*) and deep-water (*M. paradoxus*) Cape hakes. Economically, it is the most important fishery in South Africa, generating ZAR ~5 billion in revenue, mainly from exports, and it supports an estimated 30 000 jobs. Whereas there are a number of single-species and ecosystem models that assess hake stock dynamics and examine the food web dynamics of the southern Benguela ecosystem, the human social hake fishery system is less understood. In order to address this need, this study's aims are to i) analyse the structure and dynamics of the economics of the South African offshore demersal hake trawl fishery from empirical data and stakeholder interviews, and ii) produce a prototype economic simulation model of this fishery to better understand the dynamics of the industry and the relative importance of its internal and external drivers, e.g. industrial organization, environmental uncertainty, exchange rate and fuel price.

The empirical analyses confirm that the offshore hake trawl fishery is an economically mature and highly vertically integrated industry. That is, most companies control much of the value-chain, catching, processing, marketing and distributing their fish products, with access to economies of scope and scale. Nine company clusters, formed through consolidation of fishing rights and a variety of catch-share agreements, have been identified. Based on their size and operations they have been categorized as small, medium, large and super-cluster types. Fishing vessel numbers have declined since 1978 to streamline operations, with current effort optimising restrictions based on vessel engine power and the ability to catch the full quota. During the observation period (2005-2012), high-value export markets have bought 60-70% of the South African hake total allowable catch (TAC), comprising nine major markets and a number of smaller ones. The lower-value domestic market takes ca. 30% plus imports equivalent to another ca. 15% of TAC. Hake export volumes have shifted from fresh to frozen and increasingly to value-added products, especially after the 2008 banking crisis. This corresponds to an industry-confirmed price-convergence between fresh and frozen hake products. This product displacement trend is largely due to changes in the largest export market, Spain, and is mirrored by an increased reliance on freezer trawling in the industry.

These empirical results are captured in the design of an agent-based simulation model, *HakeSim*, which was built using a rapid prototyping approach. The different company types, the variety of fishing vessels that they own and the markets that purchase from them are explicitly captured as

individual model entities (i.e. 'agents') with unique and heterogeneous traits and behaviours. Dynamics are modelled with a monthly time step, driven by TAC, catch per unit effort (CPUE), company attributes, quota, exchange rate, fuel price, price paid by markets for hake and market demands. The first model version (*HakeSim 1.0*) behaves more simplistically with frozen and fresh fish as the only model currency. An assumption analysis (*HakeSim* versions *2.0 – 2.3*) reveals the necessary changes to carefully increase complexity in the model, while retaining confidence in model behaviour. The full model prototype, *HakeSim 3.0*, incorporates these changes and adds money (Euros and South African Rands) as model currency.

HakeSim 3.0 behaves realistically, its outputs supporting the findings on fishery structure and operation at a strategic level. It is sensitive to changes in fleet size, the quota of large and medium companies, CPUE, exchange rate and TAC. Model companies have different strategies for trading off risk against profit: large and medium companies have a riskier higher-profit strategy than small and super-cluster companies. In line with expectations, a weak South African Rand and a high market value (Euros) of hake can buffer the effects of increased fuel prices on profitability in the model. Model companies are able to achieve price increases in hake market value by shifting to a high-value or high-profit hake product. Interactions between total allowable catch and CPUE are important for company profitability. When total allowable catch is high and CPUE is low model companies make a loss in the observed price bracket; the present industry fleet size appears to ensure that companies catch their entire quota and reduce losses under such conditions.

From the simulations, risk increases when the stochasticity of catching fish (a proxy for environmental uncertainty) is raised, but profit does not. There are clear interactions of fuel price with other model variables. CPUE affects profits more than fuel price does. Changes in fuel price are more important than the stochasticity of catching fish, possibly due to this proxy insufficiently capturing environmental and trophic processes. However, increased stochasticity reduces profits. Since the proxy for environmental stochasticity affects catches of fish both directly (e.g., through weather conditions) and indirectly (e.g., through recruitment and CPUE), as well as profit and company risks in the model, better understanding of environmental stochasticity, and its interactions with catch, are highlighted as important areas for future ecological research. Unfortunately, it was not possible to include size-structure of hake in the current version of the model. Doing this in the future will make it possible to link the economics model to existing ecosystem models, and then allow the assessment of trade-offs between different fisheries in the southern Benguela, such as small pelagics and a possible new mesopelagics fishery, and the hake demersal trawl fishery.

CHAPTER 1:

INTRODUCTION

Chapter 1: Introduction

1. Problem statement & overall aim

The most valuable component in South Africa's fishing industry is its hake fishery, which targets two species, shallow-water Cape hake (*Merluccius capensis*) and deep-water Cape hake (*M. paradoxus*). Despite good management and recent Marine Stewardship Council (MSC) certification of some sectors, the hake fishery is not without its problems, environmentally, socially and economically, and it faces an uncertain future.

National legislation and international policy state that South Africa should move towards an ecosystem approach to fisheries (MLRA, 1998; WSSD, 2002). Such an approach requires that ecological, social and economic considerations for present and future generations be taken into account and conflicting objectives be balanced. It is in this context that this project was conceived with the recognition that the sustainability of our fisheries depends not only on the management of fisheries based on the dynamics of the target stocks, but also both on the sound understanding and management of fisheries in their ecosystem and a better understanding of the social and economic drivers of hake (resource) exploitation. One means of improving this understanding is through modelling, an approach that allows the testing and development of a system-level understanding, the synthesis of knowledge and the ability to make predictions, as well as being a useful tool for interdisciplinary research (Blackford *et al.*, 2010; Starfield and Jarre, 2011). Indeed, the focus of this thesis is modelling.

The broad aims of this thesis are to:

1) Develop a semi-quantitative understanding of the South African demersal hake trawl industry, as contextualized within the ecological, economic and social systems, through data collection and analysis, as well as industry consultation.

2) Produce a prototype social system model that specifically considers the economics of, South Africa's offshore demersal hake trawl fishery, which operates in the Southern Benguela, to gain a preliminary understanding of its structure, dynamics and the relative importance of

internal and external drivers e.g. industrial organization, market demand, exchange rate and fuel price.

In hindsight, this was achieved through a two-fold approach – by conducting ongoing consultation with stakeholders and experts (fully described in Chapter 3, section 2.2), data collection and analysis, and by using the outcomes of the consultations and analysis to develop an economic agent-based model, *HakeSim*, in an iterative approach.

2. <u>Background</u>

2.1. The hake fishery in South Africa: A brief review

The South African hake fishery is the most economically important fishing industry in South Africa; it accounts for more than 50% of the overall value of SA fisheries (Butterworth and Rademeyer, 2005; Powers *et al.*, 2010). Landed catch was valued at about R2.5 billion in 2008 (Petersen *et al.*, 2010), and in 2014 estimated at approximately ZAR 5 billion, ±€342 million (Durholtz, 2014). The sector is reportedly responsible for roughly 30 000 jobs (Rademeyer *et al.*, 2008a), and contributes to local foreign exchange earnings as well as food security. Bacela *et al.* (2003) estimate that 50% of all fish eaten in South Africa is hake.

The hake fishery is well-established. Fishermen around the South African coastline have been harvesting hake since the 19th century, when shallow-water hake was initially a bycatch species in the Agulhas sole (*Austroglossus pectoralis*) trawl fishery (Rademeyer *et al.*, 2008a; Field *et al.*, 2013). By the end of World War I in the early 20th century the demersal trawl fishery had expanded to have a hake-focused component targeting *Merluccius capensis* and, additionally, the deep-water Cape hake, *M. paradoxus* (Atkinson *et al.*, 2011); composed of inshore and offshore trawling. Later, in 1990, a hake-focused hand-line fishery was established as an expansion of an already existing hand-line fishery that used small boats (Bacela *et al.*, 2003; Petersen *et al.*, 2010). By 1994 a longline fishery was experimentally introduced, becoming a licensed and fully commercial fishery in 1998 (Petersen *et al.*, 2010). In 2004, the majority of the hake demersal trawling fleet was certified as sustainable by the MSC [1] and recertification was granted subject to conditions in 2010 (Powers *et al.*, 2010). However, the other smaller hake sectors remain uncertified.

In South Africa the demersal trawl fishery focuses on shallow-water hake, *Merluccius capensis* Castelnau, 1861, and deep-water hake, *M. paradoxus* Franca, 1960, whose distributions overlap at 250 – 450 m (Butterworth and Rademeyer, 2005; Dankel *et al.*, 2008). A smaller proportion of bycatch species(i.e. 'joint-product') which can sometimes be quite valuable are also caught and sold, e.g. kingklip (*Genypterus capensis*) and monk (*Lophius vomerinus*) in deeper waters or silver kob (*Argyrosomus inodorus*) in shallower waters (Bacela *et al.*, 2003). Generally, *M. capensis* is caught in depths of 50 – 350 m predominating on the Agulhas Bank in the South and *M. paradoxus* is fished at greater depths (250 – 600 m) (Field *et al.*, 2013). The fishery is comprised of four sectors (Table 1.1), the offshore trawl sector accounting for 85% of the landed catch, the inshore trawl (6.5% of total landed catch), the longline (6.5%) and handline (2%) sectors (Rademeyer *et al.*, 2008a), for *Merluccius spp.* catch Field *et al.* (2013) update these figures to 85% offshore trawl, 7% inshore trawl, 5% longline and <1% handline. In the different sectors fishing occurs at different depths and locations and with different vessel and gear types, which target varied sizes of the two hake species and catch different bycatch species. Offshore demersal hake trawling typically occurs on both the West and South Coasts of South Africa, along the edge of the continental shelf, while inshore trawling is located close to the coast on the Agulhas bank at less than 110 m (Field *et al.*, 2013). Handline fishing, although virtually inactive at present, has historically been primarily on the Agulhas bank, and similarly for the longline sector but it also overlaps with the offshore sector. Offshore trawling does processing of fish both at sea (i.e. sea-frozen) and ashore, i.e. lands both fresh and frozen hake, while the other three sectors land almost exclusively fresh fish.

The offshore demersal trawl fishery, the sector of interest for this thesis, is a mature industry comprised of companies with economies of scale and scope where super-profits no longer exist (largely as a result of foreign fleets depleting hake populations in the 1960's). According to Bacela *et al.* (2003) the offshore trawl is characterised by significant capital assets to the replacement value of R2.4 billion at 2002 prices. It has largely operated as a single-species fishery for much of its history, since the two species of hake appear very similar; until well into the 20th century *M. paradoxus* was not described as a separate species (da França, 1960). High-value bycatch species such as monk and

[1] MSC Certification applies to vessels and companies from the inshore and offshore demersal hake trawl sectors that are South African Deep-Sea Trawling Industry Association (SADSTIA) or South East Coast Inshore Fishing Association (SECIFA) members (Powers *et al*., 2010).

kingklip are also retained (according to maximum limits set by government) and sold. The catch is destined for domestic and export markets. The export market has long been important for the hake industry, which played a minor role in the post-world war seafood export-boom but the central role in the post-1990 South African seafood export-boom (Crosoer *et al.*, 2006).

Table 1.1: Attributes of the different sectors of the hake (*Merluccius capensis* and *M. paradoxus*) fishery in South Africa circa 2002 / 2006, taken from Bacela *et al.* (2003) and BCLME (2006b). Values pertaining to 2006 are highlighted in bold.

	Handline	**Longline**	**Inshore Trawl**	**Offshore (Deep-sea) Trawl**
# of vessels	180*	56 / **64**	29 / **31**	67 / **79**
Number of rightsholders		**132**	**17**	**46**
Approximate TAC (tons)		**11000**	**9000**	**124 500**
Jobs sustained‡		**1495**	**1480**	**8900**
Investments in fixed assets (ZAR)		**R 182 million**	**R 1.473 billion**	**R 2.4 billion**
% of SA fisheries employment	10.7	4.8	1.5	11.7
% total SA fisheries employment income	9	5.6	1.5	21
vessel size (m)	approx. 4 – 15	12 – 45.6	20.5 ± 14 – 31.2	49 ± 20.7 – 90.6
Average vessel age	17	30	24	24
average days spent at sea annually	167	68	91	186
capital value per fisher (ZAR)	not specified	130 000	not specified	420 000
% full-time employees	not specified	not specified	90.3	95.8
End of long term rights		**31/12/2020**	**31/12/2015**	**31/12/2020**

* currently estimated to be only 90 very small vessels (Peter Simms, DAFF, *pers. comm.*, May 2011)

‡ detailed and verifiable data obtainable from DAFF

The demersal hake trawl has an unusual history; it has operated as a 'modern' industrialised fishery since the 1890's, as opposed to all other South African (SA) fisheries that first developed from subsistence through small scale fisheries (Bacela *et al.*, 2003). For much of its history, just a few large, vertically-integrated companies have dominated the industry, beginning with the establishment of the South African trawling industry by G.D. Irvin and C.O. Johnson (I & J) back in the 1890's whose history is the history of the industry itself up until the 1960's (Bacela *et al.*, 2003). Although many new companies entered the industry over the years, few survived due to the capital-intensive and financially risky nature of trawling, and due to their lack of focus on the essential processing, marketing and/or distribution aspects of fishing that ultimately made the larger companies profitable and successful (Bacela *et al.*, 2003). Following World War II landings of hake were fairly constant around 50 000 tonnes per year (Atkinson *et al.*, 2011).

International factory fleets arrived in the SA offshore fishery in the 1960's spurring I&J to convert to diesel stern trawling and acquire more vessels to attempt to compete (Crosoer *et al.*, 2006). Nevertheless, I&J only maintained its catches while the more abundant foreign fleets fished down the hake stocks by the early 1970's with annual catches of around 160 000 t and an unsustainable yield of 300 000 t reached by 1972, reducing the catch per unit effort (CPUE) in the fishery to half and threatening the national industry and stock with ruin (Crosoer *et al.*, 2006; Atkinson *et al.*, 2011). Government intervention began in 1975 when a minimum mesh size, observer monitoring system and quotas for countries were enforced (Payne, 1989). Crucially, in 1977 a 200 nm exclusive economic zone was established, excluding foreign vessels; in 1978 conservative total allowable catches were implemented and in 1980 individual quotas were instituted to attempt to rebuild stocks, resulting in a more stable annual catch of 120 – 150 000 tonnes (Geromont *et al.*, 1999; Rademeyer *et al.*, 2008a; Atkinson *et al.*, 2011).

Prior to 2002 rights were allocated on a short-term basis, with annual applications; in 2002 medium term rights allocations took place with rights lasting until 2005, followed by the issuing of long term rights in 2006 for 15 years in the case of the offshore demersal trawling industry (Branch and Clark, 2006; Hara and Raakjaer, 2009). These apportioned a percentage of the annual Total Allowable Catch (TAC) to individual rightsholders with their fraction constant for the period for which the rights were allocated. Also in 2005 the hake Operational Management Procedure (OMP)[2], which was first

[2]OMP's entail a medium term evaluation of alternative management options on the resource and related fisheries through the use of simulation experiments. See Rademeyer *et al.* (2008b) for more details.

implemented in 1990, was altered to be coast-combined in addition to being species-disaggregated. This was to account for the consensus that South and West Coast *M. capensis* stocks were likely one population, and for the different dynamics of the two species as well as the targeting of *M. capensis* by the longlining fleet (Rademeyer *et al.*, 2008a; Rademeyer *et al.*, 2008b).

Therefore, presently the hake fishery as a whole is regulated by individual quotas issued on the basis of a two-species stock assessment and OMP. Annual catch was around 135 000 tons in 2007 and annual changes in TAC are restricted to ± 5% although a decrease of 15% may be warranted if CPUE results are well below the recent average (Rademeyer *et al.*, 2008b). Management is on the basis of a combined TAC due to the difficulty of individually targeting the two species where they occur together and in differentiating them commercially (Field *et al.*, 2013). For all rightsholders an industry-led effort restriction (number of allowed sea days) for vessels based on the horsepower of their trawler engines was implemented in 2006 (SADSTIA, 2013). This effort restriction was implemented as a step towards reducing excess capacity within the industry.

Despite positive outlooks stemming from the implementation of the two-species, coast-combined OMP and MSC certification of the trawl sector, there are still a number of important concerns surrounding the hake fishery. Petersen *et al.* (2010) argue that these concerns include i) bycatch issues, ii) the need for more focus on comprehensive trophic and ecosystem models, iii) the lack of both implementation of an Ecosystem Approach to Fisheries (EAF) for the hake fishery and good data procedures to support an EAF for hake, iv) non-compliance or enforcement issues, v) the lack of understanding of external impacts on the hake fishery, and vi) a lack of understanding of social and economic welfare of those who depend on the fishery for generating income. Additionally, there is only preliminary research on the economic context of the fishery and virtually no information on the economic implications of management decisions (Petersen *et al.*, 2010).

The current paucity of economic studies, in addition to a paucity of social studies, on the hake fishery in South Africa can provide a challenge to understanding the economic (and social) aspects of the hake system. This is concerning given that as early as 2002 there had been a call for the future collection and collation of economic data during a preliminary economic and sectoral review (Bacela *et al.*, 2003). In spite of early collaborations between industry, academia and non-governmental organizations that aimed to shed light on these gaps, a report by Petersen *et al.* (2010) further highlighted that the understanding of certain economic aspects of the hake fishery was poor. They did report back a stakeholder discussion that suggested that all sectors of the fishery had at that time "*good access to international markets*" (Petersen *et al.*, 2010), although some fishery stakeholders presently dispute this (Anonymous, 2011b).

Some sectors of the fishery have diversified their access to international markets through MSC certification, while others rely on more traditional markets. The offshore trawl sector has MSC certification for five years from 2010, but this is subject to a number of requirements being met with regards to ecological understanding and management objectives (Powers *et al.*, 2010). The handline fishery has no certification and is not well organised, which has been identified as an apparent hindrance to this sector accessing certain international markets and high market value for their products (Anonymous, 2011b). The longline sector mainly air-freights its freshly caught fish to Barcelona for sale on the European market, primarily Spain (P. Simms, DAFF, Mossel Bay; *pers. comm.* to R. Cooper, 2011). Although, back in 2011 at the start of the thesis research there were anecdotal reports of a downturn in the European hake market, particularly the fresh hake market, due to the financial crisis (P. Simms, DAFF, Mossel Bay; *pers. comm.* to R. Cooper, 2011). Research on export markets later revealed this to be true more in terms of price for fresh hake than volumes, see Chapter 3.

The lack of a (documented) comprehensive understanding of the economic aspects of the hake fishery (by all stakeholders) should be concerning since, an inadequate understanding and consideration of economic (in addition to social) factors in fisheries has been identified as a major obstacle to sound management and long-term sustainability of fish resources (Clay and McGoodwin, 1995; Browman and Stergiou, 2005; Folke *et al.*, 2007; Garcia and Charles, 2008; Pitcher and Lam, 2010). Folke *et al.* (2007) go so far as to state that there are underlying economic drivers (as well as social drivers), of the proximate causes of environmental deterioration; proximate causes being issues such as over-extraction of natural resources and pollution. These economic driving forces may include "…*international financial assistance and pressure for structural adjustment, government economic and social policy, … world commodity markets*…" (Folke *et al.*, 2007). The mechanisms by which changes in external drivers affect proximate causes of environmental degradation, including over-fishing, need to be identified and understood (Folke *et al.*, 2007). Some progress towards this has been captured in the sustainability literature. These mechanisms include time-lags, elaborate alterations of broad-scale economic and biophysical signals (Folke *et al.*, 2007). Garcia and Charles (2008) again highlight that economic sciences need to be incorporated in management and make a greater contribution to better understanding fisheries' motivations, processes, perceptions, expectations and reactions.

This is not to say that focus should be drawn away from the environmental aspect of fisheries, but rather that these three dimensions, environmental, economic and socio-cultural, should be integrated if sustainability is ever to be achieved, in line with the goals of an EAF (Garcia *et al.*, 2003). Likewise, Pitcher and Lam (2010) caution that one should *not* assume that economic management strategies (e.g. privatization of fisheries resources through individual transferable quotas or valuation of resources) or 'environmental' management strategies (e.g. single-species management or ecosystem-based management) alone are panaceas for fishery problems. They endorse a balanced approach incorporating ten management strategies, including socio-economic incentives, policy goals, historically based restoration and EAF to allow rebuilding or maintenance of fisheries, ensuring human food security and biodiversity of marine ecosystems.

In short, to effectively manage a fishery it has become increasingly understood that the fishery needs to be managed with *explicit* economic goals in addition to social and ecological goals. For society (via a well-managed decision making process) to be able to determine what these goals should be, a comprehensive, or at the very least an adequate, knowledge of the ecological, social and economic systems surrounding the fishery is required, which, as said, is incomplete for the South African hake fishery. This thesis will begin to address such issues by starting to develop a framework for understanding the drivers of the **economic system** of the offshore demersal hake trawl, its dynamics and feedback loops. This understanding will help to clarify thinking around what **economic objectives** could be for the fishery, which could ultimately help to inform possible management strategies.

2.2. The ecosystem approach to fisheries

The ecosystem approach to fisheries (EAF) is a fundamental framework for fisheries management that has emerged out of the recognition that fisheries influence the environment and vice versa; the EAF's goals and founding principles have largely come from the sustainable development paradigm and its goal for both human and ecosystem well-being (Garcia and Cochrane, 2005). The Food and Agriculture Organization of the United Nations (FAO) technical guidelines define an EAF as "*an ecosystem approach to fisheries [that] strives to balance diverse societal objectives, by taking* *account of the knowledge and uncertainties about biotic, abiotic and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries*" (Garcia *et al.*, 2003). The authors mention that the purpose of an EAF [internationally] is to improve the historically "*poor performance*" of conventional fisheries governance through a number of modifications, and they make specific reference to the importance of both human and ecosystem well-being as central goals (Garcia *et al.*, 2003). Specifically the FAO states that, "[the] *purpose of an ecosystem approach to fisheries is to plan, develop and manage fisheries in a manner that addresses the multiplicity of societal needs and desires, without jeopardizing the options for future generations to benefit from a full range of goods and services provided by marine ecosystems*" (Garcia *et al.*, 2003). Of importance the purpose of an EAF is not to replace conventional fisheries management but merely to build-upon and modify it, so that ecosystems and human social and economic components of fisheries systems are considered, in addition to governance.

A large number of binding political agreements acknowledge the importance of EAF as a management paradigm and set targets for its implementation into governmental policy (Garcia and Cochrane, 2005). These include international agreements, such as the 1971 RAMSAR Convention on Wetlands, the 1982 Law of the Sea Convention, the 1992 Convention on Biological Diversity, the 1995 Fish Stocks Agreement; the 1987 World Conference- & 1992 UN Conference -on Environment and Development; the 2002 World Summit on Sustainable Development (see Garcia and Cochrane, 2005 for a full list), and national agreements in South Africa, such as the Marine Living Resource Act (MLRA) of 1998, which explicitly refers to conservation of the marine ecosystem as a whole and long term sustainable utilization of marine living resources with fair and equitable distribution to all citizens (MLRA, 1998).

There are a range of tools for incorporating the ecosystem approach into fisheries management and these include interdisciplinary modelling. Ecological and economic systems are complex and linked and modelling is one possible tool to deal with them (Costanza *et al.*, 1993). These modelling disciplines exemplify 'systems thinking'; Garcia and Charles (2008) provide a comprehensive review of complex systems thinking and multi-disciplinarity in fisheries. They point out that the current 'scientific challenge' is to find coherence among the economic, social, ecological and institutional sectors through the utilization of all pertinent knowledge (Garcia and Charles, 2008). This thesis seeks to make some headway towards the ultimate objective of unifying thinking and knowledge from these sectors in the hake fishery of the Southern Benguela. It does this through the development of an economic model and understanding of the offshore demersal hake trawl fishery in the Southern Benguela as the first step in an interdisciplinary modelling and holistic approach.

2.3. Modelling as a scientific approach

Modelling is an approach that can be used to test understanding, synthesize knowledge and make predictions (Blackford *et al.*, 2010). Starfield and Jarre (2011) suggest that it is a useful means of conducting interdisciplinary research, since by necessity understanding and modelling of complex systems in which humans and nature interact, e.g. fisheries, requires consideration of both the social and environmental aspects of the system and therefore interdisciplinarity.

Irrespective of discipline, a model is designed to answer questions about a specific (social or environmental) phenomenon the dynamics of which we wish to understand (Gilbert and Terna, 2000; Farmer and Foley, 2009; Starfield and Jarre, 2011). In this way it is similar to the general scientific approach, since it seeks to answer a question, sets hypotheses and then tests/investigates these hypotheses through the development and implementation of a model. The model is built through the process of theoretical abstraction, in accordance with the objectives and question set out, to become a simplified representation of the real world (Gilbert and Terna, 2000; Starfield and Jarre, 2011), see Figure 1.1. The model behaviour is then calibrated with/validated against observations in the real world – social or environmental – to improve/determine the quality of the model output relative to its objectives (Gilbert and Terna, 2000; Farmer and Foley, 2009; Starfield and Jarre, 2011). Models then need to be analysed, tested – including sensitivity and robustness analyses (Grimm and Railsback, 2005), and used to draw conclusions about the system they are investigating. This contributes to the process of best answering the research question through hypothesis testing, much in the same way as scientists collect and analyse data to test their hypotheses. However, models differ slightly from this general approach in that they can be built in the absence of comprehensive (quantitative) data by using qualitative knowledge of structure and functioning of a system (Starfield and Jarre, 2011). This can be a very advantageous means of scientific investigation in situations where data are limited or are too costly and cumbersome to collect. This is typically the case when broad system-level questions are asked, which encompass a wide variety of components and therefore data. In this case, simulation models can also guide and/or prioritise data collection.

As with most scientific approaches there are specific good practice guidelines for modelling. Starfield and Jarre (2011) discuss some of the steps that are crucial to building a good model. These include first setting a clear research question and building the model with this question in mind. Second, identifying the appropriate level of scale and resolution and retaining this throughout the model design phase and, third, developing the model through a system of rapid prototyping in parallel with the development of understanding of the system. It is very important to follow the modelling cycle in the development of any model (Grimm and Railsback, 2005), but also in the use of someone else's model, as Kettenring *et al.* (2006) point out. Grimm and Railsback (2005) provide a good, detailed discussion of how the modelling process should be carried out, which is along the lines of the model development described in the previous paragraph and is illustrated in Figure 1.2.

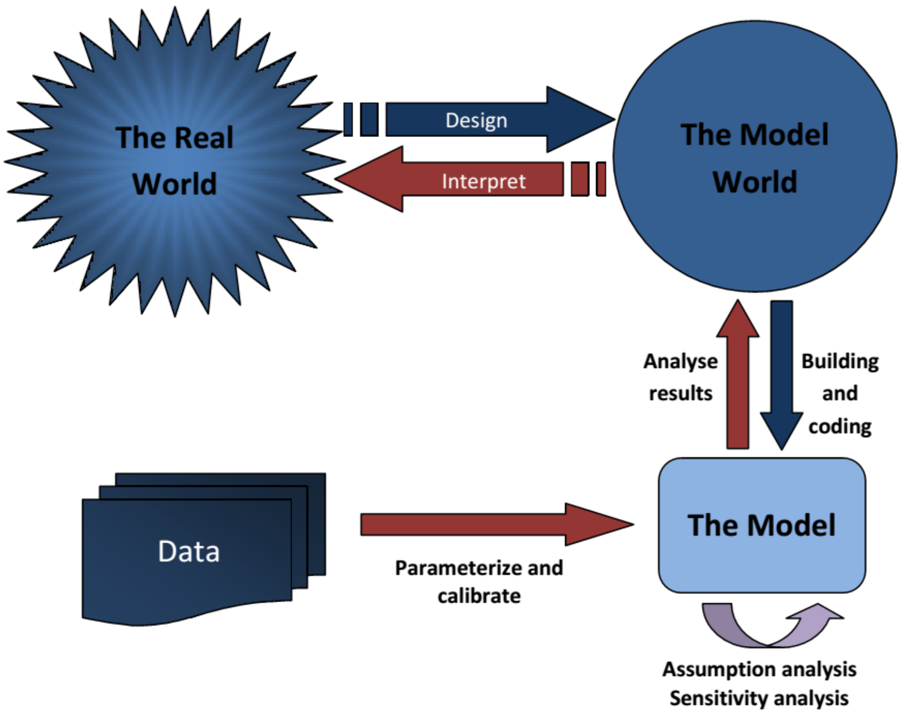

Figure 1.1: The modelling process, after the diagram of Starfield and Jarre (2011).

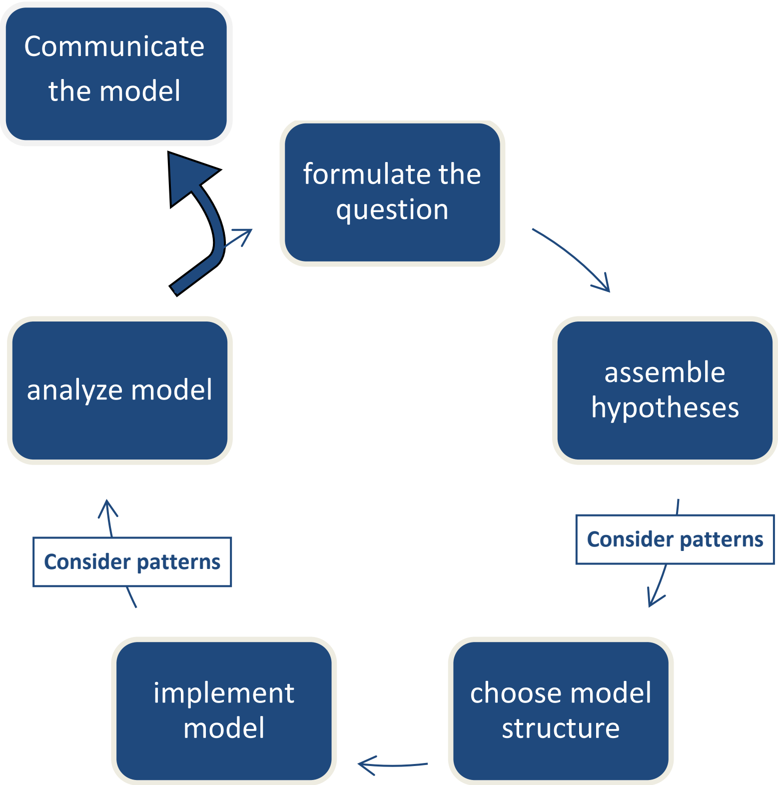

Figure 1.2: The tasks of modelling development cycle after the diagram of Grimm and Railsback (2005; p.27).

Kettenring *et al.* (2006) provide some specific guidelines on the use and development of models, i.e. for the modelling development cycle. They suggest that when a modelling project is tackled it is initially important to decide whether it will be appropriate to use/modify another existing model or to develop a model from scratch. They advise that the basic conceptual exercise of designing a model world be undertaken and understanding developed as to how that model could be used to answer the question at hand. This exercise gives insight into any challenges, advantages or limitations to either building or using a model. In the case where a new model is developed, Kettenring *et al.* (2006) suggest that it is very important to document the model in terms of its operations and uses. They state that this documentation should entail clarification of the models objectives, assumptions, key components, limitations and any essential details. Indeed, according to them, these considerations should be equally implicit in the communication phase of any good scientific approach. Grimm and Railsback (2005) also devote an entire section of their book to discussing the importance of accurately communicating model development and findings, and it can be found as an important step in their depiction of the modelling development cycle (Figure1.2).

In circumstances where an existing model seems to be applicable to the research question, its appropriateness still has to be evaluated with a number of important considerations. Kettenring *et al.* (2006) provide a discussion on evaluating the suitability of others' models and model misuse. They point out that the prospective model needs to first be understood by the user. The points of assessment of the prospective model that they discuss are essentially that i) the objectives of the model correspond to the objectives of the research question, ii) the assumptions of the model are compatible, iii) data type, quantity and resolution are appropriate or available for the new system to which the model is being applied, iv) temporal and spatial resolution between the existing model and the research question correspond, v) the deterministic or stochastic approaches correspond, vi) the prospective model will produce the required output, and vii) the (code of the) prospective model is easy to access and modify. They suggest that it is also very important to have a good idea of how sensitive the prospective model is and whether or not it will be appropriate to the new set of conditions to which it will be applied (Kettenring *et al.*, 2006). Using a pre-existing model presents advantages: i) it reduces time, effort and cost, ii) some/much debugging of the code will already have been done, iii) previous achievements of the prospective model can be cited, iv) technical details of the model have already been reported, and v) successful pre-existing models can increase a study's credibility (Kettenring *et al.*, 2006).

New models being developed for the type of complex environments that operate over a range of scales, the kind with which this study deals, present a number of challenges (Blackford *et al.*, 2010). The methodology of such models therefore needs to be rigorously analysed, along with the results, which need to be carefully interpreted and understood. This is especially true in light of increasing demand for models to be used for management purposes (Blackford *et al.*, 2010). New modelling approaches, from complex adaptive systems and stochastically defined emergent systems, have presented the possibility that model structure could be produced as an emergent property of the system itself; this could be especially useful for complex systems with a multiplicity of scales where model structure is difficult to define (Blackford *et al.*, 2010). Agent- or individual-based modelling can achieve this. Agent-based modelling seems particularly relevant to the complex South African hake fishery system; the social, economic and ecological systems span a range of scales (e.g. Perry and Ommer, 2003; Cumming *et al.*, 2006), are complex adaptive systems and to some extent their structure is difficult to define from the onset of the study.

3. <u>The Economic Model</u>

3.1. The social & economic context

With the aim of implementing an EAF there have been a series of economic studies on hake, and other fisheries, in the Benguela regions carried out for the Benguela Current Large Marine Ecosystem Programme. BCLME (2006c) looked at whether beneficiation (value-adding) processes could be used to improve the profitability and benefits of the hake fishery, among others, to communities of the Benguela region, and concluded that for hake the applicability and type of beneficiation processes depended on fish size, quality and freshness and the fishing method applied to catch the fish (BCLME, 2004; BCLME, 2006c). Findings of a further comprehensive micro-economic analysis of the hake fishery for South Africa were that the economic risk profile of the fishery had been increased by the restructuring of the fishery that occurred during the 1990s and early 2000s (BCLME, 2006b).

Economic considerations can have a large impact on both the way the fishery is structured and the way that the resource is harvested. For example, BCLME (2006b) point out that the way a resource like hake is fished is affected by contracts between companies and their employers and financers and between processors and retailers, including foreign buyers. Thus to understand the underlying economic and social drivers of resource use and system change as Folke *et al.* (2007) point out, it is first necessary to understand these underlying economic and social structures and their dynamics.

3.2. Agent-based modelling

Management choices in terms of social and economic arrangements may sometimes lead to unintended social and economic consequences for different parts of the industry and for the way the resource is used. In other words, policies implemented at the individual level can lead to unintended or unexpected consequences at the system (fishery/resource/ecosystem) level (e.g. Ommer and Team, 2007). Systems that display this characteristic are frequently referred to as complex systems. Indeed Costanza *et al.* (1993) point out that economic systems, like ecological systems, are complex, since they represent systems in which the whole is greater than the sum of its parts and simply aggregating the behaviour of the parts does not represent the true nature of the system as a whole. Agent-based modelling (ABM) provides the possibility to model such complex systems where simple, rational choices at the level of individuals, can sometimes lead to unintended and often unexpected emergent consequences at the system level.

Agent-based modelling is a comparatively novel method of examining human-environment interactions. Where traditional approaches have failed to take into account individual-level information, complexity, interdisciplinary and cross-scale perspectives on data and methods, agent-based models have succeeded, giving them greater predictive and explanatory power (An *et al.*, 2005). This ability to deal with such discipline- and scale-crossing problems emerges from the fact that much of the development of ABMs (also called multi-agent simulations) has come from interdisciplinary work (Bousquet and Le Page, 2004). Levin *et al.* (1997) suggest the use of mathematical and computational approaches, of which ABM is an example, to answer biological questions. Similarly, Bonabeau (2002) discusses their applications to the social sciences. Bousquet and Le Page (2004) discuss how the ABM approach is appropriate to environmental or ecosystem management issues, where the interactions between social and ecological dynamics should be considered.

Levin *et al.* (1997) state that ABM approaches are powerful tools that can offer a structure for synthesis and analysis, directing empirical studies and expanding understanding of nature. Agent-based models can be applied to systems, e.g. ecosystems, for predictive purposes under different hypothetical future conditions, such as climate change, and as tools for examining hypotheses on mechanisms underlying system processes such as ecosystem processes or the preservation of biodiversity (Levin *et al.*, 1997). The advantages for using computational models like ABMs to understand systems are that the stochastic nature of complex systems is acknowledged, local and individual characteristics can be included in models, and it is possible to model how the activities of elements (e.g. individuals) at one scale (or level) have impacts on the patterns observed at another scale (Levin *et al.*, 1997; An *et al.*, 2005). ABMs are also suited to interdisciplinary – social, environmental and economic – analyses of future scenarios such as global environmental change, since such scenarios are complex, bottom-up, have socio-economic as well as environmental consequences and require novel modelling of integrated social and ecological systems, which ABMs are capable of (Hare and Deadman, 2004).

ABMs have been used in a wide variety of economic applications, from resource economics and supply chain management to modelling the entire European economy (Deissenberg *et al.*, 2008; Fuks and Kawa, 2009; Kawa, 2009; Nolan *et al.*, 2009; Nair and Vidal, 2011). Unlike the more traditional and sometimes limited analytical economic models, they allow the modelling of heterogeneous economic agents and as such represent a new and alternate way of modelling and understanding economic systems (Deissenberg *et al.*, 2008). This may be especially advantageous in modelling the economics of resource-extraction systems, such as fisheries, where not only are the economic agents heterogeneous but where environmental heterogeneity also plays an important role (Nolan *et al.*, 2009).

Despite these advantages ABMs have not often been applied to the economic aspects of fisheries, and this represents a significant area for potential future development. Previous applications in fisheries have been largely centred around the topic of understanding fleet dynamics (Little *et al.*, 2004; Soulié and Thébaud, 2006; Schafer, 2007; Wilson *et al.*, 2007; Yu *et al.*, 2009a; Bastardie *et al.*, 2010; Cabral *et al.*, 2010). These have provided some extremely useful insights into fleet behaviour and the way that resources are used. For example, Boschetti and Brede (2009) examined how competitive versus collaborative fishing strategies prevailed under different scenarios of fish abundance. One paper has taken the fleet effort allocation scenario a step further and examined how individual transferable quotas affect a multi-species, multi-sector fishery in terms of fishing fleet behaviour, discarding, catch-levels, profitability and so forth (Little *et al.*, 2009). Another study examined the trade-offs and potential social and ecological impacts of multiple sector, including fisheries, use of a coastal area for the purpose of integrated regional planning and management of marine and coastal systems (McDonald *et al.*, 2008).

Generally, ABMs have been more widely applied in agricultural resource economics, with some interesting applications, including value chains (Ameden *et al.*, 2009; Filatova *et al.*, 2009; Ross and Westgren, 2009). Rich *et al.* (2011) suggest that ABMs provide a useful tool for improving value chain analysis in agricultural livestock markets, since ABMs can depict complex, macro-level patterns of behaviour that emerge from non-linear interactions, path dependence, stochasticity and system feedback. They suggest that this also applies to system dynamic (SD) models and that a choice between ABMs and SD models should depend on the specific application. ABMs do provide an advantage over SD models in that they can capture how individual behaviours of a set of heterogeneous agents can result in emergent patterns at the macro-level, while SD models use a set of homogeneous agents (Rich *et al.*, 2011). A more detailed review of very specific ABM applications related to value chains, which were not directly relevant to the present study, can be found in Rich *et al.* (2011). The application of ABMs to the social (economic) model of the hake fishery seems appropriate since I am interested in emergent patterns in the fishery that result from the local, heterogeneous individual behaviours of companies or vessels under different economic and natural environment scenarios.

At its core producing an ABM involves the modelling of a system as an aggregation of agents (or individuals in Individual-Based Models – IBM's), which represent independent, heterogeneous, decision-making entities that interact with each other and their environment (Bonabeau, 2002; An *et al.*, 2005; Grimm *et al.*, 2006; Farmer and Foley, 2009). Agents are adaptive, consider the conditions independently, make decisions based on a set of rules and then execute appropriate behaviours based relevant to the system under consideration (Bonabeau, 2002; Farmer and Foley, 2009). The agents interact with each other and the environment in which they occur (which can be the economic, social, and/or ecological conditions), in some cases modifying each other's behaviours and interactions with the environment and frequently modifying and responding to changes in the environment, and can produce complex, emergent and sometimes unexpected patterns / phenomena at the system level. In some (typically more complex) ABMs, agents can also have properties such as 'intelligence', self-awareness, independent actions and awareness of the environment and other agents, and capable of adaptive or evolved behaviour (Bonabeau, 2002; An *et al.*, 2005; Farmer and Foley, 2009).

Two other advantages are that ABMs are adaptable and allow for a more natural portrayal of a system (Bonabeau, 2002). The more natural portrayal of a system is an important advantage in the context of this study and may therefore make ABM ideal for modelling the fisheries social system, since, as Bonabeau (2002) points out, ABMs model an organization or social structure from the viewpoint of individuals within the organisation and do not attempt to model broad-scale processes directly. Instead the processes are generated through the interactions of individual activities and provide a useful pattern to check the emergent properties of the model system against. It is also easier for people in a social structure, such as company representatives, to describe to the modeller what they do, rather than explaining a process (Bonabeau, 2002). Additionally, the flexibility of ABMs mean that agents can be added to the model and their level of complexity can be adjusted according to their behaviour, level of rationality, aptitude to learn and evolve and the rules of their interactions and that the degree of description and aggregation of agents can be changed. This means that ABMs are ideal for use in a system where the level of complexity and aggregation is not fully known at the outset of the project (Bonabeau, 2002), as is the case with the economic system of the hake fishery.

There are also some potential problems with the application of ABM to human social and economic systems, although most of these considerations are also applicable to ABMs used in most fields. The ABM needs to be directed at a specific question with the appropriate level of detail and scale. If the ABM is very large it will require a large degree of computing power and some time to run, since it is composed of many agents with different behaviours, characteristics and interactions (Bonabeau, 2002), although present advances in computing power have reduced this problem significantly. In the social sciences, an ABM may have to deal with “soft factors”, e.g. irrational behaviour, subjective decisions and complex psychology of humans, which can make it difficult to quantify outputs of the model and in some cases may only allow for qualitative outputs. Nevertheless it has been suggested that ABMs are the only type of model appropriate for dealing with such soft factors (Bonabeau, 2002).

Nolan *et al.* (2009) provide a good discussion of the merits and challenges for the use of ABMs in agricultural resource economics. The advantages include i) the ability of agents to interact in a simulated market as opposed to simply aggregating individual supply and demand functions into market supply and demand functions, ii) the ability to model systems where economic equilibrium does not occur, as opposed to assuming equilibrium as is generally done in traditional models, iii) the assumption that agents operate in conditions other than full rationality, i.e. they operate in bounded rationality, which means that they have imperfect information, resources and computational abilities, iv) agents having the ability to learn and adapt to their environment and to develop profit-maximizing behaviours, and, as discussed earlier, v) the ability of the model to produce emergent, macro-scale properties of economic systems, such as resource use (patterns) over time, resource distributions and market clearing prices, from the interactions of agents at the micro-level. Some of the disadvantages include, i) depending on the viewpoint, the lack of full rationality of agents, ii) the inapplicability of standard analytical methods, such as comparative static analysis, due to the assumption of non-equilibrium means that the behaviour of the modelled system is problematic to wholly characterise, and related to this iii) the shortage of tractable analytical techniques (Nolan *et al.*, 2009). Nolan *et al.* (2009) conclude that despite these shortcomings ABMs present an overriding set of benefits in terms of the wide scope of research questions that they can be used to explore.

3.2.1.Consideration of other pre-existing models

Before embarking on the design of my own agent-based model I considered a number of pre-existing models for their possible application to my research question.

MEFISTO (Mediterranean Fisheries Management Tools) is a multi-species, multi-gear and multi-fleet, bio-economic simulation model, which aims to model the bio-economic conditions in which the fisheries occur (Lleonart et al., 2003). It details species that contribute to the economy of a fleet of vessels; this includes primary species for which the population dynamics are known and secondary species for which they are unknown. The model converts catches of these different species to revenue and models the revenue of each vessel, which then determines whether the vessel will increase or decrease its effort and/or investment, or leave the fishery at the next time step (Lleonart *et al.*, 2003; Mattos *et al.*, 2006). The objectives of the original model were to replicate the fishing conditions distinctive of the Mediterranean and to simulate alternative management strategies (Lleonart *et al.*, 2003). The assumptions are outlined in Lleonart *et al.* (2003); of importance is the assumption that catchability dictates fishing mortality, as vessel fishing effort remains fixed. This may not be the case for the South African hake fishery. The temporal resolution can be set from a week to a year and the model can be set to be stochastic or deterministic (Lleonart *et al.*, 2003). It has been applied to the European hake (*Merluccius merluccius*) fishery in the Mediterranean and to the Pernambuco State hand-line and gillnet fisheries in north-eastern Brazil, where it was used to examine the effect of fuel prices (Lleonart *et al.*, 2003; Mattos *et al.*, 2006). It was also applied to examine the interaction between trawlers and beach seiners in the Saronikos Gulf in Greece (Merino *et al.*, 2007), and to examine the effect of fuel price and fishing period length on the sustainability of the small pelagic fishery in the northern Adriatic sea in north-eastern Italy (Silvestri and Maynou, 2009).

ISIS-Fish is a grid-based simulation model that is spatially and seasonally explicit and is used to evaluate the performance of temporal and local management using seasonal and spatial control variables to regulate fishing (Mahévas and Pelletier, 2004). It is based on three sub-models of fisheries population(s), exploitation and management that interact within a fishery that is mapped on a regular grid (Mahévas and Pelletier, 2004). A more detailed description can be found in Mahévas and Pelletier (2004). It was updated by Pelletier *et al.* (2009) to include a bio-economic component that allowed the quantitative bio-economic evaluation of management scenarios. Revenues from fishing are considered at the level of the vessel owner, fishing crew and vessel and the fishing trip. It has assumptions that may be adapted to suit different fisheries and as such constitutes a generic model (Pelletier *et al.*, 2009), unlike MEFISTO.

InVitro is an end-to-end agent-based model that overtly models human behaviour and various coastal industries (Fulton, 2011). It has been used in a number of applications including evaluating management strategies for areas of the coastline that are used by a variety of sectors including oil and gas, fisheries, urban and industrial development and conservation (McDonald *et al.*, 2008). It examines management actions, but also different model assumptions and structures (McDonald *et al.*, 2008). InVitro is composed of sub-models of coastal bio-physical and anthropogenic activities (McDonald *et al.*, 2008).

MEFISTO seemed to address issues related to my research question, but appeared specialised to the Mediterranean fisheries (although it has been applied elsewhere). And, like ISIS-Fish, was set largely at the level of the fishing vessel. It did not consider the possibilities of vertically integrated economic structure in the fisheries (i.e. vessels belonging to processing companies, and so forth), which is important in the South African offshore demersal hake trawl fishery. There were therefore some disparities between the model assumptions and objectives and those of my thesis. As discussed in section 2.3, it is important that these correspond. InVitro seemed to be a very broad scoping model that was complex and concerned with coastal management issues that spanned beyond the scope of fisheries alone and its documentation, objectives and assumptions were slightly vague or contained in technical reports which would not be easily available. Therefore, none of these models seemed ideally suited to the nature of my project and following the advice of Kettenring *et al.* (2006) it seems better to develop a new model more appropriate to my research question.

3.2.2.Designing an agent-based model

Grimm and Railsback (2005) suggest that the design of an agent-based model should follow the standard modelling process. Firstly, it needs to be realised that the model is a simplified version of the real system with assumptions, simplifications. It is developed under constraints and should be designed for a specific purpose, i.e. to meet specific objectives (Grimm and Railsback, 2005; Starfield and Jarre, 2011). The first step is therefore to specify objectives and constrain the model by these. Secondly, a conceptual model needs to be created where the hypotheses of essential processes and structures can be tested. Scales, state variables, processes and parameters need to be chosen and carefully stated as these will define the structure and dynamics of the model (Grimm and Railsback, 2005). For agent-based models the state variables and parameters should describe the state of individuals and their behaviour and the variables and parameters should describe the environment of individuals. These should all be placed within the correct scale in terms of both the spatial and temporal extent and resolution (Grimm and Railsback, 2005). Following this model implementation, analysis and communication can follow in the modelling cycle iterations (Grimm and Railsback, 2005).

Macal and North (2010) suggest that agent-based models need to have three essential components: an environment that agents can interact with and in, a set of agents with traits and behaviours and a set of agent interactions and the means of interaction. They go on to describe the essential characteristics of agents from a practical modelling point of view; agents need to: i) be self-contained, ii) be autonomous and self-directing, iii) have a state that changes over time, and iv) be social, i.e. interact with and adjust behaviour according to other agents. They also suggest some additional and potentially practical agent attributes: adaptive and goal-directed behaviour and heterogeneity within the agent population. Agents are generally associated with traits and methods; the latter includes behaviours or representations that connect the agent's circumstances with its behaviour (Macal and North, 2010).

3.3. What type of modelling platform is appropriate?

ABM structure is diverse and includes everything from simple, academic models to massive, detailed and validated decision support models of an entire system (Macal and North, 2010), thus it is not surprising that there are a diversity of ways to implement these models. The question is then what software development environment will be most appropriate to build the ABM of South Africa's hake fishery? This question is difficult to answer, given the diversity of agent-based modelling platforms available, in addition to the possibility to build models from scratch, and given that there is more than one appropriate way to build an agent-based model. Macal and North (2010) provide a good review of ABM implementation and the various approaches available, and Railsback *et al.* (2006) provide a comparison of some of the major ABM platforms, which is outlined here.

After excluding the idea of building a model from scratch, which Grimm and Railsback (2005) recommend avoiding if a model can be built in an already existing platform and Macal and North

(2010) warn is extremely costly, I narrowed down the choice of platforms to three potential candidates. There were many platforms to initially choose from, such as AnyLogic, CORMAS, GAMA, Janus, NetLogo and RePast Symphony. I reviewed many of these, but only discuss the final three that I seriously considered for implementation here[3]. The choice of the three was mainly based on the ease of use for a non-expert programmer, the capability of the software platform to support the type of model to be built, the track record of previous software applications, the availability of user support groups and the affordability. These three modelling platforms were: NetLogo, RePast Symphony and CORMAS, which are all free, open-access software packages.

Each of these modelling platforms provides an example of one of the three different, approaches that ABM platforms commonly use to implement models (Macal and North, 2010). Firstly, in the integrated development environment (IDE) approach, model structure is organized by writing/editing code in a program, which may either be a single file of code, structured one line beneath another as in NetLogo, or a set of files as in Eclipse. This approach is easy to learn, but limited in scope to smaller, less complex models. Secondly, in the library-oriented approach, to build a model the modeller calls a series of functions from a library of routines that are arranged into an application programming interface or API using the modelling tool kit. This approach provides much flexibility in the way that models can be defined and includes approaches such as RePast for Java. The third approach combines elements of the other two in a hybrid and includes such platforms as RePast Symphony and AnyLogic. In this approach either the stand-alone library may be used or it may be used as a factored multiple-file IDE. This approach can be more easily expanded to large scale models, but it does require more specialised computing/programming skills to use (Macal and North, 2010).

The first modelling platform that I reviewed was NetLogo. As mentioned above this platform is easy to learn to use, but is limited to simpler applications of models and can become problematic to build and edit as models become larger since all of the code for the model is in a single continuous text file which then becomes long, complicated and easily disorganized (Railsback *et al.*, 2006; Macal and North, 2010). Railsback *et al.* (2006) do, however, suggest that NetLogo may have a wide range of applications and may be suitable for prototyping very complex models. These include use in general

[3] This discussion of agent based modelling platforms and software is by no means exhaustive. A useful summary of the different agent-based software available, including links to the individual support pages for each of the software packages, which provide much more detailed descriptions, is available at https://en.wikipedia.org/wiki/Comparison_of_agent-based_modeling_software.

ecology, resource and land-use management, economics and fisheries, see for example (Grimm and Railsback, 2005; Schafer, 2007; Filatova *et al.*, 2009; Fuks and Kawa, 2009; Kawa, 2009). One disadvantage of NetLogo is that it does not distribute its source code (Railsback *et al.*, 2006). The implication of this in practical use is that one is limited to building models using the commands that NetLogo comes built to recognize. All other non-default commands must be built using the commands in NetLogo.

Cormas (Common-pool Resources and Multi-Agent Systems) is a platform developed by researchers at CIRAD (centre de coopération internationale en recherche agronomique pour le développement) in France that is run on the VisualWorks programming environment and uses the object-oriented programming language SmallTalk (Bousquet *et al.*, 1998). Objects or individuals within a model can be created from generic classes in SmallTalk through adaptation and enhancement (CIRAD, 2007). There are suitable algorithms and structures that allow the creation of links between and among agents and their environment and that allow the generation of societies or hierarchies of agents, where agents can be individuals or at a higher level of organization, such as villages or companies (Bousquet and Le Page, 2004). Cormas, like RePast, is a platform developed with suitability for the implementation of social dynamics and its interaction with natural resource dynamics and allows the simulation of resource management problems (Bousquet and Le Page, 2004). Cormas is a complete tool for the building of models of social or ecological systems and it has spatial capabilities, functions for implementing Monte-Carlo-type methods and the ability to be linked to other software packages such as Geographical Information Systems and databases (Bousquet and Le Page, 2004). It has been applied to a range of different resource management and other economic applications, for example to model the emergence of resource-sharing conventions (Thébaud and Locatelli, 2001), to model of a water catchment in Thailand and farmers decisions (Becu *et al.*, 2003), to examine duck hunting and associated land-use management trade-offs (Mathevet *et al.*, 2003), and explore social and economic choices/behaviours of Sahelian farmers in Nigeria (Saqalli *et al.*, 2010). It has also been applied in fisheries in the examination of fleet dynamics (Soulié and Thébaud, 2006). This modelling platform would have proved a viable option for building the ABM of South Africa's hake fishery. Unfortunately, despite trial and error and communication with its developers I could not get Cormas to run appropriately in standard, modern operating systems (e.g. Window's X-versions) at the time of model development and there appeared to be underlying errors in the programs operation when attempting to run it. This lack of flexibility with modern operating systems was a definite limit to Cormas, especially for sharing of models and for linking-up with other programs and analysis tools. This practical challenge coupled with the fact that the SmallTalk language could potentially have some limitations that could not be discounted without thorough testing of the programme led to the decision to abandon this approach.

Finally, RePast Symphony 2.0 Beta, the current version at the time of the modelling platform assessment, was considered. This package was released as the most updated version in 2010. According to RePast's website this platform was a Java-based modelling system and was compatible with most operating systems. This recent edition had the advantage of allowing models to be developed in several different forms – using the Java, ReLogo or Groovy languages or point-and-click flowcharts – which are easily interwoven. The ReLogo language was related to the Logo language used in NetLogo and meant that NetLogo models could be imported. RePast symphony has been applied to a range of fields including supply chains and social science (Argonne National Laboratory, 2011). RePast has also been applied to a variety of social and economic applications, such as modelling markets (López-Sánchez *et al.*, 2005; North *et al.*, 2010), land-use in agricultural systems (Bert *et al.*, 2011), and supply chains (Valluri *et al.*, 2009), for a good review see Macal and North (2010). I found the RePast Symphony package interface generally straightforward, although it became clear that developing a model in RePast required a great deal more computing skills than a simple interface like NetLogo (Nolan *et al.*, 2009; Macal and North, 2010). Further, Railsback *et al.* (2006) cautioned that there are a number of questionable design features in RePast (at least the version available circa 2006, see paper for details) and that basic documentation of the software was incomplete. Obtaining adequate support and guidelines for RePast proved challenging and this platform was abandoned as unsuitable for the thesis within the given constraints.

Netlogo was selected as the modelling platform with which to implement the prototypes of the economic agent-based model, since it was found to be well-suited to a prototyping approach and a good learning platform for first time programmers. Furthermore, it was well supported with courses, online user groups and a recently published textbook on its practical use in model development (Railsback and Grimm, 2011). For the prototype economic model versions developed in this thesis the level of complexity for the model does not become severely limiting. More complex later prototypes, beyond the scope of those developed in this thesis, may need to be re-implemented in more flexible platforms or independently through the use of a coding language.

4. Thesis objectives and structure

This section gives a brief overview of the objectives and layout of the thesis.

The main objective of the data collection and model development in this thesis are to answer the following broad questions:

1. How does the market of hake function and how does hake flow from resource extraction to export market? In other words how is the hake fisheries system structured within South Africa?

2. How do consumer (i.e. market) preferences / national and international market relations affect the quantity of fresh and frozen hake targeted?

3. What are the relative effects and trade-offs of different costs and revenue sources for the fishing industry, such as fuel price, exchange rate, market value, quantity of fish demanded, total allowable catches and catch per unit effort? What does this mean for ability to catch fish and profitability?

4. Following from the model findings, what then appear to be the most important drivers of the fishing industry and what further conclusions can be drawn for further research and/or what recommendations can be made?

To speak to these objectives and to follow the good-modelling practice described above, the thesis layout will attempt to follow standard modelling practice and the model development cycle as summarised earlier in Figure 1.1 and 1.2.

In this the first chapter of the model the context to the modelling process is given, including some description of the real world and some of the questions and problems that define the purpose of building the model. In the second and third chapters, data are collected from the real world through stakeholder and expert consultation and from national and international databases. These data serve to refine understanding of the real world and speak to the above questions, providing a more solid understanding of the hake industry in South Africa. The data collected also informs the design of the model world for later chapters and provide the means with which to parameterize and calibrate the model. Chapter 2 examines the industry structure and Chapter 3 its function, with particular reference to exports.

In Chapter 4 the first prototype of the model is designed (i.e. the model world is refined) based on Chapters 2 and 3 and ongoing stakeholder consultation. It is then implemented into software using the Netlogo 5.0.1 programming platform, and it is thoroughly tested, including sensitivity analysis. This first prototype includes a number of important and simplifying assumptions that are made in order to allow it to be carefully developed, tested and understood. Following thorough testing and confidence in the initial model version, an analysis is made of the consequences of relaxing some of the major assumptions made in the first prototype one at a time. This is done in the assumption analyses of Chapter 5. In Chapter 6, an additional level of complexity is added to the model to allow for the central questions of the thesis to be addressed through testing a variety of scenarios. These chapters therefore represent an example of the rapid prototyping approach described in Starfield and Jarre (2011), wherein complexity is incrementally increased in the model and each iteration of the model cycle is carefully carried out with thorough testing and refining of model objectives, hypotheses and design. Finally, in Chapter 7, the results of the data chapters are collectively examined to provide a picture of the South African hake fishery with special reference to the offshore demersal trawl sector. Specifically, the central questions and findings of the thesis are discussed and limitations and areas for future developments and possible applications of the model (and research) are identified.

Throughout the thesis special effort was made to follow general good modelling practice. Considerations specific to agent-based models have been followed and documentation has been completed appropriately, in line with internationally recognized standards and protocols (Grimm and Railsback, 2005; Grimm *et al.*, 2006; Grimm *et al.*, 2010; Macal and North, 2010). The Overview, Design concepts, and Details (ODD) description for *HakeSim* can be made available by the author of this thesis upon request.

CHAPTER 2:

AN ANALYSIS OF THE STRUCTURAL ATTRRIBUTES OF THE OFFSHORE DEMERSAL HAKE TRAWL FISHERY IN SOUTH AFRICA

Chapter 2: An analysis of the structural attributes of the offshore demersal hake trawl fishery in South Africa[4]

1. Introduction

The hake fishery, as described in Chapter 1, is composed of four fishing sectors that operate at different depths and locations and with different gear types, targeting varied sizes of *Merluccius capensis*, *M. paradoxus* or a combination of the two species. They also harvest and sell bycatch, sometimes called joint product, of high-value species such as kingklip (*Genypterus capensis*) and monk (*Lophius vomerinus*) (Bacela *et al.*, 2003), as well as lower-value species such as Jacopever (*Helicolenus dactylopterus*) and Snoek (*Thyristes atun*). The offshore hake trawl sector constitutes the bulk of the hake catch by volume (Rademeyer *et al.*, 2008a). It also accounts for the majority of hake export value and volume, particularly of frozen hake. Additionally, interviews with industry and government stakeholders[5] have indicated that the handline and longline sectors have been particularly hard-hit by a combination of the international banking crisis of 2008 and subsequent recession in global markets and elevated fuel costs. In the case of longline a stronger Rand and diminished international demand for high-value fresh hake was said to lead to a lowered hake market price and decreased revenue. For both the longline and handline sectors increases in the international fuel price dramatically increased fishing costs in the study period and the years directly preceding it. This was said to have led to the volumes and values of these sectors' catches having decreased in recent years. One would expect, therefore, that the offshore trawl sector has an increasingly dominant role in the hake industry. Added to this, is the fact that most of the large conglomerate companies hold rights or catch-share agreements with rightsholders from the longline and particularly the inshore trawl fishery sectors. This means that examining the main offshore trawling companies will account for the bulk of the hake caught and sold by South African hake fishery and its main structure and functioning. This should provide a description of the 'real world' and suitable information (including data) to begin appropriate model development (i.e. model design).

[4]This chapter was also modified and some of its contents, with additional material, were presented in a publication by the author, Cooper, R., Leiman, A., and Jarre, A. 2014. An Analysis of the Structural Changes in the Offshore Demersal Hake (*Merluccius Capensis* and *M. Paradoxus*) Trawl Fishery in South Africa. *Marine Policy*, 50, Part A: 270-279. DOI: http://dx.doi.org/10.1016/j.marpol.2014.06.006. This chapter largely focuses on the content of the paper as it relates to the modelling process described in this thesis.

[5] see Chapter 3, section 2.2 for industry interview details

For modelling purposes (of the economic ABM) the offshore trawling sector of the hake fishery will therefore be assumed to represent the bulk of fishing behaviour in the model. For this reason it is critical to understand both the structure (this chapter) and function (Chapter 3) of this hake sector to produce the best possible prototype of the model in the thesis and for iterating the model into a more realistic version in future. Within this context, there are two phenomena that are thought to be important in the industry structure: vertical integration of companies and horizontal clustering (or consolidation) of rightsholders.

For much of South Africa's fishing history a few large companies dominated the offshore hake trawling industry, before the 1960's it was essentially just Irvin & Johnston (Bacela *et al.*, 2003). Many of these companies have been vertically integrated, i.e. harvesting, processing, marketing and mostly distributing their own fish products, for a long time. Vertical integration has been thought to improve their long term viability and profitability through economies of scope and scale that reduce risk and improve company profits (BCLME, 2006b). Bacela *et al.* (2003) have even gone so far as to state that ongoing profitability and survival of companies over the long term has only been achieved by those who focused on processing and distribution of their products, for little money is available in catching alone. Some authors suggest that these vertically integrated companies can also pose a challenge for new companies to enter the industry (Raakjær and Hara, 2006); new companies also struggle to derive the full profits potentially available in their products if they were to have the economies of scope and scale to similarly process or market products (BCLME, 2006c). Nevertheless there are still a diversity of business models within the offshore sector, spanning from the highly vertically integrated to the simple catch-and-sell operation (Crosoer *et al.*, 2006). Almost all of these companies, or rightsholders have organized themselves into the South African Deep Sea Trawling Industry Association (SADSTIA) and still actively participate therein (Raakjær and Hara, 2006). For the sake of realism, or at least the context thereof, it is important to identify to what level the industry is currently vertically integrated and the diversity of strategies (or behaviours) of processing, marketing and so forth within the industry.

Interview-based and written reports from industry[5], along with other mentions in the literature, suggest that in addition to this vertical integration in the industry what can be described as 'horizontal clustering', in which new entrants or existing companies have merged, been absorbed by or otherwise (via leasing or joint venture contracts) joined to separate companies, also occurs (Crosoer *et al.*, 2006; Raakjær and Hara, 2006). Crosoer *et al.* (2006) suggest that the historical shift to export production in the South African fisheries as a whole may have driven concentration of ownership within the fishery in the past. In recent decades, Raakjær and Hara (2006) suggest that rightsholders (in the demersal and pelagic industries) that owned small quanta practiced vessel sharing with other small quota holders, by entering into catch, processing, or marketing agreements, such as joint ventures with larger companies, or by selling their rights. As a result of this, the number of functional 'clusters' and/or companies (i.e. functioning, fishing businesses or entities) within the industry has changed through time. In the context of the model this means that the number of functional company-entities within the industry is likely *not* equal to the number of active rightsholders or companies. No detailed reports or descriptions exist on the exact structure or even numbers of clusters in the offshore trawling sector to inform the number of entities in the economic agent-based model (ABM). Aside from clustering and vertical integration, details of the offshore trawling industry's fleet and post-harvest operation and structure are also significant to the model design. Some of these details are already known and easily available from existing reports and are summarized here.

The offshore sector, which is both capital and labour intensive, employed around 8600 people in the early 2000s of which about two thirds were land-based. Bacela *et al.* (2003) put these figures slightly lower for the 2000 to 2001 period at 7667 employees. Of these, 1880 employees were sea-going and the remainder were largely shore-based (1449) and processing workers (3889) with an additional small number of marketing (133) and administrative staff (316). All employees tended to be permanent and formally employed labour with benefits (Bacela *et al.*, 2003). Offshore trawl companies owned either wet-fish stern trawlers in which fish are kept refrigerated on ice and landed fresh, factory stern trawlers (also known as freezer stern trawlers) in which fish are highly processed and stored in on-board freezers and fish is landed frozen, or a combination of the two vessel types (Bacela *et al.*, 2003; BCLME, 2006a; Raakjær and Hara, 2006). All stern trawlers may by law only fish offshore trawl rights in waters deeper than 110 m (see table 2.1 for details), as the inshore trawling has rights to fish in depths less than this. Fish caught on offshore vessels are either processed at sea (in the case of factory ships; i.e. sea-frozen product), or processed and value-added in land based facilities and then sold to the domestic and/or export markets (BCLME, 2006a; Chapter 3, this thesis).

Despite the existence of some good quality data, however, much of the information in the reports cited above is unfortunately outdated. Information such as capacity of vessels, how they are used, their build-date and so on does not date so badly and may still be relevant, particularly since no new or second-hand vessels have been purchased or introduced to the industry in well over a decade. However, data such as the number of active vessels, a potentially important factor for the model structure is reported to have changed significantly through time. Similarly, data on the level of processing or the types of product outputs and the diversity or variation of this between fishing companies are not well described.

Given the above this chapter seeks to serve two purposes:

1. To describe changes in the company clusters through time and the overall structure of the industry in order to be able to produce a model prototype with some realism of structure, or *at least* to provide awareness of the actual structure so that later iterations of the model could be made to be more realistic and so that simplifying assumptions in the first prototype could be identified.

2. To collect and present additional data on the offshore demersal hake trawl fishery, with the aim of providing a more comprehensive picture of the present overall structure of the industry that can be contextualised within historical and existing studies.

Table 2.1: Aggregated data on the hake offshore demersal trawling fleet, adapted from table 2.3 in BCLME (2006a) (abbreviated as BCLME) and table 2.5 in Bacela *et al.* (2003) (abbreviated as ESR) and from the texts of both documents. More detailed information can be found in these reports. Data are presented as mean values ±standard deviation (SD) or with their range.

Characteristic	Total Fleet		Freezer vessels		Wet-fish vessels	
	BLCME	ESR	BCLME	ESR	BCLME	ESR
Length (m ± SD) or (m range)	42.9 ± 12.3	49 (20.7 - 90.6)	49.8 ± 14.0		39.2 ± 9.6	
GRT (tons ± SD)	647.6 ± 519.6		906.7 ± 713.6		507.7 ± 302.6	
Horsepower (kW ± SD) or (kW range)	1097.4 ± 578.5	1464 (582 – 3600)	1317.6 ± 724.2		976.1 ± 443.3	
Crew (± SD)	30.9 ± 14.8		40.0 ± 18.6		26.0 ± 9.3	
Construction Year (± SD)	1977.4 ± 11.6		1977.6 ± 13.6		1977.3 ± 10.5	
From the text - no of vessels	81	61	23 (+ 4 com*)	21 (+ 4 com*)	54	36
Average (range) number of sea days per annum		191.2 (11 – 291)				
Average (range) catch per sea day (nominal tons)		13.3 (4.2 – 25.4)				

* combined vessel which can act as either wet-fish or freezer trawler vessel

2. Methods

A copy of the long term rightsholder successful applicants from 2006 for offshore trawl was downloaded from the Department of Agriculture, Forestry and Fisheries (DAFF) repository of public information. Rightsholder information was then sorted to determine whether rightsholders shared any sort of administrative information such as contact details or contact person, and whether they had any vessels in common. This was to determine whether several rightsholders constituted a cluster. The SADSTIA webpage, which indicated how its members (i.e. rightsholders) might be grouped, was also consulted. Any possible associations between rightsholders in the offshore sector were then used to generate a preliminary cluster diagram to represent how they may be organised to do business together (Appendix 1). The resulting 'structure' of the industry was then put through qualitative review with a representative of the deep-sea (i.e. offshore) hake trawling industry for comment and clarification in early 2013.

As an outcome of the consultation process industry data were provided on quota allocated to companies over time, associations or amalgamations of companies and company vessel ownership that were current at the time of the interview[6]. The cluster diagram and information was then updated to reflect these data, producing a more accurate snapshot of the existing business arrangements within the industry. The quota allocated to each rightsholder was calculated as a percentage of the *total* quota for the entire offshore trawl fishery. The (%) quotas of individual rightsholders were summed to represent the proportion of total offshore quota held by each of the clusters to which they belonged. Information on the number of vessels owned by each cluster was also included. Changes in the number of rightsholders (i.e. participants) in the fishery with time was assessed in the perspective of various allocation processes, fluctuating total allowable catch (TAC), business buy-overs, and vessel numbers through the use of the industry and DAFF data. Changes in vessel type and numbers through time were also determined with these data. Herfindahl–Hirschman indices (HHI), which provide a statistical measure of industrial concentration (Rhoades, 1993), were computed for the time series. These indices may be applied to measure concentration in a number of contexts and are useful for analysing horizontal amalgamations because these directly affect market (or in this case quota) concentration, which is a feature of market (or in this case industry)

[6] The interview followed the same format as those in Chapter 3 section 2.2, a semi-structured interview. Except that, as a representative of the industry, this participant was consulted more regularly. That is, there were several follow-up interviews. In addition to qualitative data that were provided through the interviews themselves, actual quantitative data were provided by industry. These data are not provided in an Appendix in their raw format due to their confidential nature.

structure and measure of competition. The HHI in this chapter is calculated by squaring the quota share of all firms and then summing them.

$$HHI = \sum_{i=1}^{n} (QS_i)^2$$

……. (2.1)

Where QS_i is the quota share of company or cluster *i* and there are *n* companies (or company clusters) in the industry. In this chapter the HHI is based on the number of individual rightsholders and their quotas for the complete time series. For 2011-2013 the indices were also calculated using the quota held by the clusters identified. Foreign vessels catches were ignored for all calculations and figures. This is because industry data showed that only a small portion was allocated to foreign catch up until 2004 (ranging from 12 000 tons in 1980 to around 1000 tons in 2004, i.e. ca 10% - 1% of the TAC). To calculate HHI, quota percentages were given as fractions. As such, HHI has a maximum value of 1, where 1 indicates that a single company (cluster) has a true monopoly, owning 100% of the quota in the industry. An increase in concentration and decrease in competition with respect to quota is shown by increases in HHI.

Finally, qualitative information was obtained on clusters and companies through their websites and through consultation with some of the industry's major stakeholders in 2012 (as per description in Chapter 3, section 2.2). This involved meeting with representatives of six of the major rightsholders who collectively held 92.8% of the offshore hake trawl quota allocations, which was 78.3% of the entire hake TAC, and who owned 88% of the industry's offshore trawl vessels. These interviews provided some insights into the catch share arrangements, level of vertical integration, processing and business models of the different clusters.

3. <u>Results</u>

3.1. Clusters

From the interviews and analysis nine clusters were identified for the period encompassing 2012 to the start of 2013. These consisted of 49 rightsholders from the offshore demersal hake trawl sector with an additional two rightsholders from the inshore sector whose rights had been converted to be fished offshore in recent years (Figure 2.1). Three clusters were small (<5% each). Five were medium to large (>5% each), two of which comprised over 60% of the entire industry catch (i.e. two large). The ninth 'cluster' was a complex association which could be considered a super-cluster made up of three rather smaller cluster units that collectively constituted 5.9% of the offshore quota. Altogether these rights, which accounted roughly 83.5% of the overall hake TAC in South Africa, were caught on 50 vessels. The three largest rightsholder clusters comprised 75.7% of the offshore quota and owned 70% of the active vessels, while the smaller clusters had just a few vessels each. During the 2012-2013 period in which this study was made one of the clusters was undergoing a sale of all of its offshore rights to another cluster, this was subsequently finalised reducing the number of clusters to eight.

Large companies tended to be owned by shareholders, investment companies, or parent companies while the smaller companies appeared to be privately owned (Figure 2.2). These conclusions were reached through consulting the public webpages and reports of the various companies at the time of writing (early 2013).

I&J was found to be a subsidiary of AVI (Ltd., 2011). AVI is a parent company with a large brand portfolio of over 50 brands including a range of food products (snacks, beverages, fresh and convenience foods), household products, clothing, accessories, shoes and cosmetics. I&J, which is a chilled and frozen convenience food subsidiary, forms one of the core brands of the business. Within this context I&J also partook in a joint venture with SimPlot (Australia) Pty (Limited) during 2012 (AVI, 2012).

Sea Harvest Corporation (Pty) Limited is a private company that is owned by a consortium of investors, primarily Brimstone Investment Corporation Limited, followed by Kagiso Trust Investments, and Sea Harvest management and staff (Sea Harvest, 2010). Brimstone Investment Corporation Limited is a managed investment company incorporated and based in South Africa

(Brimstone Investment Corporation Limited, 2013a). Brimstone also owns 58.1% of Sea Harvest, 20.12% of Oceana group limited, and 0.95% of Tiger Brands. Apart from its food shareholdings, it also has healthcare, financial services and other services such as clothing included in its group of holdings (Brimstone Investment Corporation Limited, 2013b). KagisoTiso holdings is another investment company that had investment holdings in media, property, resources, infrastructure, power, financial services, investment companies, health (pharmaceutical), IT and food companies (Kagiso Tiso Holdings, 2012a; Kagiso Tiso Holdings, 2012b).

Oceana is owned by Tiger Brands (37.4%), Brimstone (20.12%), Khula Trust (11.8%), and other shareholders (34.0%) (Oceana Group Limited, 2012; Brimstone Investment Corporation Limited, 2013b). Tiger Brands Limited, is a multi-national company traded on the JSE (Johannesburg Stock Exchange) that has acquired shares in businesses in food, home and personal care (Tiger Brands, 2013). MarPro, another fishing company, is part of FoodCorp, South Africa's third largest food company producing a wide range of products and brands (Foodcorp, 2010). Pioneer fishing, a trawling and fish processing business, is owned by Suiderland Dev Corp (50%), African Pioneer Ltd (40%) and an employee share option (10%) (Pioneer Fishing, 2013).

Interviews revealed that the two largest clusters focused on domestic retail and wholesale export sectors. They shared similar strategies, producing a mix of fresh and frozen product, which translated to the use of a mix of wet-fish (fresh) and freezer trawler vessels (Sea Harvest, 2010; AVI, 2012). For a full breakdown of product types see Figure 2.3. These company clusters were highly vertically integrated so that most products, apart from prime quality, whole fresh fish, were highly processed; value addition leading to a higher price paid per kg.[7] Companies indicated that the high level of processing, though, meant that there was a higher level of labour cost because of a large amount of land-based processing, than on-board factory vessels where crew double as processors and the operation is quite mechanised. In the 2012 interviews, managers of companies indicated that for that period their profit margin did not increase with the increased levels of processing as a result of decreased hake market value at that time and high labour and other running costs. Instead, processing was merely said to be necessary to meet the consumer demand that had shifted away

[7] In general, value adding allows i) a greater perceived profit margin, ii) access to more (and diverse) markets, since there are more product options (e.g. sauced oven-bake, crumbed, or frozen cutlets) for consumers, and iii) it helps to stabilize market prices. Selling only fresh, whole fish means that prices would fluctuate with supply (catches), i.e. a volatile market. Whereas, having a diversity of products that include frozen allows for the storage of large catches thereby stabilizing prices, and lengthy (non-air-freight) transport of hake to distant markets that might not otherwise have access to purchase fresh fish, expanding the market.

from whole fish to processed products. Some of the frozen product continued to be processed at sea on board of 'factory' freezer ships at a slightly lower cost than land-based processing. Freezer trawled product (from factory *and* non-factory trawlers) appeared to be slightly more important than wet-fish vessel product in terms of volume. The high levels of processing also represented a larger expenditure and capital investment by these companies. From a social viewpoint value-adding of fish is important due to the generation of many jobs in shore-based processing facilities. Some members of the industry also indicated that landed fresh fish (i.e. those processed ashore) were more flexible in terms of what products could be produced and therefore represented a lower risk catch where the market product preference could rapidly change.

The other three medium clusters had similar strategies with only slight variations between them. Primarily they focused on freezer trawled catch, with one cluster taking a small amount of wet-fish catch. Two of these clusters did more processing of product at sea, where it was frozen, and their land-based operations served mainly as a distribution/storage centre from which orders were collected shortly or immediately after landing or sent directly for export. The third company, which had some wet-fish operations, did a portion of its processing and freezing of product at sea, while other chilled product was processed in land-based facilities. All three companies produced high quality (value) product of largely frozen fillets and some headed and gutted (fresh and chilled or frozen) or PQ ("Prime Quality", fresh, chilled) fish. They supplied the wholesale market with the majority of catch going for export and only a smaller percentage (between 5% and 33%, depending on company) going to the domestic wholesale market. They were fairly vertically integrated, but did not appear to do their own exporting or distribution, in contrast to the two larger companies.

Of the smaller clusters only the largest (3.3% of offshore quota) of these was consulted with. This cluster did only freezer trawling and minimal processing of fish. The remaining small rightsholder clusters and the 'super-cluster' of small rightsholders were not consulted or could not be reached, but represent only a small proportion (7.3%) of offshore quota. Very little information could be found on these companies from their websites, where such websites existed.

3.2. Vessels & participants

An overall trend of decreasing vessel fleet size in offshore trawl can be observed from the late 80's onwards and it sharpens from 2005 (Fig. 2.4). Although the presently available DAFF time series ended in 2011, industry data indicated that the number of vessels further declined to 50 vessels that were actively catching in early 2013 (industry meetings/interviews seemed to indicate that vessels were preferentially not held in reserve, but this fact was not entirely clear for all companies meaning that some may have had extra unused vessels for a time). From 2005 the decreasing number of vessels mirrored declines in TAC and number of participants. (It is also worth noting that offshore trawling made up the vast majority, 86.8% ±0.6% standard error, of the hake TAC for the entire time series, Appendix 1) The decline in vessels appeared to predominantly reflect decreased numbers of wet-fish vessels, while the number of freezer trawlers had remained similar since the early 1990's, with a slight upsurge in numbers in the early 2000's, corresponding to the Medium and Long Term Rights Allocation Periods (Fig. 2.5). During industry meetings all participants also stated that they had been eliminating excess vessel capacity and that the fleet was aging and old vessels were being retired. There had been no investment in new or imported second-hand vessels in recent years. There was also mention by most of the industry, particularly the medium-sized clusters, that freezer trawling was at the time the preferred fishing method as it had a lower cost per ton of landed fish and less fuel needed to be spent on steaming backwards and forwards from port to deliver chilled fish while they were fresh. These stakeholders indicated that this allowed the industry to remain profitable in the face of rising costs, such as fuel price increases.

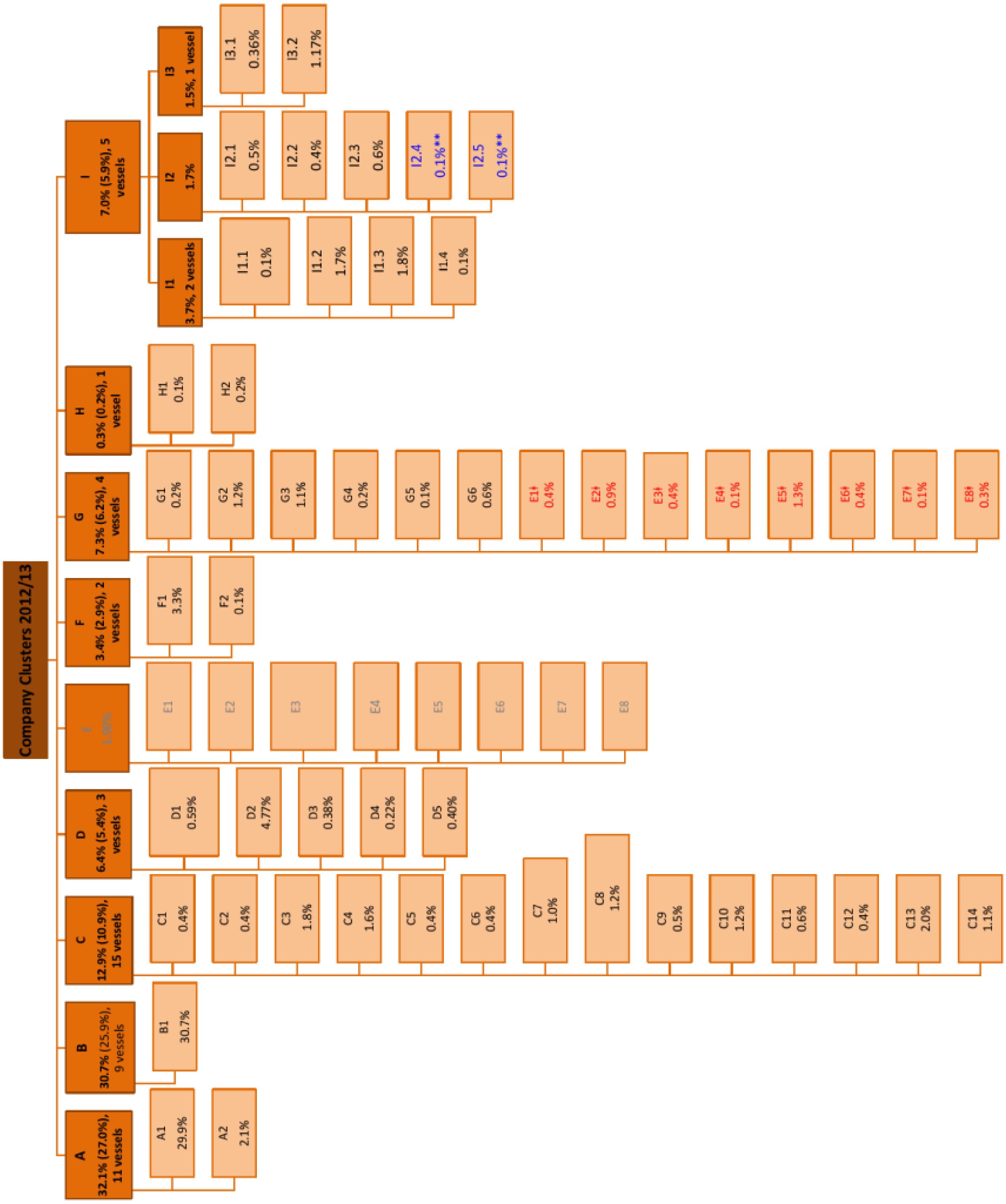

Figure 2.1: A schematic representation of the structure of the offshore hake demersal trawling industry, showing how rightsholders operate as clusters. The proportion of the total hake quota for the offshore trawling industry is indicated (along with the proportion of the entire hake TAC) and the number of vessels per cluster is given. In the case of two rightsholders (**), the rights have been moved from inshore trawl fishery to be caught in the offshore trawling sector.

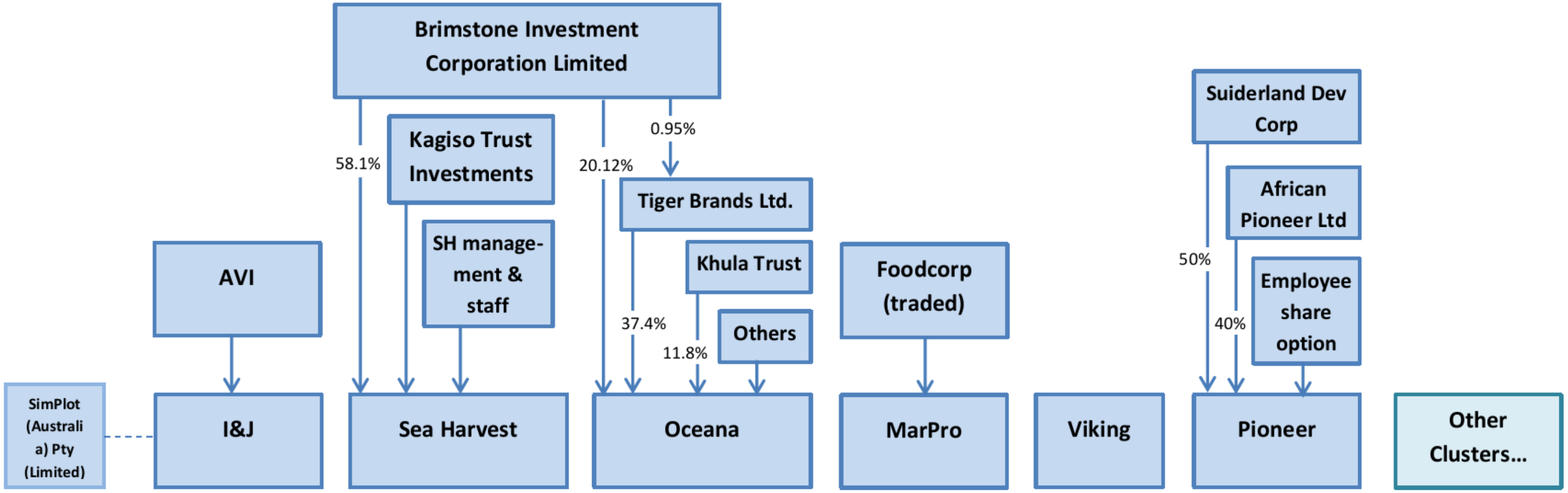

Figure 2.2: A schematic representation of cluster ownership within the industry, as extracted from company websites. Viking and other small clusters were assumed to be private companies as there was no information on ownership of the former and no information on the latter at all.

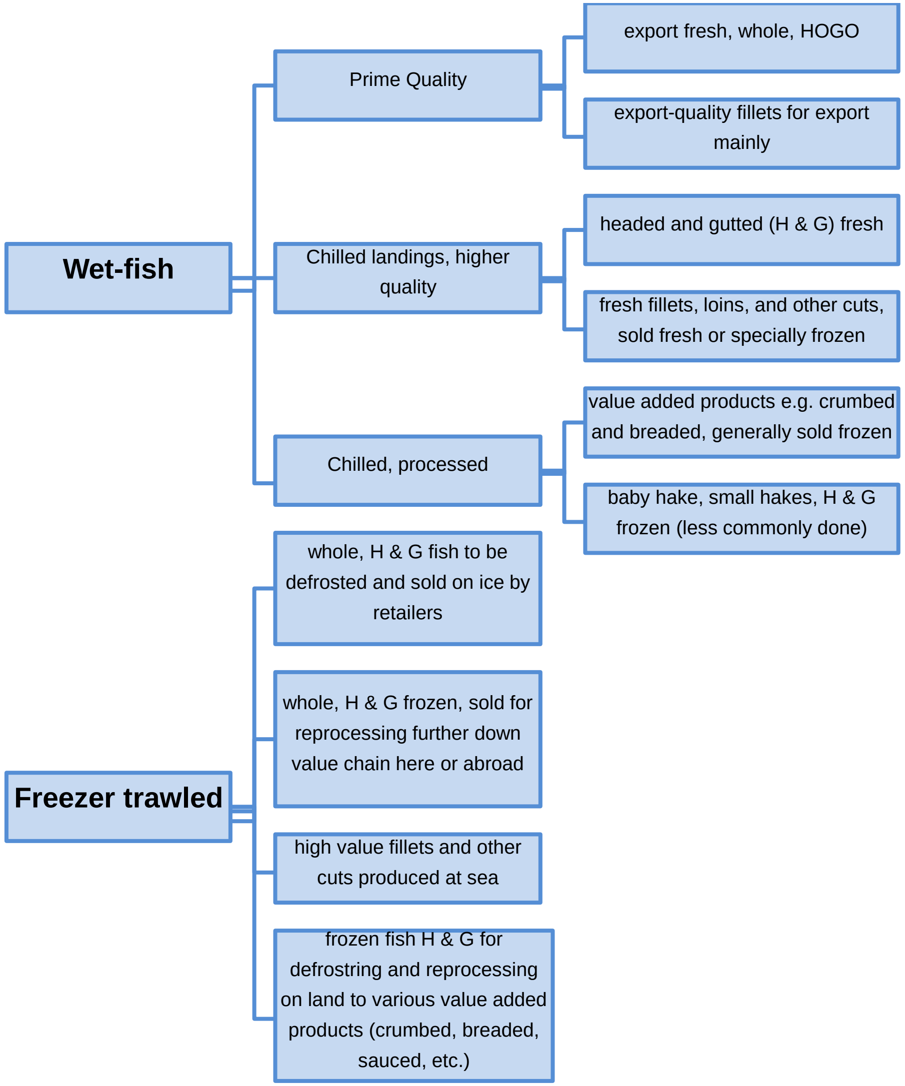

Figure 2.3: Overview of the variety of hake products produced from both freezer trawled (i.e. sea-frozen) and wet-fish trawled (i.e. land frozen or fresh) hake.

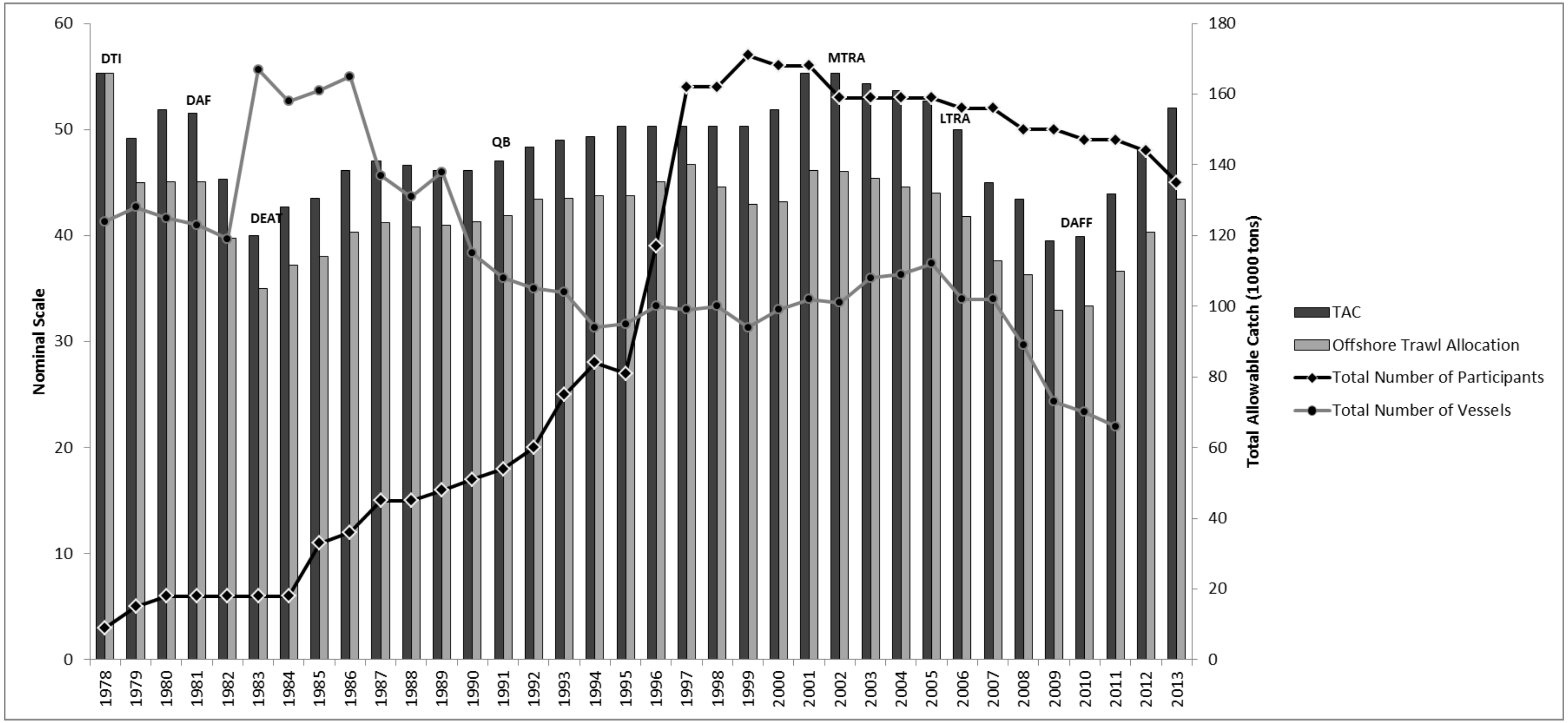

Figure 2.4: Trends in number of participants and vessels in the offshore demersal hake trawl in South Africa from 1978 to present (primary y-axis) in relation to the total allowable catch (TAC) for the entire hake fishery and the proportion of that allocated to this one sector (secondary y-axis). Significant managerial changes are indicated as DTI (under the jurisdiction of the Department of Trade and Industry, 1978), DAF (Department of Agriculture and Fisheries, 1981), DEAT (Department of Environmental Affairs and Tourism, 1983), QB (Quota Board Allocations, 1991), MTRA (Medium Term Rights Allocations, 2002), LTRA (Long Term Rights Allocations for subsequent 15 years, 2006), and DAFF (under jurisdiction of Department of Agriculture, Forestry and Fisheries, 2010). Generated with DAFF data and SADSTIA data generously put at my disposal in 2013. Further details on TAC by sectors can be found in appended Table A1.2.

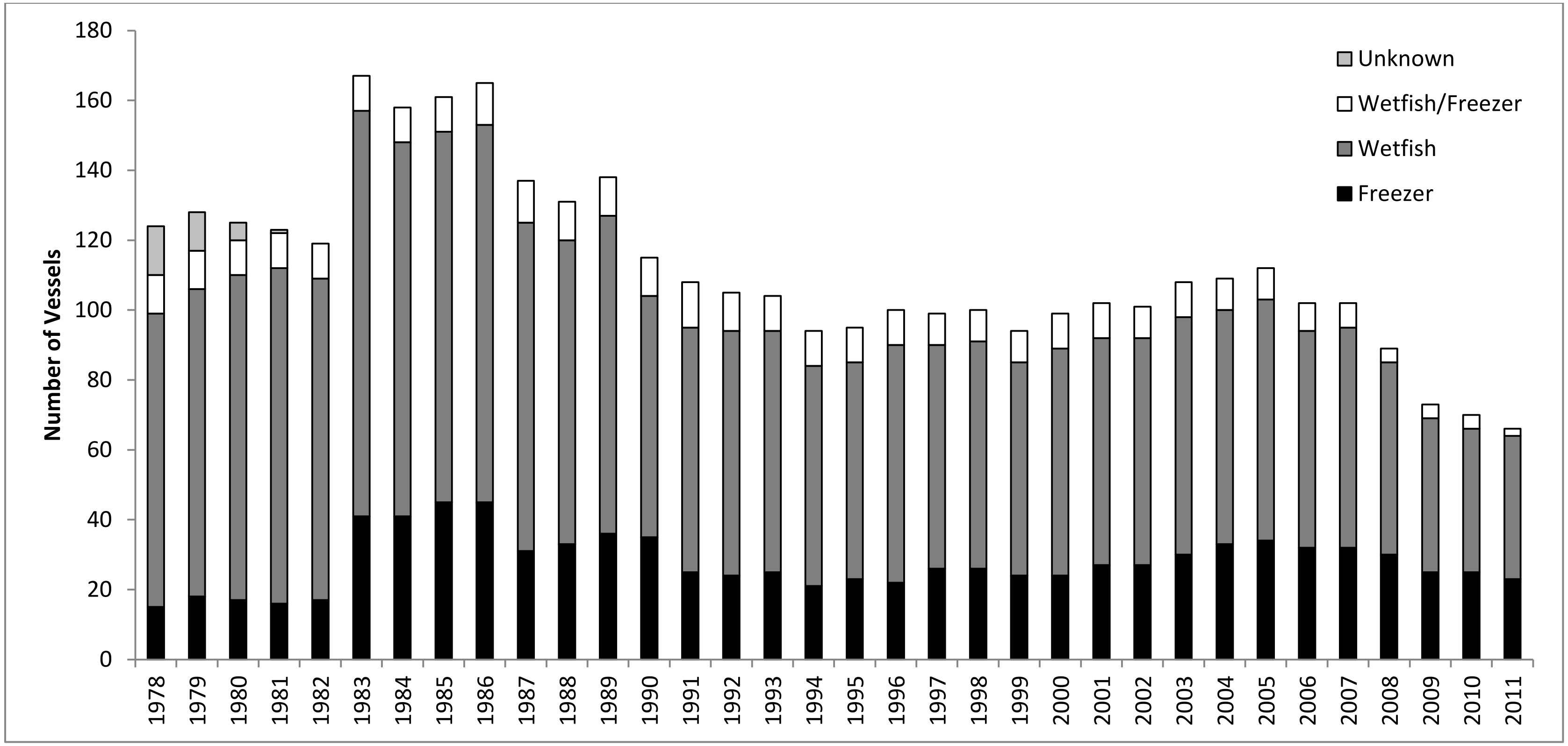

Figure 2.5: Changes in the number of vessels, by type, in the offshore demersal hake trawl sector, according to data provided by Deon Durholtz of DAFF in 2013.

4. **Discussion**

The findings of this chapter provide an understanding of the basics of the structure and patterns of aggregation within the offshore demersal trawl sector of the hake fishery in South Africa. This represents a fundamental structure with which to compare and design the economic ABM of the hake industry in later chapters, since, as verified in this study, the offshore sector accounted for the bulk of the industry and hake quota allocations (86.8%) in South Africa and an even larger proportion of the catch in the years up to and including 2012. Furthermore, a quick glance at the webpages of most major offshore trawl companies revealed that many of the large clusters identified within the offshore fishery also held rights or otherwise were affiliated to rightsholders in the other hake and fishery sectors, as could be viewed in their product profile. To add weight to this statement, in recent years two inshore hake trawl quotas have been moved offshore, demonstrating the linkages between sectors. All of this provides a reasonable premise to use solely information collected on the offshore hake sector in the production of the first prototype of the ABM. The analysis of the behaviour and structure of these major offshore trawl companies carried out here (and in Chapter 3) should provide good insight into the structure and function of the hake industry as a whole.

Clustering or what could otherwise be termed aggregation of rightsholders in the hake fishery appeared to be an important behaviour as predicted from anecdotal evidence (Anonymous, 2011a; Anonymous, 2012; SADSTIA, 2013) and allusions in the literature prior to the study (Crosoer *et al.*, 2006). Clustering or consolidation of rights and or fishing companies is known from the international literature (Eythórsson, 2000; González Laxe, 2006; Abayomi and Yandle, 2012).Clustering behaviour was confirmed through both consultation and interviews with industry and analysis of quantitative data; the decreasing trend in vessel numbers coupled with a historical increase in quota holder numbers by inference indicated that rightsholders must have shared vessels. Indeed both industry data and data on companies and vessel ownership from the 2006 LTRA (long term rights allocations) showed this. Post-LTRA the number of participants in the industry had also decreased and this represented the selling of rights to other participants, which may be equated to clustering behaviour. Clustering behaviour is regulated legislatively but it has been allowed, as outlined briefly in the court case *Surmon Fishing (Pty) Ltd v Compass Trawling (Pty) Ltd* (162/2008) [2008] ZASCA 142 (27 November 2008); pooling of rights has been allowed, and according to this court case document was encouraged, subject to the approval of the relevant minister (presently DAFF).

Many of the large clusters (companies) were found to be owned in part or whole by parent companies. This means that these companies were, in some cases, indirectly traded on the stock exchange. In addition to this, vertical integration as previously found (BCLME, 2006b; BCLME, 2006c; Raakjær and Hara, 2006), was an important characteristic of the industry with at least 89.4% of offshore quota caught and processed in vertically integrated companies. The two largest clusters of companies (collectively 62.8% of offshore quota) were highly vertically integrated performing everything from fishing to marketing and distribution. Only one of the interviewed companies hardly processed its product.

On the whole, the industry could be described as a mature one in economic terms where there are no super-profits to be had, with a high level of vertical integration and a fairly stable structure where the main changes have been in the direction of consolidation of rights, at least within the present context of long term rights. The previous major change to the number of participants and therefore industry structure occurred when the LTRA process was begun and it seems probable that some re-shuffling of structure may occur after the rights are reviewed at the end of 2020. Past trends suggest that this is most likely to take the form of consolidation of rights should the number of rightsholders be initially increased.

There have also been gradual but long-term changes in the fleet structure and operations of the industry. In the years directly preceding 2013 much of the downsizing of the fleet has been driven by the establishment of an effort restriction (number of allowed sea days) based on the horsepower of the trawler engine in 2006 (SADSTIA, 2013). Throughout the time series the removal of fishing vessels was said to represent the removal of excess capacity from the fleet which necessitated extra maintenance costs. The majority of vessels that have been removed from the fleet were wet-fish trawlers, while the number of freezer trawlers remained more consistent. This matched with the quantitative trends observed in export product displacement (Chapter 3) and with the qualitative information provided by industry in a favouring (by most clusters) of sea-frozen product due to a lower catch cost per ton of landed fish, particularly in the face of rising fuel costs in the last decade.

Finally interviews indicated that the two largest clusters in offshore demersal trawl (60.7%) continued to have large land-based processing facilities and produced products that were highly value-added and processed. The medium-sized companies (26.6%) had in two out of three cases processed fish on-board of freezer vessels and only one medium company still owned a wet-fish vessel and land-based processing facilities. From meetings with the largest of the small clusters it would appear that processing on freezer vessels was also an important strategy for them. From this and the fact that wet-fish vessels had declined to numbers almost as low as freezer trawlers by 2011, an estimate of about 40-50% wet-fish landings that were land-processed in the trawl industry seems a reasonable estimate for the present time.

In conclusion, the qualitative and quantitative data in this chapter agreed with each other, the findings of the following chapter, and with information previously stated by stakeholders or alluded to in the literature, indicating that the data were fairly reliable. Thus the findings of this chapter should be borne in mind when designing the structure of the economic ABM prototype, through the various iterations of the model in future, and in assumption analyses where simplifications are to be made.

CHAPTER 3:

AN ECONOMIC OVERVIEW OF THE HAKE FISHERY IN SOUTH AFRICA WITH SPECIFIC REFERENCE TO IMPORTS AND EXPORTS

Chapter 3: An economic overview of the hake fishery in South Africa with specific reference to imports and exports

1. Introduction

South Africa currently plays an important role in fish export, particularly in supplying white fish to the world market (FAO, 2010), and is one of the three major producers of marine products in Africa (FAO, 2012). A fish export boom to the European Union, among other developed nations, followed South Africa's (SA) reintegration into the world economy at the end of Apartheid. Exports have been predominated by whitefish, hake, from the demersal fishery since 1990 to meet the international demand, particularly in Spain, that stemmed from the cod crisis. In the early 2000's imports into SA of alternatives to local products were minimal while exports of local product from SA were high due to a weak Rand and a price sensitive local market (Crosoer *et al.*, 2006). More recent comments from industry, government and other stakeholders in the SA hake fishery indicate that this has changed somewhat in the latter half of the decade and that export markets have been relatively poor in the wake of the ongoing (2008-present) international economic crisis and that import substitution of whitefish and other marine products has become more important in local (SA) markets. However, to the best of my knowledge, no comprehensive analysis of export data for South African whitefish has been published in almost a decade. This makes producing a model of the system near impossible without at least a preliminary analysis first.

The complex nature of fisheries, where economic, social and environmental factors interplay, has significant import for their sustainability and the success of their management. Understanding and managing such a complex system sustainably requires consideration not only of the biological but also of the social, historical and economic context (Folke *et al.*, 2007; Pitcher and Lam, 2010). In the majority of fisheries, of which South Africa is no exception, economic data are limited and the use of proxy data from the literature can lead to a loss of realism in system representations and erroneous recommendations for management, particularly for human sub-systems (Garcia and Charles, 2008). It is therefore imperative that country-specific economic and social data be collected as far as possible prior to building a system model. In addition to this, the fishery sector contributes significantly to net foreign exchange in South Africa due to its large level of international trade, particularly through hake exports to Spain (FAO, 2010). This study therefore has as a broad aim to provide some preliminary analyses of hake export data over the last decade in as much detail as possible, to give some insights into the economics of the fishery in South Africa.

Hake from demersal trawls can be processed and frozen at sea in large factory ships, about a third of the catch (Hutton, 2003). It can also be landed fresh and sold fresh as premium quality, fresh, whole, gutted, head-on fish and fresh fish fillets. Alternatively it can be landed fresh and frozen within a few days of catching and processed in large, land-based and highly mechanised processing plants to produce value-added products, such as crumbed or moulded fillets, fishcakes and other ready-to-cook meals (see Figure 2.3 for a summary of product types). A significant proportion of this hake has historically been exported to Spain, but the market is rumoured to be diversifying into or increasing in other parts of Europe and America following Marine Stewardship Council certification of the offshore trawl sector and the economic recession in Spain. Hake (*Merluccius* spp.), kingklip (*Genypterus capensis*) and monk (*Lophius vomerinus*) that are landed fresh from the longline sector are predominantly subjected to minimal cleaning and directly exported to Europe, while a small quantity of this longlined fish is processed into value-added products that are sold locally (FAO, 2010). As a first step, this chapter aims to provide specifics on the total quantities of different hake products exported internationally for the entire fishery.

Apart from the heterogeneity in product type there is also heterogeneity in terms of the way different fishing companies operate and how they catch or target hake – many small fish, fish that are immediately filleted and flash frozen, large whole fish etc. This means that there is variation in the way that the harvest and post-harvest hake industry functions and in the different strategies major companies use to maximise profit. Consequently, differences in factors affecting profitability and overall sales in this industry, such as overheads of fuel oil, diesel and electricity, exchange rate, size structure distribution of the catch (as a result of hake population structure and environmental conditions), overall market demand and changes in market preference, would all be expected to impact the fishing industry.

Take for example an increase in the cost of fuel oil and diesel as the result of crude oil price increase. This would mean an increased cost to run vessels and refrigeration on board of (particularly freezer) trawlers with these fuels, which could increase the cost of producing frozen fish products and the cost of steaming. This has differing consequences for longlining where there is a lot of steaming, with short fishing trips, but limited on-board refrigeration, versus offshore freezer trawlers where there is less overall steaming, but a great deal of diesel used to power on-board freezers and machinery. Thus the cost is differently born by different companies and fishing sectors. Switching from one technology to another is a slow and expensive business. Big fishing companies that have multiple vessel types in their fleets (e.g. wet-fish and freezer trawlers) or shares in a variety of sectors (i.e. multiple technologies at their disposal) have the advantage of being able to shift to the use of some vessel types over others in the face of differing conditions. This is one of the reasons that these large vertically integrated and highly (horizontally) consolidated companies have done well over the long term.

Similarly changes in the fish size mix (composition) of catches have impacts on profitability, and the possibility to produce different product types. Given a great deal of variability in the fisheries system and heterogeneity between companies (Chapter 2), it is interesting to understand what types of strategies and product streams companies opt for under differing environmental (both economic, social and natural) conditions.

In addition to this, factors such as exchange rate dictate the relative profitability of export versus domestic products and there is the additional consideration that in the international market local fishing companies may be price takers due to their relatively small international presence, versus the local market where there are relatively fewer fish companies and large companies could be price makers, dictating local market value of fish. This is an interesting aspect to explore by examining the relative apportionment of hake between the domestic and international market under differing market conditions (i.e. international demand and supply nationally and internationally) and exchange rates. This can be done through a combination of examining quantitative export data and qualitative data on domestic and international hake markets and companies' business strategies.

2. Methods

In order to understand the relative importance of, and changes in, the domestic and export markets and how companies or the industry as a whole might have responded to these, it was necessary to first determine what was actually happening to exports and the domestic market as a whole. This was achieved by 1) rigorously analysing hake exports from South Africa for general trends and in relation to changes in fuel price, exchange rate, total allowable catch, and (qualitative information on) overall market demand; 2) a) receiving qualitative feedback on these export data and analyses from industry stakeholders and b) collecting (qualitative) data on export behaviours from stakeholders through individual meetings; 3) collecting (qualitative) data on the domestic market for hake from industry; and 4) collecting qualitative information on how companies cope with changes in domestic and international markets and apportion their efforts in resource collection, processing (i.e. product streams) and sale (domestic versus international market) of hake.

2.1. Quantitative analysis of export data

No detailed export data, collected by the South African government are publicly available. However, SARS (the South African Revenue Service) does deposit non-specific (i.e. no details of fishing sector or company of origin) export data into international databases of export data such as TradeMap. This database has export and import data stored under Harmonized System (HS) codes. HS codes are a standard format under which the governments of countries record exports and imports for tax and information collection purposes. HS codes undergo revisions every few years, meaning that codes are specific to time period as well as to product.

TradeMap data on South African exports and associated imports of hake related products were only available for 2004 until the end of 2011 at the time of analysis. Due to a major revision of codes in 2012 and the lack of data available on this year at the time of analysis only data for the period 2004 to 2011 were analysed. These years also corresponded well with the period of the rights allocation process and subsequent long term rights allocations in the hake (demersal) fishing industry, meaning that at least the harvest industry would have been of a fairly consistent structure through this time in terms of rightsholders.

Export data on quantity and value of total exports from South Africa by HS codes were therefore downloaded from the TradeMap database (http://www.trademap.org/) for the period 2004 to 2011 and cleaned for use in this analysis. Only codes that could be specifically linked to hake (Table 3.1) were analysed. Hake-related codes were identified through extensive inspection of all TradeMap codes for hake-related products and through industry and government consultation on standard export codes used. Six digit versions of the HS codes follow an international standardization, while the remaining two to four digits (to make an eight or ten digit code) are reserved for countries to add further (country-specific) details. Most of the six digit HS codes under which South Africa exported hake were *not* hake-specific, meaning that they represented aggregate export data for a number of similar fish products of different fish species. To complicate matters there were no or limited South African eight or ten digit HS codes to give greater specificity on the exact species of fish and type of export product and thereby identify the exact quantity of hake exported. This necessitated the use of corresponding import data from countries that provided a greater degree of specificity, to first indirectly estimate the proportion of hake in the exports.

To accomplish this, the major importing countries to which South Africa exports fish were identified for each of the relevant six-digit codes. The quantities and values of fish imported from South Africa were then collected from TradeMap for each of these major importing countries at the six-digit and eight- or ten-digit level of detail (see Table 3.1 for corresponding import codes at high resolution). These data were then aggregated to total quantity of imports by country and for all major importers combined under the six-digit code and the hake-specific eight- or ten-digit codes for every year. Comparison of SARS export values and quantities, for the major importing countries, with corresponding import data of these countries in a particular year then allowed the proportion of hake actually exported from South Africa to be estimated as follows:

$$\text{Approximate quantity of hake exported from South Africa} = \sum_{x_1}^{n} \frac{\text{Quantity of hake imported from SA into country } \boldsymbol{Y}}{\text{Quantity of fish } \boldsymbol{A} \text{ imported from SA into } \boldsymbol{Y}} * \text{Quantity of fish } \boldsymbol{A} \text{ exported from South Africa} \quad \text{....... (3.1)}$$

where *x* is the number of countries purchasing the fish exported from South Africa, *Y* is a country that buys South African hake exports and fish *A* is some fish product that may include hake and was represented by a six digit HS code. All quantities were from the same time period (year). A schematic demonstration of this calculation is provided in Figure 3.1.

Once all import and export data were collated a number of calculations were made. Firstly, total export volumes which represented the weight of processed hake (e.g. headed and gutted fish, fillets or crumbed) were converted to whole-mass estimates using the conversion factors in Table 3.2. A whole-mass estimate is the estimated weight of the whole fish that was processed and parts discarded to produce some end product. This is relevant since, for example one kilogram of filleted fish might actually be equivalent to 2.219 kg of fish that was caught by vessels before it was processed. Gross export volumes and estimated whole-mass equivalent volumes of hake were also calculated as a percentage of total allowable catch (TAC). The volumes and values of exports were determined and used to calculate the value per ton of processed product exported, and they were analysed in Statistica 10.0 by running a standard linear regression against foreign exchange rates and TAC.

Table 3.1: A description of the HS (harmonized system) of export and import codes for various hake products, as defined in TradeMap. The first six digits of HS codes are internationally standardized, while the last two/four digits of HS eight/ten digit codes are those specific to relevant importing regions.

HS 4-digit code	description	HS 6 digit international	description	HS 8/10 digit national	description	years
1604	prepared or preserved fish and caviar	**160419**	fish nes§, prepared or preserved, whole or in pieces, but not minced	**16041994**	Hake "*Merluccius* spp., *Urophycis* spp.", prepared or preserved, whole or in pieces (excl. finely minced and fillets, raw, merely coated with batter or breadcrumbs, whether or not pre-fried in oil, frozen) - European Union	2004-2011
0302	Fish, fresh, whole	**030269**	Fish nes, fresh or chilled excl heading No 03.04, livers and roes	**03026966**	Fresh or chilled cape hake "shallow-water hake" "*Merluccius capensis*" and deep-water hake "deep-water cape hake" "*Merluccius paradoxus*" - European Union	2004-2011
				03026968	Fresh or chilled hake of the genus "*Merluccius*" (excl. cape hake "shallow-water hake", deep-water hake "deep-water cape hake" and Southern hake) - European Union	
0303	fish, frozen, whole	**030378**	Hake, frozen, excluding heading No 03.04, livers and roes			2004-2011
0304	fish fillets and pieces, fresh, chilled or frozen	**030420**	Fish fillets frozen	**03042055**	frozen fillets of cape hake "shallow-water hake" "*Merluccius capensis*" and of deep-water hake "deep-water cape hake" "*Merluccius paradoxus*" - European Union	2005-2006
				0304200043	Frozen hake fillets in packs - Australia	
				0304200033	Frozen hake (*Merluccius* spp., *Urophycis* spp.) fillets in processing blocks - Australia	
		030429	Frozen fish fillets (excl. swordfish and toothfish)	**03042955**	Frozen fillets of cape hake "shallow-water hake" "*Merluccius capensis*" and of deep-water hake "deep-water cape hake" "*Merluccius paradoxus*" - European Union	2007-2011
				0304290063	Hake (*Merluccius* spp., *Urophycis* spp.) fillets, in processing blocks, frozen - Australia	
				0304290062	Hake (*Merluccius* spp., *Urophycis* spp.) fillets, in packs, frozen - Australia	
		030499	Frozen fish meat whether or not minced (excl. swordfish, toothfish and	**03049951**	Frozen meat "Whether or not minced" of hake "*Merluccius* spp., *Urophycis* spp." (excl. fillets) - European Union	2007-2011

§ "nes" is the abbreviation for "not elsewhere specified"

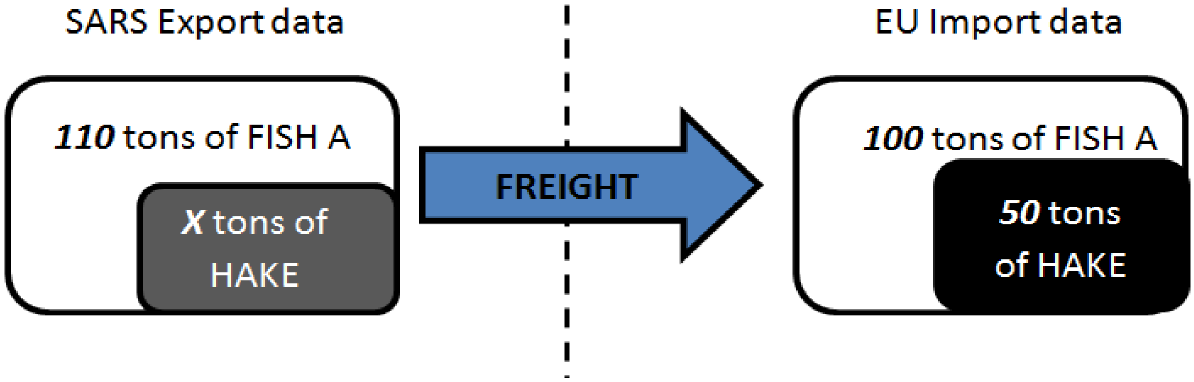

Figure 3.1: Schematic illustrating how the quantity of hake exported from South Africa was estimated. For example, SARS export data lodged in TradeMap indicated that 110 tons of Fish A was exported from South Africa (SA) in a year to several European Union (EU) countries and some unknown portion of this export (x) was actually hake. It can be determined from corresponding higher-resolution EU import data from TradeMap that 100 tons of fish A (represented by a six digit HS code) was recorded to be imported from SA into these countries and that 50 tons of this was hake (represented at the eight or ten digit level). It could then be estimated that 55 tons of hake was exported from South Africa under the code for Fish *A*.

Table 3.2: Conversion factors suggested by industry to convert the weight of processed hake export products back to a whole-mass value (i.e. the weight of whole fish that were caught before they were gutted and otherwise cleaned and processed). See also appended Table A2.1 for details of consultation.

HS Code	TradeMap description	Conversion factor suggested by industry	Description of actual exports suggested by industry
160419	fish nes prepared or preserved excl…	Mostly 1.54† & some 2.25=1.54*0.9+ 2.25*0.1 **= 1.611**	Crumbed & coated product for northern Europe
030269	whole fish nes fresh, chilled excl heading	1.10 & 1.30‡ = 1.10*0.4 + 1.30*0.6 **= 1.22**	PQ and fresh hake, predominantly HOGO & also used largely by longline sector PQ is exported as whole weight‡
030378	whole hake frozen, excl heading	**1.46**	Frozen whole hake, headed and gutted; predominantly used by freezer trawling companies
030420	fish fillets frozen (in packs or blocks)	Mostly 2.25 & some 1.94 = 2.25*0.90 + 1.94*0.10 **= 2.219**	Frozen fish fillets, medallions, cutlets, portions and loins; predominantly Sea - frozen product; some fresh fillets of hake
030429	frozen fish fillets (in packs or blocks)		
030499	frozen fish meat whether or not minced		

†Value suggested by industry for converting crumbed or battered product to whole-mass

‡One company stated that they exported about 8000 tons of Prime Quality hake (PQ) as 030269 annually and this was whole-mass. This company also stated that 1.3 is a more accurate estimation for converting whole fish with guts out (PQ) to whole fish with guts in (whole-mass). Since 8000 tons is on average 60% of the annual export volume, 1.30 is weighted heavily.

2.2. Qualitative studies

In late 2012 meetings were conducted with various stakeholders from the hake fishing industry including, harvest and post-harvest companies and conglomerates, industry representatives and non-governmental organizations. A list of all relevant stakeholders from the industry was first made and these stakeholders were then contacted telephonically and/or by email, depending on available contact details, to arrange meetings. All those who agreed to an interview were interviewed. Ten semi-structured, face-to-face interviews were thus conducted with ten people (one interview consisted of two individuals from the same company and one individual was interviewed twice) from six companies and from an industry association. The companies interviewed accounted for 92.8 % of the total offshore hake trawl quota allocations, and 78.3% of South African hake TAC.

Prior to the interviews a detailed plan of what to include in interviews was made and carefully refined. Specific questions and talking points were formulated to provide information that was necessary to inform the model design and the data studies that underpinned it. As far as possible these points sought to avoid bias. They were collated into the format of a talking point questionnaire/interview sheet, presented in Appendix 2. Along with this an illustrative diagram was produced (Figure A2.1) that had talking points on the value-chain of hake. Table A2.1 was also presented to each of the interviewees to elicit exact conversion factors that they thought were appropriate/used to convert fish product weights back to whole-mass equivalents of fish for every HS export code relevant to South African hake exports. In addition to all the materials in Appendix 2, graphs from Appendix 3 and from this chapter that covered gross export volumes and prices as well as break downs by code and export country were presented to interviewees for comment on their perceived accuracy and trends. All interviewees were asked the same series of questions and were guided by the same talking points and supplementary material (figures and tables), ensuring replication between interviews. Of course, individual interviews because of their semi-conversational nature occasionally provided additional insights to the main talking points. Where possible, any such ideas that emerged in the earlier interviews were also explored in later interviews as an additional talking point, which was generalised to become a concept and avoid any association to a company or entity. Identities and facts from individual interviews were never revealed to other interviewees. All information was treated confidentially both to protect the interviewees and to avoid bias between interviews.

Interviews lasted between one and three hours, wherein interviewees were first provided with an information sheet and verbal communication explaining the nature and purpose of the interview, that the information would be treated anonymously and why they had been selected for the interview. (This was also previously done at the stage where interviews were initially contacted to arrange the meetings.) A conversation was undertaken guided by the series of key questions, talking points, graphs and tables described above. Oral permission was given to record the details of the interviews in writing. These detailed notes were typed-up and provided to the respective interviewee/s for comment. At all times the written records were kept anonymous and notes were associated to a randomized letter of the alphabet.

The qualitative written recordings were subsequently collated and aggregated into a group set, in an anonymized format, from which general observations on the industry could be made. Specifically, all data were collated under the topics (talking points) outlined in Appendix 2 in a spreadsheet. The comments of each company related to that topic were summarized and recorded accurately within this spreadsheet. No qualitative data were omitted from this process. Companies (associated with their random letter name) were also categorized as small, medium, large and super-cluster in this spreadsheet. Only information that was verified by more than one company (of each company type) in this spreadsheet format, or through quantitative data, was accepted and presented in the qualitative results section of this chapter and Chapter 2. Finally, of relevance to this chapter, qualitative information that was obtained on the state and nature of export and domestic markets over the last decade is presented in the results section. The results of quantitative assessments of export data from TradeMap performed in this chapter were also verified with the stakeholders, as described above, and qualitative information on the trends observed and possible reasons for these trends were also obtained and are presented.

3. <u>Results</u>

3.1. Quantitative results

Detailed quantitative information has been provided in Appendix 3, while the most essential information has been provided here. From Figure 3.2, it is apparent that proportionally the 0304 codes collectively made the greatest overall contribution to potential hake exports, particularly from 2008 onwards, followed by the 030269 HS export code. The crumbed and processed fish export code 160419 contributed the smallest proportion by volume. The exports under 0304 can fall under several higher resolution HS codes, of which only 030420 and 030429 made significant contributions to the total volume.

Overall, potential processed hake exports remained between 40 000 and 50 000 tons over the seven years, which equated to about 55 to 65% of total allowable catch (TAC) being exported, when whole-mass estimations were considered, Figure 3.3. Post-2008 exports declined slightly overall with the onset of the global recession, but made a small recovery in 2011. Most of post-2008 decrease was accounted for by a drop in the exported quantities of 030269 products. This decline was not visible when volumes were calculated as a proportion of TAC.

On average, processed hake imports were similar to total fish exports from South Africa, but only accounted for about 90% of total imports in foreign countries, as shown in Figure 3.4 and Table 3.3. There was a discrepancy between South African exports and corresponding imports overseas, indicating that exports were under-reported or exported under different codes than they were imported overseas.

The trend for all potential hake exports, when codes were cumulated, shows that world price increased from ZAR20 112 per ton in 2005 to a high of ZAR32 225 per ton in 2008, but subsequently declined with the recession of 2009/2010 when the Spanish market did poorly, with a slight recovery by 2011 (ZAR29 615 per ton). On average 030429 fish obtained the highest value per kilogram and 030378 obtained the lowest. The values of frozen 030378 and fresh 030269 fish declined and converged after 2008. On the other hand, the value of 160419 increased substantially over the period 2005 to 2011.

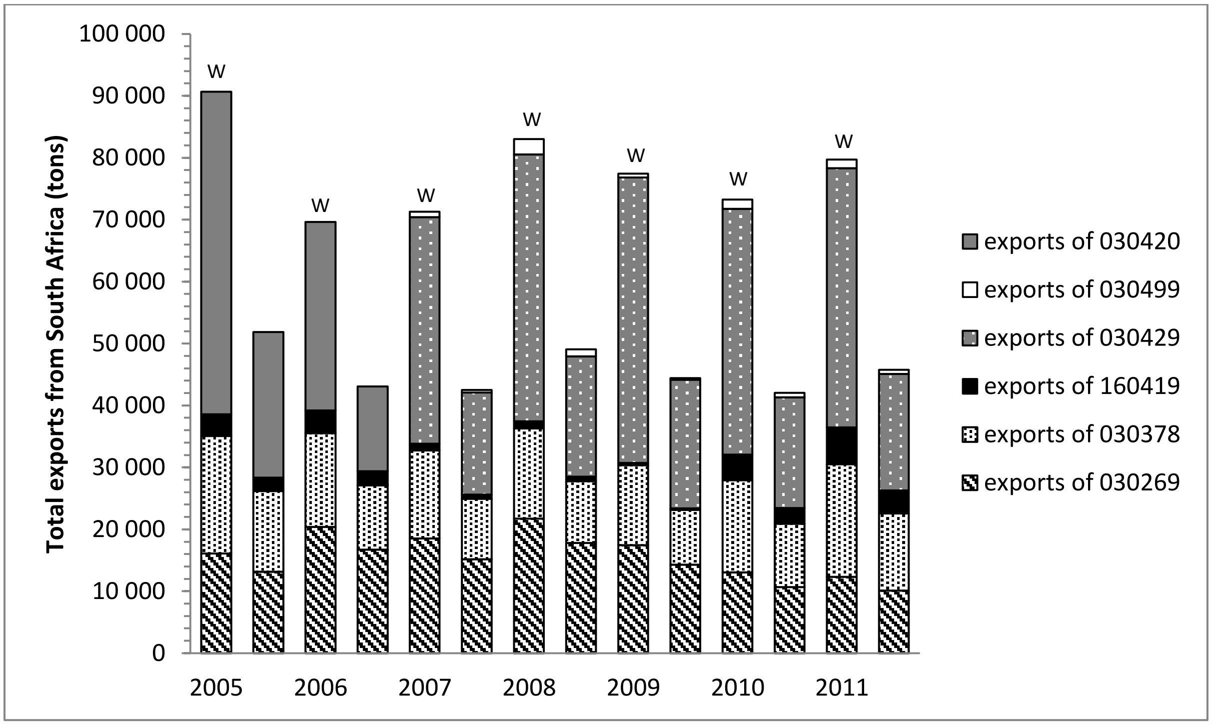

Figure 3.2: Total annual quantities of fish, and corresponding whole-mass estimations (W), exported from South Africa under the Harmonized System (HS) codes that could include hake, as extracted from South African Revenue Service (SARS) export data in TradeMap.

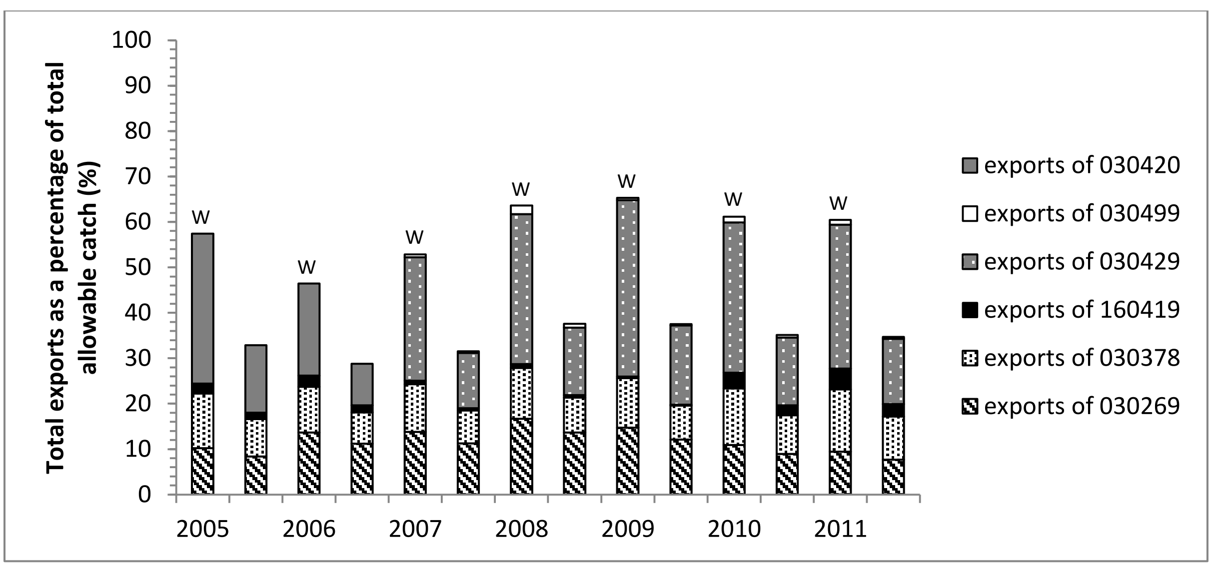

Figure 3.3: Gross total annual exports, and corresponding whole-mass estimates (W), shown as a percentage of total annual allowable catch of hake.

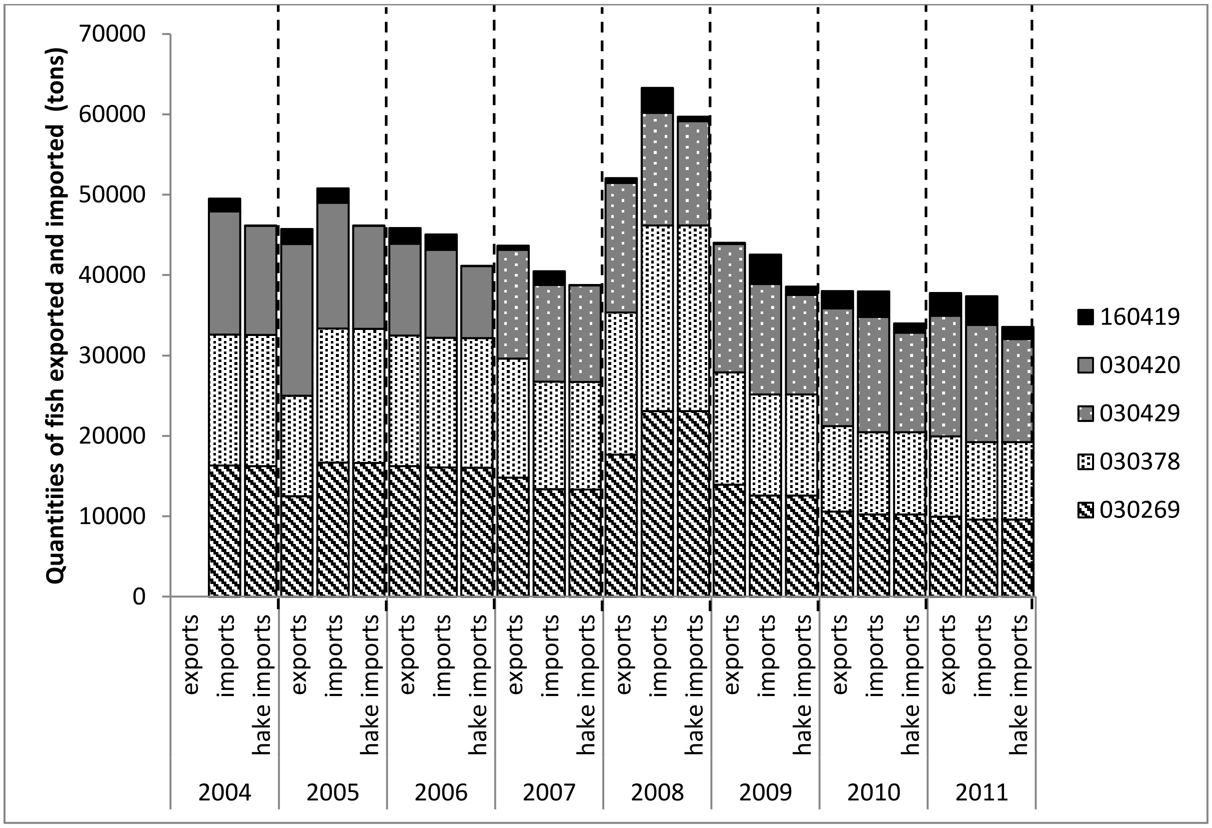

Figure 3.4: Total exports of fish (general code that includes hake) from South Africa, corresponding quantities of imports by buyers worldwide and specific quantities of hake imported under the same Harmonized System (HS) codes for buyers worldwide, calculated from TradeMap data.

Table 3.3: Estimated proportion that hake contributed to exports and corresponding imports for the various Harmonized System (HS) codes and all codes considered together. Average and standard error are presented.

		2004	2005	2006	2007	2008	2009	2010	2011	Average	SE
hake imports as % of exports for	**030429**				88.46	80.53	77.58	84.37	85.48	**83.28**	**1.91**
	030420		67.84	78.43						**73.13**	**5.30**
	030269		133.20	98.98	90.21	130.59	90.10	96.46	96.42	**105.14**	**7.03**
	030378		133.31	99.14	90.37	130.66	90.16	96.54	96.47	**105.24**	**7.03**
	160419		1.11	2.41	0.78	87.44	749.08	54.00	53.29	**135.45**	**103.06**
	all codes		100.86	89.81	88.67	114.62	87.64	89.42	88.85	**94.26**	**3.80**
total hake imports as % of total imports		93.23	90.86	91.36	95.64	94.33	90.64	89.56	89.75	**91.92**	**0.79**
total imports as % of total exports			111.00	98.30	92.71	121.51	96.69	99.85	99.00	**102.72**	**3.78**

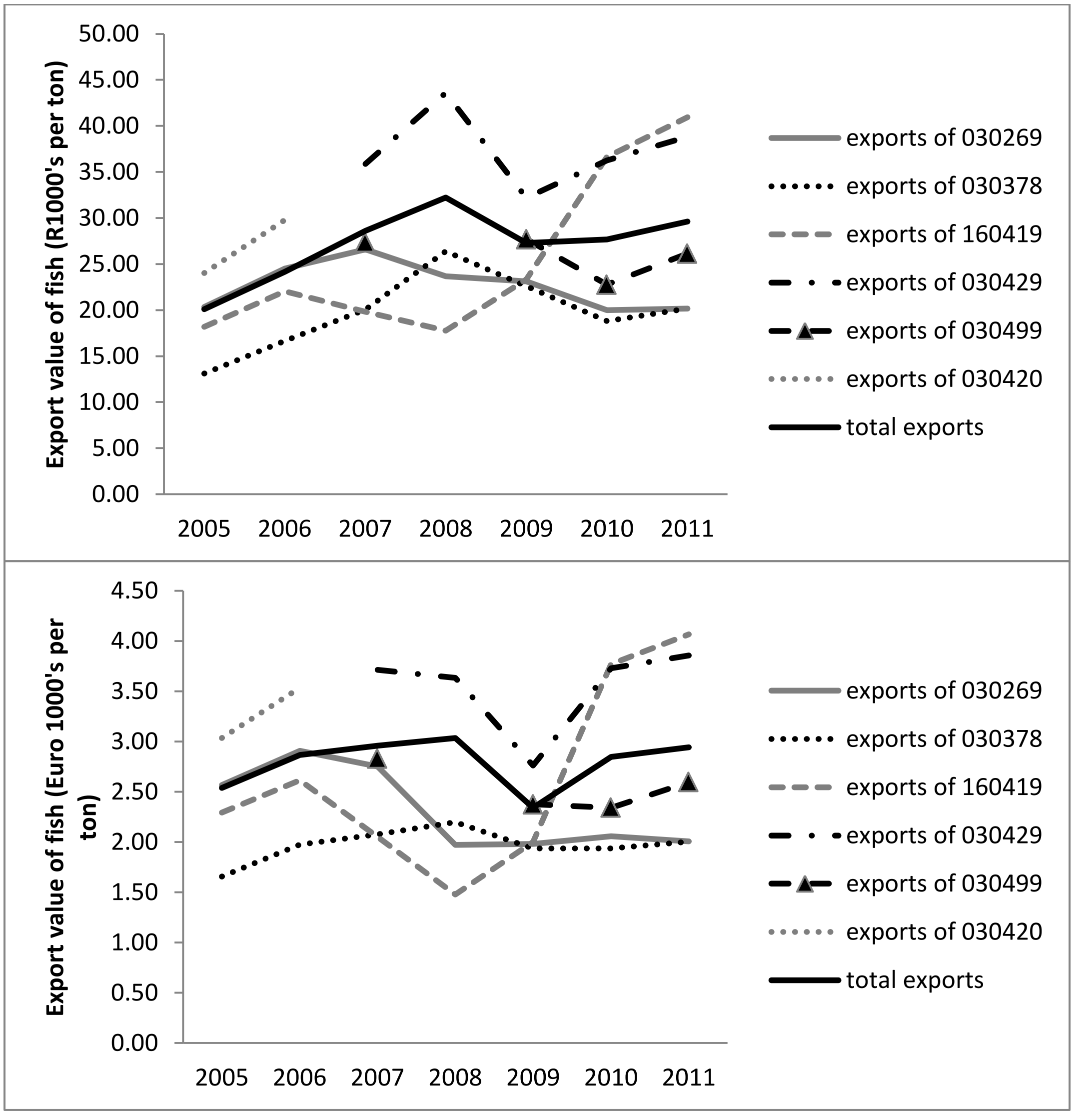

Figure 3.5: Unitary value, in thousands of South African Rands and Euros per ton, of fish exported from South Africa under the HS codes that could have included hake, as extracted from South African Revenue Service (SARS) export data in TradeMap, and the fluctuating price paid per ton of these exports when codes were grouped together.

These trends were quite interesting when taken in conjunction with the fact that 030429, 030378 and 030269 made up the majority of exports by volume. The value per ton for all three of these codes declined quite significantly from a high in 2008 by about ZAR6000 to ZAR9000 per ton, atlhough there was a slight recovery in the price of these products in 2011 of around ZAR200 (030269), ZAR1400 (030378) and ZAR6600 (030429) per ton, Figure 3.5. The significantly lower value of these products, which were sold in large quantities, could represent a signficant decline in overall profits from exports to the industry. The lower price obtained for these fish products from 2009 to 2011, when taken for total exports together (i.e. all those exported under the hake HS codes considered), translated to a decline in total South African hake export value from ZAR1,746 912 000 in 2008 to lower values of ZAR1,211 793 000 in 2009, ZAR1,163 530 000 in 2010 and ZAR1,354 983 000 in 2011. This was a loss in value of up to ZAR583 381 900 (~ZAR583 million) per year, approximately 33.40% less than the 2008 value, if at least the 2008 value was considered to have continued into the future (see Appendix 3, Figure A3.1, for a detailed breakdown of export values by HS code).

The only variable that export quantities of hake were significantly correlated with was the South African Rand/Euro exchange rate given in Table 3.4. The positive correlation indicated that when exchange rate was high (i.e. the Rand is weak) exports increased. International fisheries trade is known to increasingly be influenced by exchange rate changes, because of their effects on relative prices (Tveteras and Asche, 2008)

Table 3.4: Results of regressions of hake export quantities and export values (for all codes combined) against various foreign exchange indicators and the South African Annual TAC for all hake. A significant, positive correlation for ZAR/EURO with hake export quantities is indicated in bold. Exchange rates used in the analysis can be found in Appendix 3, Figure A3.2.

	Adjusted R^2	DF	F statistic	p-value
Hake Export Quantities (tons) vs.				
ZAR/EURO	**0.507**	**1, 5**	**7.160**	**< 0.05**
ZAR/USD	0.343	1, 5	4.136	0.098
ZAR/GBP	0.296	1, 5	3.528	0.119
ZAR/AUD	0.334	1, 5	4.004	0.102
Hake TAC	-0.009	1, 5	0.946	0.376
Hake Export Values (ZAR 1000's) vs.				
ZAR/EURO	-0.168	1, 5	0.135	0.728
ZAR/USD	-0.156	1, 5	0.191	0.680
ZAR/GBP	-0.198	1, 5	0.007	0.937
ZAR/AUD	-0.116	1, 5	0.377	0.566
Hake TAC	0.108	1, 5	1.730	0.246

3.2. Qualitative results

3.2.1. General operation of the offshore hake trawling industry

Interviews with stakeholders indicated that there were two major business models that operated in the industry. The first type of company was highly vertically integrated, dealt with both fresh and frozen product (i.e. both sea-frozen and land-based processing), had a high level of value-adding (processing) of product (fish) and sold to both wholesale and retail on the domestic and international markets. The second type of company was less vertically integrated, primarily dealt with frozen product (freezer-trawled and sea-frozen fish) and generally sold to wholesale markets either domestically or for export. That being said, for the second type of company every processing or vessel cluster or conglomerate had a slightly different business strategy, different processing efficiency and minor differences in the way they dealt with their product. In other words there was heterogeneity between companies in terms of structure and business strategy (function).

3.2.2. The domestic and export markets for hake

Export market

The large offshore trawling companies interviewed stated that they exported most of their catch and that their collective exports formed the vast majority of South Africa's total annual hake exports. An industry representative estimated that about 70% of the TAC was exported annually (a value quite close to the whole-mass estimates of 55-65% obtained from the quantitative calculations in section 3.1). Offshore (and inshore trawling) dominated volume in terms of having the greatest proportion of quota. Additionally the longline sector was under-catching in terms of their quota and the handline sector had been virtually inactive in the preceding few years. (According to the offshore trawling industry, the longline sector was badly affected by a low Spanish demand for fresh hake, since they did not produce diversified product from their catch, e.g. by value-adding, and were highly focused on the Spanish and Portuguese whole, high-quality, fresh fish markets. The increase in fuel price also affected them negatively by hugely increasing their costs, because of the considerable amount of steaming.)

In terms of export markets, Spain was identified as South Africa's biggest customer for hake by all offshore trawling companies. One company estimated that as much as 85% of its exports went to Spain. Companies also identified northern Europe and Australia as important, albeit smaller, markets. Some exports were also destined for the United Kingdom and Germany, although companies suggested that a great deal of the fish landed there was on route to Spain and only a small proportion remained behind in the UK (according to most companies) and Germany (one company) for local consumption. These markets identified by industry correspond closely with the major export markets (those taking an annual average of more than 500 tons of hake from South Africa) that were identified in the analysis of TradeMap export data. These countries were: Spain, Italy, Portugal, UK, Australia, France, Germany, USA and the Netherlands, as summarized in Figure 3.6.

Exports of hake from South Africa could all be effectively treated as South African-caught hake, according to industry. This was because product imported into South Africa from South America and even Namibia was destined for local consumption. In the case of Namibia this was thought to be reinforced by the lower export tariffs on hake (0%) than for South Africa (7% or 11%). In other words, it would have been much cheaper for companies to (process and) export fish from Namibia directly rather than route it via South Africa for export elsewhere. However, it was thought likely that the reverse could occur. That is, that South African exports to Namibia were almost certainly destined for re-export elsewhere, because of the lower tariff on Namibian exports and because the Namibian domestic market was (and continues to be) virtually non-existent.

The rise of frozen product & product displacement on the export market

Companies indicated that with the onset of the international crisis in about 2008 there was a shift in the type of product exported. Before the crisis the desired and most valuable hake had been a large, freshly caught prime quality (PQ) fish. However, with the onset of the crisis and afterwards the major export products were processed and whole, headless frozen hake. The value and quantity of fresh fish exports, particularly of PQ, declined. Conversely, the frozen exports increased in quantity, representing a product displacement. Even large conglomerate companies reported a shift in the market towards frozen product, although they still kept about half of their catch in wet-fish and half in frozen fish. Smaller companies tended to stick to all or majority sea-frozen product caught on freezer trawlers.

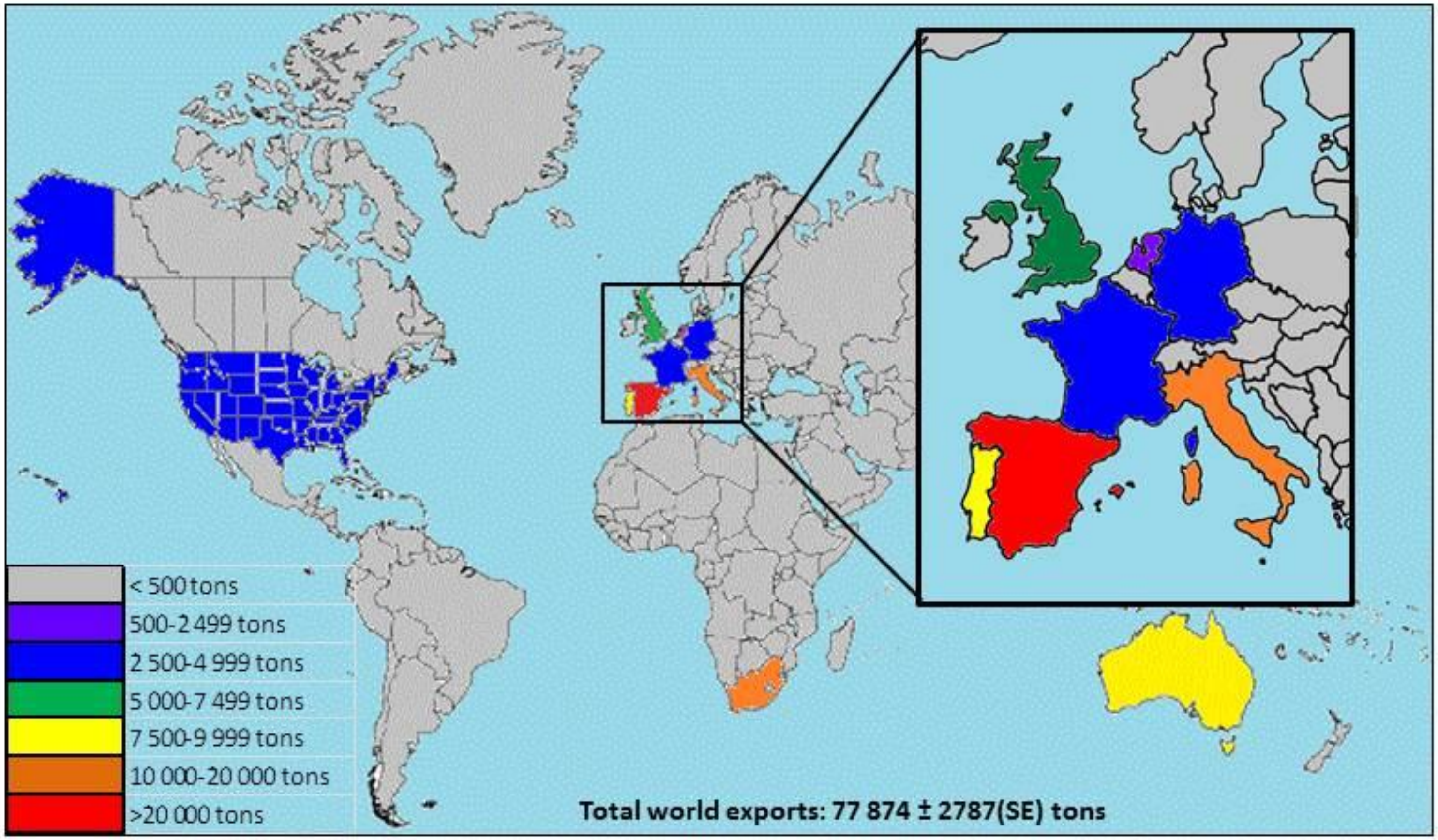

Figure 3.6: Major markets, shown by country, that purchased more than 500 tons of South African hake exports per annum, averaged for the 2005 to 2011 period. There were nine major countries whose volumes of hake purchases (tonnes) are indicated according to the colour key. Industry interviews and export data were used to estimate the size of the South African domestic market, which is also represented. Export data was extracted from South African Revenue Service (SARS) export data in the TradeMap database. See also Appendix 3, especially Table A3.3 for further details on annual exports of South African hake to major export markets.

The largest market for fresh and generally PQ fish[8] was Spain. This market had been willing to pay a premium for PQ hake that was air-freighted from South Africa before the crisis. However, two events coincided to erode this market.

Firstly, in Spain, fisheries policy over a few years preceding 2012 had allowed a much higher catch of fresh, longlined hake in Spain, driving their local prices of fresh hake down and providing a large amount of very fresh local product to the market there. Hake flown from South Africa to Spain was considerably more expensive (in Spain) than Spanish-landed hake because of the additional airfreight costs that fresh South African hake accrued to be immediately flown (retaining freshness) to Spain. Companies indicated that airfreight costs (an example ball-park price mentioned was €2.40 per kg) alone were the same as the market price (also around €2.40 per kg) of the locally-landed Spanish hake. The higher priced, fresh South African PQ hake (e.g. €4.50 per kg after air-freight) simply could not compete with this. One company indicated that five out of their six Spanish customers had stopped buying fresh PQ hake altogether due to the availability of cheaper Spanish-caught product. Asche and Guillen (2012) did an interesting study that indicated the general consumer preference in Spain for hake products of Spanish origin over hake from other locations such as South Africa[9]; given a lower price for Spanish-caught hake it is not then surprising that consumers bought less South African hake at that time.

The second reason for the Spanish market erosion that companies gave also centred on the high price of air-freighted, fresh PQ hake. The international banking crisis and subsequent recession in Spain had left consumers extremely price-conscious. In 2012 (and before) most consumers were buying frozen as a cheaper alternative to fresh South African hake in order to save on their household expenses. Frozen SA hake was (and is at present) shipped to Spain (Europe) by sea, which was a significantly cheaper freighting option and equated to a much lower price upon arrival in Spain. An industry representative estimated that in 2012 Spain was taking double the quantities of frozen as compared with fresh hake

[8] A PQ fish is usually a large, whole fish (hake) that has been caught, kept fresh on ice and transported in a short period of time (at most a few days) to port and landed. Generally considerations that make a hake PQ are the lack of parasites, high quality of the fish, large size, excellent appearance and the firm flesh texture and clear eyes indicating premium freshness. PQ fish is generally inspected and cleaned immediately on landing and rapidly air-freighted to its export destination to ensure its extreme freshness and quality.

[9] In the *Mercabarna* wholesale market in Barcelona, Spain, the origin of fish has been shown to be the main attribute that determines hake price; Mediterranean hake from Catalonia fetched the highest prices, followed by French and then Spanish Atlantic caught hake, while Namibia was the least preferred origin with an average price reduction of 7.60 Euros from the highest priced hake (Asche and Guillen, 2012). It is therefore not surprising that given a similar pricing of hake from South Africa and Spain, or a more expensive South African product relative to the reduced-price Spanish hake that Spanish hake would be chosen.

from SA. Export data for the period leading up to 2012 did not show this level of frozen product directly destined for the Spanish market, but rather similar volumes of fresh and frozen products, see Figure 3.7. However, a glance back at Figure 3.2 revealed that global frozen hake exports from South Africa were approximately double the quantity of fresh hake exported globally. It is quite plausible that frozen hake was first exported to another (European) country and then trans-shipped to Spain, not reflecting this trend reported by industry in the South African hake exports to Spain, but reflecting it in South African global exports.

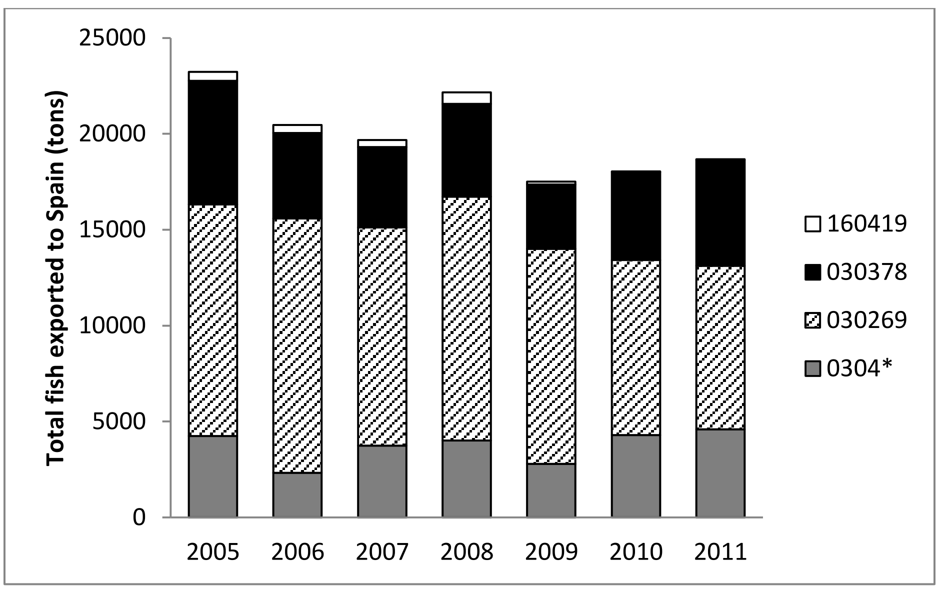

Figure 3.7: Total annual export quantities of hake products exported to Spain from South Africa under the Harmonized System (HS) codes that could include hake as extracted from South African Revenue Service (SARS) export data in TradeMap. The codes 160419, 030378 and 0304* represent almost exclusively frozen hake products, while 030269 represents only fresh products, as described in detail in Table 3.2. The HS code 0304* represents the aggregate of hake products exported as 030420, 030429 and 030499.

Companies pointed out that this market transition to largely (sea-)frozen product, with fresh product losing importance, had occurred over the five years up to 2012 (although there was a *slight* demand for wet fillet late in 2012) and that they believed that this change would persist over the long term. Smaller companies estimated that as much as 95% of their exports could be frozen product. Whereas, one or two of the larger companies stated that they still had a fairly even mix between freezer and wet-fish trawlers and that they exported as much as 8000 tons of fresh fish per year. Even these larger companies did point out the shift in the market towards frozen product, though. One effect of this product displacement was that longline companies were not able to sell (much) fresh fish and PQ hake onto the Spanish market, which was previously their main customer. As such, industry stakeholders suggested that the longline sector had been performing very poorly, trying to sell fresh fish cheaply onto the domestic market for at least the 3 years up to and including 2012, and that it had been struggling to break into other markets overseas. However, one company estimated that about 50% of fresh fish that was being exported from South Africa as of 2012 still came from the longline sector.

A shift to more frozen product could have meant an increased use of freezer trawlers as opposed to wet-fish vessels. This could have a number of implications for vessel and company behaviour, which need to be incorporated into model decisions. Firstly, companies indicated that freezer trawlers were much cheaper to run than wet-fish vessels per kg of fish caught or product produced. Secondly, the need for land-based processing was reduced as frozen fillets prepared at sea, or whole, headless frozen fish also frozen at sea merely need to be landed and shipped. Thirdly, some stakeholders pointed out that the use of freezer trawlers alone could significantly increase risk in the business; the sea-frozen (i.e. freezer-trawled) product market has been known to change very fast with rapidly falling prices, largely due to competition with product from Argentinian factory ships on the international market. In other words, it was pointed out that sea-frozen may yield high short term gains in terms of profit, but low long-term price and market stability.

Some companies reported that there had been another form of product displacement in the hake fishery. This displacement was away from whole fish toward increasingly processed (value-added) product, which was already ‘retail-ready’ without a perceived benefit in product price. In other words, export markets/clients have demanded a higher-end product at the same price as unprocessed, so trawling companies have had to invest much more money in processing the hake into fillets, loins, coated, battered or other value-added products without receiving a higher price per kg for the raw hake. This means that their profit margins (higher cost, same perceived sale value) have declined in order to retain clients. In 2012 growth was reported for the export fillet market.

Domestic market

The South African domestic market was said to be smaller than the export market for hake and most trawling companies and stakeholders indicated that it was largely a frozen fish market. This was because most distributors within South Africa were not geared for fresh fish distribution, only for frozen, making it difficult to supply fresh product within most of South Africa. Even in the Western Cape, where the fishery is based, almost all fish sold was previously frozen; fresh fish counters in grocery stores most often thaw and sell headless hake as 'fresh fish'. Companies that added value indicated that most value-added product sold in South Africa either came from sea-frozen South African product for sale to retailers, or from imported frozen fish that were re-processed locally and sold to wholesalers, e.g. Namibian fillets for the catering industry. Not all hake on the domestic market were *sea*-frozen. Companies with wet-fish vessels estimated that about 50% of fish on the domestic market were sea-frozen and 50% were from wet-fish vessels. Another company estimated that only about a third of South African hake on the domestic market were from the trawling sector and that there were a lot of longlined hake of a lower grade (for three years preceding 2012 due to a poor fresh export market).

There were also strong indications that a large proportion of the hake sold domestically were *not* South African in origin and that Namibian hake, in particular, were important (see also *Import substitution*). Stakeholders attributed this to South African consumers not being that discriminating on the basis of origin and more concerned about price, because of cheaper protein alternatives such as chicken. Local consumers were also believed to be accustomed to smaller fish and to largely buy value-added, e.g. crumbed or battered, fish products.

Large companies concentrated on value-added product supplied to retailers (about 70% of domestic sales) and to a lesser extent to the wholesale market (30%). One company estimated that they alone sold about 13 000 tons of hake annually onto the domestic market. Smaller trawling companies (in the sense that they have access to a smaller quota share) sold around 100% of their hake as wholesale on the domestic market. (These smaller companies did not have their own distribution networks to supply retailers and also preferred to receive immediate cash from sales rather than wait up to 90 days for retailers to pay.) Wholesale product would have been marketed largely to the service industry – catering, hospitality and fish and chip shop chains – and to local distributors and would typically be headed and gutted (H&G) frozen fish or fillets. Whereas, retail products were estimated to be about 40% fish fingers (mostly minced hake), 15% fillets, 30% coated fish, and the balance as other value-added products such as sauced products.

Overall, the domestic market was thought to have grown in the decade, particularly in the last few years, preceding 2012. It was reported to have absorbed a 'surprising' amount of hake from South Africa and Namibia following falls in European market demand. Some large companies found the local retail market to be favourable to the export market in the year or two preceding 2012. The growth in volume of fish sold was reported to have been largely in the wholesale (food service) sector, while retail volumes were constant at best. Value increases were seen in both; wholesale values increased by around 8%. (As a percentage of total retail food market in South Africa fish consumption had previously been declining.) Some companies reported better prices on the domestic market for all marine products than seen in previous years and some companies stated that export and domestic prices were not very different in 2012. There was some belief that the domestic market could be further 'educated' and grown to take up more hake in the event of a decline in exports in the future, but a price-drop would be necessary. Domestic market penetration was thought to have doubled in the 5 years preceding 2012, due to increases in the presence of seafood restaurants, but remained low overall – only about 20% of South Africans were estimated to have ever eaten hake.

A great deal of uncertainty in domestic demand and market price (particularly in wholesale) remained, primarily because the domestic market had largely been supply-driven and there were previous floodings of the market with local or foreign product, e.g. (often Namibian) baby hake, that quickly lowered the price. Many companies also still based decisions on whether to sell on the domestic market largely on exchange rate and whether a better return would be gained in South Africa or overseas.

Import substitution

The importation of substitute products, i.e. alternatives to domestic hake, was fairly important for the domestic market. An industry representative estimated annual hake-related imports equated to about

15% of the total allowable catch (TAC). All industry clusters were not purely local, but were fed by specialised importers (i.e. fishing clusters themselves often dealt with various imported products or fish). Imports tended to be frozen and to a large extent from Namibia. Products such as 'baby hake' (small hake sold whole, headless and frozen), fillets and frozen blocks, which were re-processed in SA, were imported. Imports often represented a cheaper alternative to locally-caught product, as the domestic market was thought to absorb only a limited amount of higher-priced hake product.

Imports also had a negative side. At times there had been international dumping of product on the local market from Namibia and other countries making it difficult to sell locally-caught hake in SA and reducing the price extensively. In some cases this resulted in sales of imported product at prices below the catch-cost of local product. This problem was thought to potentially have confounded with poorly performing European markets, since European exports were low for SA and Namibian product and Namibia sold much product onto the domestic market in SA reducing the price and demand for hake. This could have resulted in local companies having taken a price cut on the local as well as international markets. Namibian product was also said to have been sold at an under-valued price (i.e. compared to the international white-fish price) on the local market, because Namibian companies could not afford to wait for shipping and payment for product from Europe and would rather take a quick payment albeit at a lower value from SA buyers. A commonly cited example of market flooding over the four years preceding 2012 was importation of baby hake from Namibia. In years of good recruitment the catches of baby hake rose, but the demand for them was usually limited. It made financial sense for companies to sell the hake at a low price in the nearest market and cut losses rather than use limited storage space and/or pay for expensive storage. Large quantities had driven SA domestic market price for baby hake extremely low making it unprofitable for local companies to sell it. Consequently there was more processing of baby hake by some companies to value-added product.

Large amounts of imports could also have influenced the decision of whether to sell SA-caught hake on domestic or international markets, because substitution affected hake price parity. In other words, the availability of cheap imports locally which depress domestic hake prices could also have made export markets appear more attractive.

Domestic/export decision

Historically companies have long been largely export-based due to only a small domestic market for seafood. Stakeholders generally estimated that about 70 to 75% of hake TAC was exported and the remainder sold on the domestic market. A lot of imported product (±15% of hake TAC) was also sold on the local market, some of which was first processed in South Africa (indicating that at low prices the domestic market demand was larger than could be satisfied with surplus hake catches). The export market has remained dominant up to present times, but, as pointed out in the previous section, some hake has been sold domestically in the last decade and the export market had been performing poorly from the onset of the banking crisis and recession in Europe until the time of consultation. For this reason, a number of important factors came into play on companies' decisions of whether to export or sell domestically. These factors included the size mix of the catch, demand for hake and/or bycatch domestically and abroad, domestic and international price parity, exchange rate and long term relationships with clients. Companies reported being price-takers in both the international and domestic markets, i.e. there was no possibility of influencing local pricing of hake because of other imports and alternative proteins, so this did not affect the decision of whether to export.

The size mix of the catch typically influenced the acceptability of product for the export market. The export market was said to generally prefer larger fish and fillets, particularly southern Europe, while companies agreed that the domestic market, and other minor markets, were more accepting and accustomed to smaller fish. Small hake that were freezer-trawled were frequently sold on the domestic market as baby hake or were occasionally processed into value-added products. Companies that only did freezer trawling reported that they directly exported hake and bycatch >900g to 1 kg whole-mass as they were landed, without any processing ashore. Conversely the smaller hake (< 900g) that they landed were either directly exported or re-processed ashore for the local market. Lower value bycatch was often sold unprocessed (i.e. whole) to local companies that process it, while high-value bycatch species, such as monk and kingklip, were mainly exported. Companies agreed that an exception would be made to the 'only-large-for-export' rule for whole fish when catch rates for large fish were very low. In this case, smaller fish would be caught and exported.

The real price ratio between local and foreign markets was a key determinant of business decisions in the industry and was largely driven by two factors, exchange rate and the levels of demand. Most companies indicated that they sold to (or at least attempted to sell to) markets where they would get the best returns over the long term. As the SA Rand weakened additional export markets became viable for selling to because of (exchange rate driven) increased Rand returns. The domestic market was slow to track these exchange-rate induced price increases. All but one company indicated that they did *not* make decisions on overnight change in exchange rates, the Rand being a volatile currency, but rather on the basis of long term trends. One of the reasons behind this was that different markets purchased slightly different product types, which required different production lines. Changing production and operations of a factory was not something that they would change overnight and, as such, companies stuck by their markets for the long term, sometimes bearing (forex-driven) short-term losses. Companies were also reluctant to exit markets to take a short term profit on the basis of exchange rate.

Related to this was the tendency for companies to maintain and uphold long term relationships (five to ten years) and contracts with clients, irrespective of exchange rate and price changes. Relationships with large international clients and domestic retailers were considered particularly important. Companies stated that relationships were essential because quota and therefore the quantity of product companies could sell was limited, i.e. they could not supply everyone. Most companies said that they would stay with long term customers unless those markets became unviable for extended periods of time, particularly because they were reluctant to exit markets altogether. Anecdotes were relayed of past experiences of exiting international markets (e.g. the United States of America) proving unwise in the long term, because when economic conditions changed (Euro became unfavourable) it was near impossible to break back into those markets. In other words, there was an appearance of bounded rationality driven by uncertainty about future market conditions, exchange rates and quota allocations. Within these long term business relationships the type of product sold under contract might vary with the vagaries of fishing and higher prices might be argued from customers if product pricing had drastically changed internationally. Some companies also had insurance to protect against drastic changes in foreign exchange rates. Only one company stated that it treated hake as an international commodity and that it closely followed foreign-exchange pricing and adjusted its sales accordingly when there were a lot of short-term, rapid and severe fluctuations in exchange rates. This company indicated that if exchange rate was only changing very slowly then they would continue to supply the same customers over a longer term.

3.2.3. Effect of the international crisis and recession in Europe

With the international banking crisis in 2008 and 2009 and the subsequent recession in Europe there were significant downturns in export market volumes of hake purchased from South Africa and the prices paid. This was largely due to a drop in the financial status of export clients and a structural collapse. Subsequently there was a slight recovery in volumes that levelled off in 2012, but no recovery in prices was reported. Companies reported declines of as much as 50% turnover at the onset of the crisis, with some, but not full subsequent recovery in profitability. Pre-crisis as much as 80% of frozen catch and 80% of fresh, Prime Quality (PQ) fish was exported, whereas this had declined to 50% of frozen and 40-45% of wet-fish PQ post-crisis. Before the crisis there was also a price differentiation between fresh and frozen, which disappeared post-crisis.

Most of the changes in companies export behaviour were explained by the changes in one export market, Europe. Companies reported that the type of product demanded by European markets had changed with the crisis. Pre-crisis there had been bulk wholesale of hake to the European Union (EU), but subsequent to the crisis to sell in the EU companies had to produce supermarket quality, processed product with no increase in price paid per kg. (Increases in cost to produce value-added product due to inflation, rising labour costs and so forth could not be passed to the EU consumer.) There had been an increased demand for frozen fillets and, more recently, wet fillets. Overall, demand for fresh product had declined post-crisis; the decline in fresh, PQ represented more fish being processed to fillets for domestic and export markets. This shift was mostly reported to be due to sea-freight for frozen fish being significantly cheaper, and causing a cheaper end product, than the costly air-freight needed for fresh product, as discussed earlier, in a market where consumers had become very price-conscious.

Companies reported that before the crisis the 40% and 80% of their product that was for export accounted for 60% upwards of company revenue. Post-crisis export volumes were reported to have as much as halved by some companies and more importantly revenue from export was reported to have dropped as low as 30% of total revenue at one point. This later recovered so that by 2012 export accounted for about 50% of revenue. Companies also reported having to grow other markets, such as domestic and African, for hake. This meant that they had to take a significant price drop, reducing their profit margins significantly, as these markets were not willing to pay a premium for fish.

3.2.4. Thoughts on quantitative export analysis

All companies, save one, agreed that the overall quantities, values of exports and value per ton by HS product code were a good reflection of the actual values for the industry. One company thought that the volumes may have been a slight underestimation of actual volumes and that, especially, there were more fillets exported than indicated in the data.

There was a large drop in 2009 in volumes and value of exported hake. The reason for this was that in late 2008 the credit rating of many (large) European companies changed all of a sudden. Many banks called in their debts and re-evaluated the credit rating of their outstanding debt. In most cases they severely cut credit ratings. For some companies this meant that their loans and/or credit was downsized from as much as 8 million to 300 000 Euros almost overnight. They then had to come up with large amounts of money to pay off debts and their cash flow was reduced (no buying on credit). This was particularly bad in Spain, where Spanish companies were said to behave irrationally and on the basis of paranoia and there was difficulty in selling fish through the entire supply chain. Spain had a system of inventory buying, where large quantities of (frozen) fish would be held by inventory buyers that would then sell this stock on to other companies. This system worked differently to places like Italy where there was a rapid throughput of stock (and who continued buying from SA). When the credit rating was cut Spanish suppliers were holding extremely large quantities of stock and the buyers that they were selling to suddenly did not have the credit to buy stock. This meant that inventory buyers stopped buying SA hake for several months while they cleared the stock that they were holding and generated more capital for when they resumed purchasing. In other words, a ‘back up’ was generated through the entire supply chain. Once the inventories were cleared in late 2009/early 2010, things returned to a more normal situation where SA exports were going to Spain again.

As a more specific detail, companies also pointed out that there was a product displacement within the HS 160419 export code to more processed and therefore higher-value products, leading to the illusion of a greater value per ton of product. However, companies did not perceive this as an increase in profit. They were processing products more to obtain the same profit they were previously making on non-processed hake.

3.2.5.Important drivers of company behaviour

There were a number of important factors affecting company behaviour, including Catch Per Unit Effort (CPUE, a reflection of catchability of fish and under certain conditions stock abundance), TAC (a good reflection of relative population levels in the South African hake fishery example), fuel price, interactions between these three, fishing and operational costs, labour costs, exchange rate of major currencies with the South African Rand, size mix of catch, and less tangible issues such as perceptions of political stability, fishing right allocation uncertainties and ecological certification. All companies stated that their primary objective was to catch their entire allotted annual fishing quota within the horsepower effort restrictions imposed. This was partly motivated by concerns around being prejudiced against in future rights allocations should they under-catch. An industry representative stated that this motivation to catch regardless of fuel price or CPUE meant that this often represented an over-investment in fishing by companies.

After quota two major factors affecting the cost of fishing and therefore profitability were CPUE and fuel price; both of these have been subject to fluctuations in the last decade. Companies reported observing an increase in CPUE from 2008 and all but one company reported a drop in 2012. This CPUE drop, and hence fuel usage increase, was estimated to be from 390 to 500 litres of fuel per landed ton of fish. Companies continued to catch despite changes in CPUE so long as catching was still profitable, although they were willing to take short-term losses to catch their quota and meet contractual demands and trade these losses off against potential future gains. One industry representative identified that there were sometimes mismatches between TAC and CPUE because of time lags in CPUE being incorporated into hake population predictions and therefore TAC recommendations. This was thought to lead to mismatches between fishing capacity (number of boats) and CPUE, i.e. desynchronised investment. Most companies admitted, assuming that they would want to continue catching, that if CPUE were to decrease severely they would need more boats to be able to catch their quota, although in some cases lease agreements could be arranged.

The size mix of the catch was not only important for decisions relating to whether or not to export, as discussed in *Domestic/Export Decision*, but also for profitability. Small hake had very few options, they could only be processed to very small fillets or headed and gutted and sold in bulk, both of which yielded a low price per kg. If the catch was composed of larger fish the total tonnage and catch cost per ton was the same, but the processing costs on land were lower and there were more product options, so that a greater profit could be made. Most companies agreed that medium to medium-large sized fish were the most profitable and favoured because of a wide variety of product stream options and the ability to make perfectly graded, uniformly sized fillets. An industry representative pointed out that some companies tended to specialise in the size of fish they caught and processed, while others were more generalist, targeting specifically sized hake to meet product demands as they arose.

Foreign exchange rate similarly had other effects than just the decision of whether or not to export. It could affect baseline costs of fuel (based on ZAR/US$ exchange) as well as the Rand price of fish (ZAR/€). This could lead to complex interactions in profitability of product. Changes in exchange rates and tariffs or international duties could affect local as well as international pricing. For this reason many companies measured costs, pricing and profits in foreign exchange to assess 'actual performance'.

Related to this last point, the price of fuel had a large impact on cost to company; it was the single biggest cost to the fishing industry, constituting as much as 40% of costs. Companies could not avoid changes in the fuel price, but would try to swap to cheaper fuel when possible. Fuel was said not to have affected the core operations of the business, but that if fuel increased substantially it might make fishing non-viable or less viable at some point. The next biggest cost was labour, accounting for around 30% of costs; labour costs increased annually. Labour costs were more significant for companies that land-processed their fish. The remainder of costs were comprised of general operational costs, such as repair and replacement, maintenance and fishing gear, comprising about 30% of costs. Post-2008, annually increasing costs together with lowered retail price were reported to be squeezing the industry of its profits.

Most companies also listed ecological certification (most rightsholders in the offshore trawling industry have been Marine Stewardship Council – MSC - certified as sustainable) as a necessity and therefore an additional cost that they carried. Certification was a requirement to sell to clients in most EU countries (not in SA) and particularly to access the northern and/or central European markets. Some companies indicated that they did not receive a higher price for certified products, meaning that industry bore the cost of certification and this was not passed onto the customer. It would therefore seem that it provided a benefit in terms of maintaining or broadening market access rather than improved pricing.

Unexpectedly, political issues (particularly surrounding uncertainties and interventions) appeared to be an important factor affecting the perception of companies and indirectly their behaviour. Meetings with industry coincided with a period of dissatisfaction with, and uncertainty within, the Department of Agriculture, Forestry and Fisheries in 2012, which undoubtedly heightened the issues. The major concern that industry voiced was over the uncertainty in future rights allocations (2016 inshore hake trawl and 2021 offshore hake trawl) and over maintaining their MSC certification, which represented a significant investment. Both of these hampered predictability of on-going business and were said to hinder re-investment into the industry. An industry representative stated that the closer to the deadline for rights reallocation, the more effect the uncertainty would have on business strategy. The other major political concern was over general political and social stability within the country as a whole. Industry pointed out that social and political upheaval such as labour strikes around mining and issues on nationalisation affect the exchange rate and economic climate, which has a large effect on export-related business, particularly because these events tend to be unexpected and make exchange rates and costs hard to predict.

3.2.6. Vessels

Vessel attributes

The split between whether fish was trawled fresh or frozen was vessel-designated. The two vessel types and attributes, with averages as given by companies, are described in Table 3.5 (descriptions on the overall fleet composition and numbers of vessels are provided in Chapter 2). The fresh product that wet-fish vessels produced was primarily PQ product for export and fish for value-adding. Whereas, freezer trawlers tended to produce sea-frozen fillets and H&G whole fish. Freezer trawlers cost more to run on a daily basis, but they actually cost less per ton of landed fish. Fresh fish was reported as more expensive to catch per ton, but to have more final product options. Wet-fish vessels had short turn-around times to land fish as fresh as possible. For this reason, and to reduce lost fishing days and fuel, vessels tried to reduce steaming days. That being said, vessels were said to travel to suitable fishing grounds regardless of fuel price. Companies that had both wet-fish and freezer trawlers stated that their fleets were not sufficiently large to make decisions on which vessels to send out at certain times. Rather they had attempted to keep all vessels active throughout the year as far as possible and to retire vessels over several years to reduce excess capacity in the fleet to levels where all vessels retained were active vessels. Fleet capacity did not change over the short term.

Table 3.5: The number of average vessel trips per year and what they entail.

	turnaround time	time to trip end	number of turnarounds per year	running cost (ZAR/day)	product	processing on board
Wet-fish vessel	6 days	3 to 4 turnarounds	54	120 000	fresh	minimal
Freezer trawler	20 days	n.a.	8 to 14[§]	200 000	frozen	yes

[§]can assume 1 trip/turnaround per month for freezer trawlers

Number of vessels deployed

All companies responded that they aim to keep all vessels active for as much of the year as possible in order to provide a constant supply of product to clients and to keep their staff employed and factory operational. Thus all except one company said there was little or no seasonality in their vessel deployment. The exception stated that it up-scaled its extractive capacity during the favourable season and kept a baseline activity during unfavourable times. Companies were also in agreement that vessel activity had declined through time as excess capacity was reduced, particularly in the seven years preceding 2012. CPUE had been high for three to four years preceding 2012 enabling reduction in vessel numbers, since fewer vessels were needed to catch the constrained quota. There were some concerns that if CPUE dropped drastically and it was still profitable to go fishing (or at least that losses would not be sustained over the long term)[10]more vessels would be needed and it would take at least one year to purchase a second-hand vessel or two years to have one built. Companies also stated that capital investment in a new or second-hand vessel was a major decision and implied that it required certainty in returns as well as political certainty.

Ownership and use of vessels was found to be fairly complex. At one end of the scale were the large vertically-integrated companies that held single rights and owned multiple vessels, while at the other end were vessels on which several rights were fished. In the first instance conglomerate companies in addition to using their entire fleet, as described above, may also have had catch arrangements with other companies. These companies could have been vessels or processing companies that had no quota in their own right, or more rarely, they may have been a quota-holder or vessel operator that had no

[10]This stems from the fact that companies will take short-term losses to continue meeting their contractual obligations of supplying fish and also to ensure that they catch their annual allotted quota. As discussed elsewhere, companies considered their ability to demonstrate to government that they had the capacity to catch their allotted quota to be important for future rights allocations.

processing operation. In the second instance, some vessels may have caught their limited quota and then the quota of one or several other rightsholders in the same year. The fish from these different quotas generally would have had distinct processing routes. Effectively, these companies lease or share the vessel for most of the year, because effort restriction forced them to catch their quota within a short period. The effort restriction, which was suggested by industry, takes the form of limitation of sea-days on the basis of an adjusted shaft horsepower (i.e. engine power) of vessels (SADSTIA, 2013).

Decision of where to fish

The decision of where to fish was based largely on the CPUE of fish, i.e. where to maximize catch, and secondarily where to obtain appropriate size-mix for products. Size-mix was more important for some companies than others; they indicated that if unfavourably sized fish were being caught they would either adjust location or effort so as to catch when or where a more favourable size-mix was available. Fuel price was not a deciding factor on where to fish, or when to fish. However, its interaction with CPUE was considered important and, where possible, companies would fish closer to home-port to reduce costs. One company pointed out that fishing further from home-port could add 10% to fuel costs and another suggested that CPUE had been high in the years immediately preceding 2012 minimizing the impact of higher fuel costs. Fishing closer to home-port when possible reduced fuel and wage costs and therefore kept the cost per kg of landed fish lower as well as ensured (in the case of wet-fish vessels) that fish were landed as fresh as possible. Limitation of effort in the form of horsepower-days only extended to fishing-days and therefore did not affect decisions on the steaming days to get to a fishing area.

The decision of where to fish appeared to be part company-directive driven and part skipper intuition/choice. Companies constantly did catch-cost analyses and would sometimes send directives for all boats to fish in a temporarily productive area or to pause fishing in bad weather conditions. In terms of vessel directives, the objective for vessels was first to find a particular fish size for a product and secondarily to fill the vessel. Fishing vessels have also been known to leave an area because of (high-levels of) undesirable bycatch.

Fishing grounds

All companies sent their vessels to fish more on the Western and the Eastern Agulhas Bank Areas[11] during the summer months and the West Coast (Cape Point and northwards) during the winter. The reason for this was that larger fish could be found in the respective areas at those times. During the winter the weather conditions in the Agulhas Bank area became too extreme and the currents too bad to easily fish there. Fishing on the Eastern Agulhas Bank (EAB) was said to add significantly to the steaming costs. The warmer water there also tended to yield fish of lower quality flesh and made refrigeration harder so that some companies stated that they would only fish on the EAB if the catch was significantly better (i.e. when it was much lower in the west). Weather had apparently been observed to be less predictable than historically in the three to four years preceding 2012, with catches low on the EAB in summer for at least two years. In 2012 conditions were more favourable there. During the change of seasons catch rates were also said to typically be low. Some companies estimated that overall more fishing occurred on the West Coast because there was typically higher primary productivity there and, also their home ports were based there. Only minor processing of hake was performed in the EAB, in Mossel Bay and Port Elizabeth.

3.2.7.Time scales

Timescales of consumption and processing were identified as being seasonal in nature. Prices were also thought to be affected by the seasonal availability of fish in the global market. However, longer term trends of changes in consumption, vessel activity and fish processing were also noted.

[11] In this thesis the Western Agulhas Bank is the coastal shelf area to the west of Cape Agulhas until Cape Point and the Eastern Agulhas Bank is the coastal shelf area to the east of Cape Agulhas until the area around Port Elizabeth.

4. Discussion & conclusion

Overall there was much consensus between the qualitative information that companies independently told me. Similarly there was concord between these qualitative data and my quantitative findings. This has resulted in a great deal of confidence in the quantitative economic analysis carried out as well as in the qualitative data from companies. Therefore, it should be safe to assume that the data presented in this chapter should be a sound basis on which to build the prototype agent-based model (ABM) in the following chapter. Meetings with industry also reaffirmed the choice of an ABM for the system, since there was heterogeneity in company strategies, processing efficiencies, number and type of vessels and end products, as well as potential system level patterns emerging from the collective behaviours of many individual companies in a complex system.

The information outlined in detail in the results, both quantitative and qualitative, that applies to the ABM in the following chapters can be summarised as follows. Both quantitative and qualitative estimates of export volumes were in the order of around 60 -70% of TAC being exported. The major export market for hake products (see detailed data in Appendix 3, Figure A3.3) was quantitatively and qualitatively identified as Spain. According to industry, all hake exports from South Africa could be treated as having been caught in domestic waters, because lower tariffs from Namibia discouraged export of Namibian hake through South Africa.

It was suggested that the recent trend in the export volumes of hake was away from fresh, whole PQ hake to frozen product and fillets. A trend of increased fillet (0304--) export volumes and decreased fresh, whole fish (030269) from 2008 onwards could be seen when gross volumes were converted to whole-mass equivalents; i.e. more of the actual catch was being processed to fillets and exported. According to industry much of the loss in volume of fresh exports was due to a decline in the Spanish market for fresh South African hake (observed, see Appendix 3, Figure A3.4) and represented a major decline in exports of longlined product. Suggested implications of this were that much of the longlined product had been re-routed to the SA domestic market and that there was a higher reliance on freezer trawling. The latter brings with it an associated reduction in land-based processing and some risks of frozen fish price instability on the international market in the face of competition from Argentinian factory ships. The ability of the industry to swap from fresh to frozen product, though, has remained a key aspect in allowing the industry to remain profitable by shifting its product stream to match international demand and to reduce catch costs to retain profit margin (freezer trawling bears a lower cost per ton of landed catch).

Companies also reported a slow product displacement towards increasingly more processed (value-added) product for export, without gaining a greater overall benefit. A great deal of value-added product was exported under the 160419 HS code (e.g. crumbed, frozen hake fillets) and an increasing price per kilogram (kg) can be seen for this code after 2008. Companies stated that this increase in price per kg of processed fish did not translate into a perceived price increase per kg of the whole, unprocessed fish from which the product was made. Rather, overall profits had not increased, since this price increase represented a product displacement toward increasingly value-added product where higher production costs were involved. They suggested that they had to increase processing levels to be able to continue to sell to international clients. Companies also mentioned that prior to the crisis there was good price differentiation between fresh and frozen product, but that this disappeared post-crisis. This could be observed in the quantitative data as a convergence in price between whole fresh (030269) and whole frozen (030378) hake after 2008.

It was not possible to obtain quantitative data for the domestic market and so qualitative data estimates of its performance and size must instead be used for informative and modelling purposes. The domestic market was said to be much smaller than the export market, taking about 30% of domestic TAC plus additional import volumes (largely from Namibia) being the equivalent of about another 15% of hake TAC. The price paid on the domestic market was also reported to be much lower than that obtained for exports, although it had improved slightly in recent years. Of locally supplied product, the trawling industry was estimated to only meet about a third of the demand, with longline and imports said to have catered the rest. If the domestic market is assumed to have consumed the equivalent of about 45% of annual TAC, including (the ±15%) imports, this would equate to approximately 64 600 tons per annum (taking the average TAC for 2002-2012); not an insubstantial amount. This value was also not altogether surprising, given that one large company estimated it sold about 13 000 tons to the domestic market. According to companies this market remained price-conscious, though, and treated cheaper proteins, e.g. chicken, as suitable substitutes for fish, making it difficult to grow value.

Companies that had a mixture of wet-fish and freezer trawler vessels estimated that the domestic market took about 50% each of fresh and frozen. These companies tended to make about 70% of their domestic sales to retailers and the other 30% to wholesalers (service industry, distributors and fish and chip shop chains), while smaller, frozen-only operators tended to sell 100% to wholesale. Growth in the domestic market had been predominantly in the wholesale sector, with values having increased at both wholesale and retail. Wholesale clients bought predominantly frozen fillets, while retail market demanded value added product (which was approximately 40% fish fingers, 15% fillets, 30% coated fish and 15% other value-added products).

Companies responded that the decision to export or to sell domestically was based primarily on size mix of the catch, demand for hake, price ratio, exchange rate (which also heavily influences price ratio) and long term relationships with clients. Indeed, proof could be found for exchange rate, since a positive and significant regression was found between annual volumes exported and the Rand/Euro exchange rate. Companies stated that decisions tended to be in response to long term shifts in exchange rate fluctuations and not short term fluxes.

Qualitative data on company and vessel operational decisions that were relevant for the ABM also emerged. The primary objective of all companies (as a proxy for rightsholders) was to catch their entire allotted annual fishing quota within the horsepower effort restrictions imposed. This was an overriding driver, with companies catching their quota even while bearing short-term losses because of unfavourable CPUE and fuel price interactions. (CPUE is viewed by companies as affecting catch rate and quantity of effort required to catch their quota. As such, it interacts with fuel price to determine the catch cost per ton. An unfavourable interaction between the two would be one where catch cost becomes high, reducing profits.) This behaviour was posited to be overarchingly driven by concerns of being prejudiced against in future rights allocations should they under-catch their quota. After this, CPUE, fuel price and size-mix of catch affected profitability and fishing location decisions.

Companies aimed to keep their vessels active throughout the year, at least as far as offshore trawling was concerned, and no vessels would generally be held back from deployment; seasonal changes in the number of vessels were generally not reported. Related to this vessel-sharing and leasing, particularly among small rightsholders, did occur so that vessel-owners could keep their vessels active throughout the year even once their own quota was used early in the year. Product processing lines were kept separate for different vessel users.

Of more relevance to the ecology of the hake ecosystem rather than to the economic ABM, it was found that the companies' decisions on where to fish were largely based on recent histories of CPUE and where the desired size-mix of fish could be caught (companies constantly collect and monitor these data closely). This could represent a possible link from the economic model to an ecological model in future, beyond the scope of the thesis. Fuel did not affect decisions directly, except that if similar CPUE and size-mix could be found closer to home port then this area would be fished. Vessel captains aimed to first find desired fish size and then secondarily to fill the vessel. There appear to be seasonal fishing grounds; the Agulhas Bank in summer and the West Coast in winter, when larger fish can be found in these areas. Companies suggested that overall there was more offshore hake trawling on the West Coast because of higher productivity and their home-ports being found there.

When building the model the above considerations should provide valuable information on function and should inform decisions.

CHAPTER 4:

MODELLING THE HAKE TRAWLING INDUSTRY IN SOUTH AFRICA – AGENT-BASED MODEL DESIGN AND IMPLEMENTATION

Chapter 4: Modelling the hake trawling industry in South Africa: Agent-based model design and implementation

1. Introduction

The hake fishery accounts for more than 50% of the overall value of South African fisheries (Butterworth and Rademeyer, 2005; Powers *et al.*, 2010), and is estimated to generate around 30 000 jobs (Rademeyer *et al.*, 2008a). As pointed out in Chapter 1, the fishery is largely accounted for by its offshore demersal trawl sector that takes 85% of the catch (Field *et al.*, 2013), and hence most of the revenue. Given the importance of the offshore demersal hake trawl fishery and that little literature exists on the structure and function of the fishery, the analyses of Chapters 2 and 3 were carried out. These chapters have begun to make inroads in presenting structural and preliminary information on the hake fishery in general, and specifically on the offshore trawl sector. Using existing literature and information with the results from these chapters it is possible to form hypotheses on the fishery. Modelling can serve as an important tool for testing these hypotheses, organizing the systems thinking process with regard to the industry and further identifying important areas for future research expansion. Modelling provides the next step in understanding and exploring questions surrounding the dynamics of the South African offshore demersal hake trawl fishery.

To effectively manage a fishery it has become increasingly understood that there need to be explicit social and economic goals in addition to ecological goals. To determine what these goals should be, a comprehensive, or at the very least an adequate, knowledge of the fishery's ecological, social and economic systems is needed. A modelling framework to assist understanding the economic conditions in the fishery and drivers of the economic system will be very valuable in this regard. The ultimate objective of the modelling process is, as far as possible, to clarify thinking around what good objectives could potentially be for the fishery, which could help to inform possible management strategies.

The modelling approach is particularly suited to understanding and testing some hypotheses on the structure and dynamics of the economics of the offshore demersal hake trawling industry, because i) data are limited, ii) the data collected and analysed in the previous chapters (2 and 3) of this thesis provided information on structure and qualitative functioning of the system, in addition to some quantitative information, allowing for construction of the model, but not extensive quantitative analyses, iii) system-level questions are asked and following from this iv) for a thorough quantitative analysis a huge amount of data collection would be necessary and this would be too expensive, labour-intensive and sensitive (due to the private business nature of the data) to collect.

Agent-based modelling (ABM) has been identified in Chapter 1 as a methodology particularly relevant to this complex offshore fishery. Both the economic and ecological systems of this fishing sector span a range of scales (e.g. Perry and Ommer, 2003; Cumming *et al.*, 2006) and are complex adaptive systems, which, according to Costanza *et al.* (1993), means that simply aggregating the behaviour of the system's parts will not represent the true nature of the whole system. ABM can model these complex systems where the simple, rational choices of heterogeneous individuals and their interactions can sometimes lead to unintended or unexpected consequences at the system (e.g. fishery/resource/ecosystem) level, which can for example be important for understanding the unintended or unexpected consequences of policies (e.g. Ommer and Team, 2007). As summarised from the discussion in Chapter 1, ABMs have been widely applied in economics (Deissenberg *et al.*, 2008; Fuks and Kawa, 2009; Kawa, 2009; Nolan *et al.*, 2009; Nair and Vidal, 2011), including in agricultural resource economic applications such as in value chains. But they have been little used in economic applications in a fisheries context. Where such applications do exist they have centred around topics such as understanding fleet dynamics (Little *et al.*, 2004; Soulié and Thébaud, 2006; Schafer, 2007; Wilson *et al.*, 2007; Yu *et al.*, 2009a; Bastardie *et al.*, 2010; Cabral *et al.*, 2010), fishing strategies (Boschetti and Brede, 2009), and the effects of individual transferable quotas on fishing fleet behaviour, discarding, catch-levels, and profitability, among others (Little *et al.*, 2009). Economic applications of ABMs in fisheries represent a significant area for development, and given some of the similarities between existing ABM applications and the study at hand, an ABM appears the logical choice to apply in this study.

As shown in Chapter 2, the companies involved in extraction and processing of hake in the offshore demersal hake trawling sector are heterogeneous; they have different structures, vessel fleets, product types that they produce, sizes and proportions of quota and presumably target markets. Following from this is the broad hypothesis that changes in market forces in terms of volume, price, product type demanded (e.g. fresh vs frozen) will have dissimilar effects on different types of companies (i.e. those with varying structures and capacities for producing certain product types, e.g. fresh vs sea-frozen product). An ABM is the ideal means for testing this given that heterogeneity can be modelled explicitly.

The broad aim of this chapter is therefore, to gain a preliminary understanding of the dynamics of the Southern African offshore demersal hake trawl fishery, which operates in the Southern Benguela, between target resource and markets with regard to its structure. That is, this prototype of the model will specifically i) explore changes in international and national market demands on the quantity of fish extracted in the SA hake fishery and on overall company sales or wastage, ii) explore scenarios of changes in total allowable catch (TAC) and iii) explore changes in frozen vs fresh demand of export and local markets for fish at the level of the entire industry and for each broad agent category.

2. Methods

2.1. A note on prototyping

Starfield and Jarre (2011) suggest building a final model through a series of prototypes with the first simple prototype built as fast as possible, simplifying assumptions listed and then the model tested. Subsequent prototypes are then built in much the same manner in incremental steps of complexity with full assumption listing and testing at each stage. Producing this first rapid prototype and testing it provides several advantages, including (i) not stalling the modelling process due to data gaps or poor data and (ii) rapidly producing preliminary results that allow an assessment of what the model is capable of, how different disciplinary aspects of the model interact, the direction the model development could/should take, and allow refinement or reconsideration of the model objectives (see Starfield and Jarre, 2011 for more advantages). These advantages make prototyping the method of choice for the development of this model. Rapid prototyping is a technique that is particularly useful for interdisciplinary modelling, since it minimizes problems such as imbalance in the model, data gaps, uncertainty in interpreting results and confusion in model objectives (Starfield and Jarre, 2011). This chapter covers the construction of the first prototype, within the context of one full iteration of the modelling cycle.

2.2. Conceptual framework for model

The details of the structure and function of the offshore hake trawling industry detailed in Chapters 2 and 3 form much of the conceptual framework for this model. A full, detailed description of the model follows. Figure 4.1 provides a schematic of the industry structure from fish to markets and a comprehensive (though not exhaustive) list of all types of major drivers that act on the industry in the real world.

2.3. Model design

Of the drivers listed in Figure 4.1 only a few, including the overall demand for fresh and frozen fish, the proportion fresh and frozen fish that each market (export countries or domestic) demands, TAC and individual company quotas, were examined in this first model prototype, *HakeSim 1.0*.

In order to represent the simplified structure of the trawling industry (described in Chapter 2), i) fishing vessels, ii) companies or company clusters that operate as a single entity processing and marketing fish and iii) clients in the form of international importing countries or domestic markets were created as agents in the model (Figure 4.2). Fish (fresh and frozen hake) was used as a *currency*[12] in the model and at all levels demand for fish was segregated into fresh and frozen. Depending on the stage of processing of hake in the model this may be tons of unprocessed hake caught or 'wasted' (i.e. discarded) or tons of processed product sold by companies to international markets. On a monthly time step the model simulates catching, processing and marketing of hake. It examines how changes in drivers such as international markets or TAC affected the industry as a whole at the processing and vessel level.

The eleven 'client' agents in the model represented the South African domestic market and ten international countries that formed the major importing markets for exported South African hake, i.e. those who imported more than 500 tons of South African hake per annum for the data period, identified in Chapter 3 as Spain, Italy, Portugal, UK, Australia, France, Germany, USA, the Netherlands and one substitute agent that represented the total demand of other small importing countries. 'Client' agents were given a demand for fresh and frozen fish as an input to the model. Based on this demand they

[12] Currency in this sense is a modelling term for some unit that is exchanged between different agents or entities in the model and is not currency in the monetary sense. In this version of the model the only model currency was fresh or frozen hake (measured in tons), but in Chapter 6 for version 3 of the model an additional 'currency' is added, which is actual money (Rands and Euros).

bought fish from as many companies as necessary to satisfy their demand. Individual 'clients' were activated by the model at random to execute their procedures and they purchased from random companies.

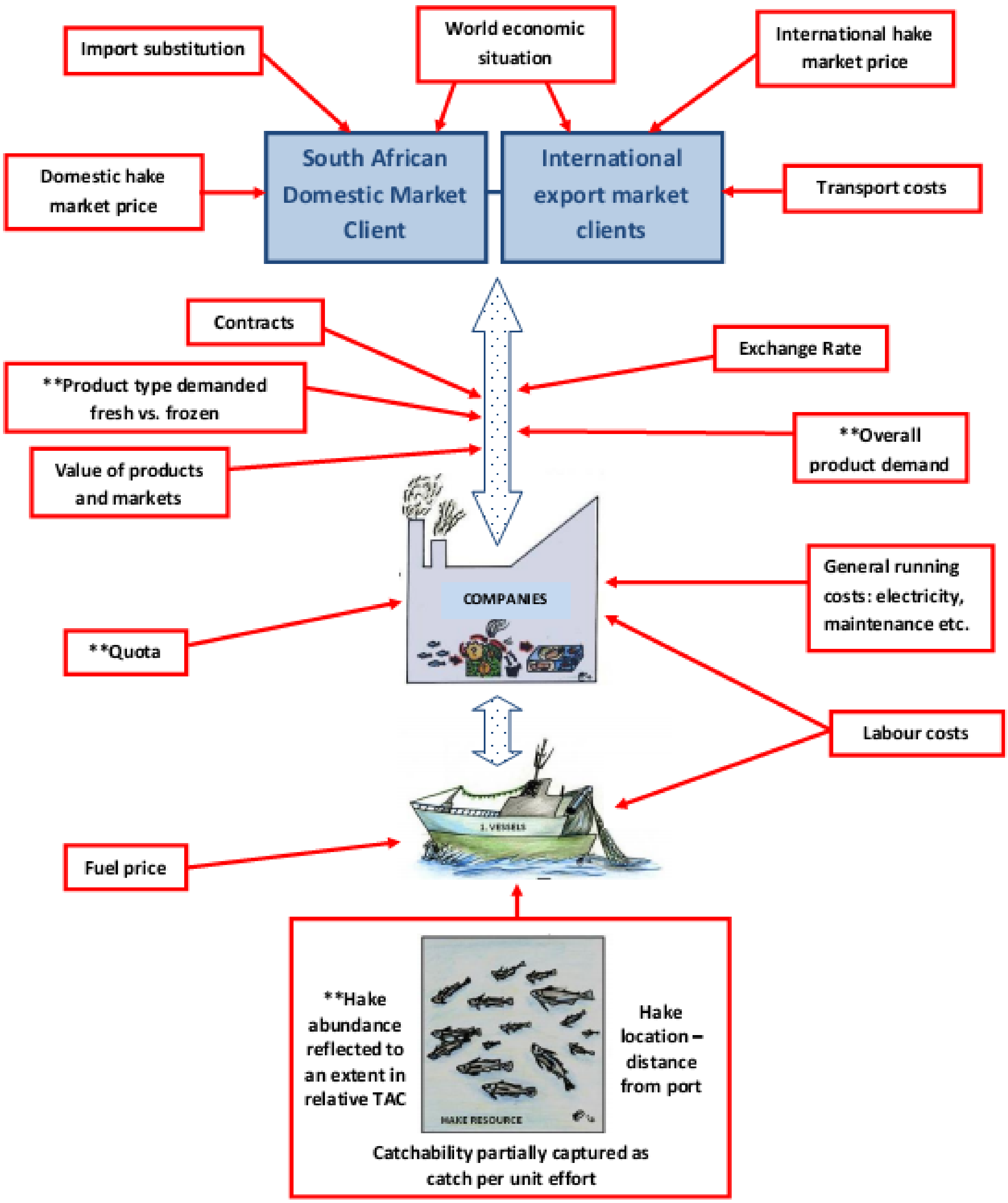

Figure 4.1: A variety of drivers known to affect the offshore demersal hake trawling industry in South Africa. Parameters captured in the first prototype model *HakeSim 1.0* are marked **. Illustrations by Rachel Cooper.

Companies, or company clusters, provided a representation of the actual clusters that existed in the industry as of 2013 (see Figure 2.1 for details; eight clusters were used and cluster E was ignored as it had been absorbed officially by another medium cluster). There were two large clusters that collectively took 62.8% of the demersal offshore hake trawl TAC (which was equivalent to 52.9% of global hake TAC, i.e. the TAC including all hake-targeted sectors), owned 20 vessels and specialized in a mix of freezer trawled (i.e. sea-frozen) and wet-fish product (i.e. fresh fish). Three medium clusters owned 26.6% of offshore TAC (22.5% of global TAC) and 22 vessels, produced predominantly freezer trawled product (one company did a mix with wet-fish) and only one of the companies did much processing of product. Finally, there were two small clusters that owned 3.7% of offshore TAC (3.1% of global TAC) and three vessels, only caught freezer-trawled product and did minimal processing, and one super-cluster of small clusters that owned 7% of offshore TAC (5.9% global TAC), five vessels and which was assumed to only catch freezer-trawled product and not process its fish. There were therefore four breeds of company agent. Each of these breeds was represented by a single agent in the model, which combined the total quantity of rights and vessels actually held by those company breeds and sold the appropriate product types. The large companies did a high level of processing, the medium rightsholders did an intermediate level and the small and super-cluster agents did little processing. This was represented in the range of processing efficiencies per agent. An estimation, based on the company data for rightsholder clusters represented in Chapter 2, was used for the number of wet-fish vessels versus freezer trawlers owned per agent type: large agent – 60% (12) wet-fish vessels, 20% (4) freezer trawlers and 20% (4) large factory freezer trawlers; medium agent – 18% (4) wet-fish vessels, 73% (16) freezer stern trawlers and 9% (2) large factory freezer trawlers; small agent – three freezer trawlers; and super-cluster agent – five freezer trawlers. In this prototype of the model, for each 'company' agent the total quota held by the agent was evenly split between all vessels.

During industry consultation TAC and hence quota were considered the two most important limiting factors by most companies. Overall market demand and specific demand for fresh versus frozen product were identified as important processes in the real world system, see Chapter 3, as international market forces and price had forced a shift of the market towards (relatively) cheaper frozen product (lower international freight costs for frozen than fresh) and more highly processed product. This was suggested by stakeholders to have had a significant effect on the industry and a shift in export volumes of different products appeared to confirm this. For later versions of the model frozen vs. wet-fish product is expected to have a good deal of financial significance at a number of different levels; wet-fish and freezer trawler vessels have significantly different running costs and different 'catch cost per ton' (i.e. the cost of catching one landed ton of fish) values, also these products fetch completely different prices on the international/national market and are favoured by different international clients. It therefore seemed important that this distinction was captured in the earliest stages of prototyping.

The first prototype of the model therefore included some of the key drivers in Chapters 2 and 3 that were possible to model with just fish (hake) as a currency in the model (see Table 4.1 for full list of model inputs). This allowed for the simplest possible prototype to be made, following Starfield and Jarre (2011), while still providing a good starting point for hypothesis testing in the model. Given that this was the first and therefore simplest prototype of the model, a large number of assumptions were made (Table 4.2).

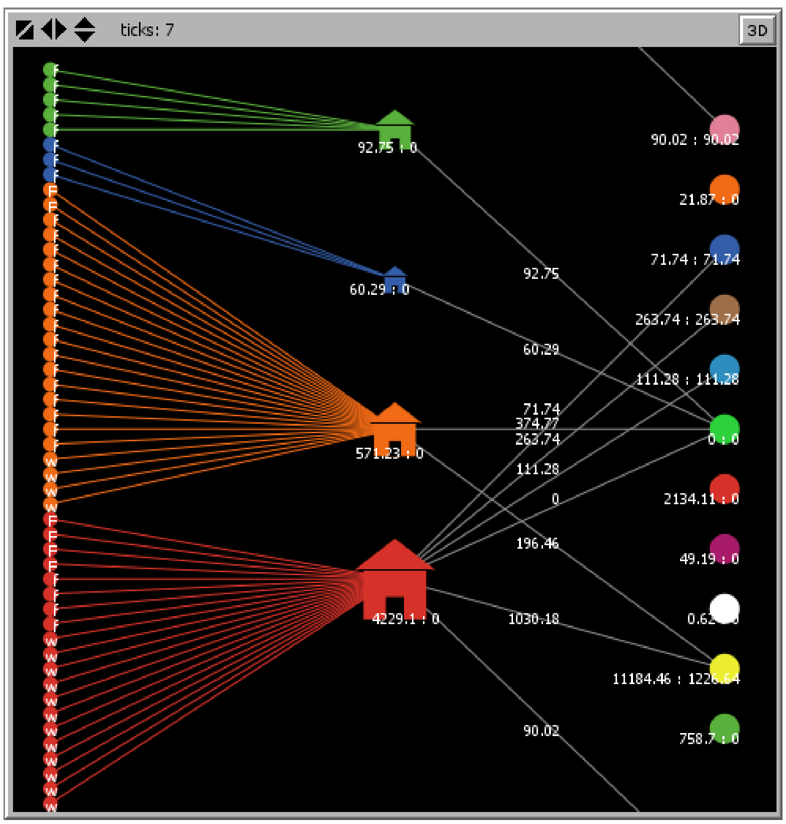

Figure 4.2: A screenshot of the model interface showing the 50 vessels to the left, 4 companies (large, medium, small and super-cluster types) in the centre and 11 client agents to the right. The lines connecting agents indicate some transactions of fish. Since the model is nonspatial the interface is just a simple visualization of the model structure.

Table 4.1: Input variables and output monitors for the first model prototype.

	Type	Agent(s) it applies to	Brief description
Input variables			
quota	proportion of 1	companies	*right = proportion of TAC that is allocated to companies, % value transformed to proportion.*
frozen processing efficiency	proportion of 1	companies	*the efficiency with which companies process whole fresh fish into final product*
fresh processing efficiency	proportion of 1	companies	*the efficiency with which companies process whole frozen fish into final product*
client demand	tons	clients	*the quantity of fish that clients demand (total of fresh and frozen fish)*
proportion frozen	proportion of 1	clients	*the proportion that frozen fish accounts out of all fish demanded by a client*
TAC	tons	entire model	*the total allowable catch, allocated annually*
Monitors			
world frozen demand	tons	clients	*the total demand for frozen fish made by all clients in the model*
world fresh demand	tons	clients	*the total demand for fresh fish made by all clients in the model*
world total demand	tons	clients	*the total demand for all fish made by all clients in the model*
world frozen fish bought	tons	clients	*the total quantity of frozen fish purchased by all clients in the model*
world fresh fish bought	tons	clients	*the total quantity of fresh fish purchased by all clients in the model*
world all fish bought	tons	clients	*the total quantity of all fish purchased by all clients in the model*
world fresh unsold	tons	companies	*the total quantity of all fresh fish that was not sold, summed for all companies in model*
world frozen unsold	tons	companies	*the total quantity of all frozen fish that was not sold, summed for all companies in model*
world all unsold	tons	companies	*the total quantity of all fish that was not sold, summed for all companies in model*
world fresh caught	tons	companies	*the total quantity of fresh fish caught by all wet-fish vessels of companies*
world frozen caught	tons	companies	*the total quantity of frozen fish caught by all wet-fish vessels of companies*
world all caught	tons	companies	*the total quantity of all fish caught by all wet-fish vessels of companies*
world fresh processed	tons	companies	*the total quantity of fresh fish produced through processing of whole, fresh fish caught*
world frozen processed	tons	companies	*the total quantity of frozen fish produced through processing of whole, frozen fish caught*
world all processed	tons	companies	*the total quantity of all fish produced through processing of all whole fish caught*
world fresh wasted	tons	companies	*the total quantity of fresh fish that is discarded as a result of processing (i.e. unusable parts)*
world frozen wasted	tons	companies	*the total quantity of frozen fish that is discarded as a result of processing (i.e. unusable parts)*
world all fish wasted	tons	companies	*the total quantity of all fish that is discarded as a result of processing (i.e. unusable parts)*
world active frozen vessels	number	vessels	*the number of frozen vessels that are actively fishing in a time-step*
world active fresh vessels	number	vessels	*the number of fresh vessels that are actively fishing in a time-step*

Table 4.2: Assumptions made in the first model prototype and reasons why they were or had to be made.

	Assumptions	Why
1	***Frozen and fresh fish weight can be used as a currency in the model rather than money***	Only fish is used as a *model currency* as this was the simplest functional and meaningful prototype that could be produced. Fish can still be transferred and transactions can be measured as fresh or frozen fish volume.
2	***There is no storage of fish (either fresh or frozen) by any agent between time steps, i.e. If vessels contained excess fish beyond company demand, fish was effectively lost since vessel fish stocks were reset to zero at every time step.***	Storage would complicate the prototype making it difficult to analyse trends and conduct sensitivity analyses. In the real world fish is sold relatively quickly, so storage by companies can be assumed to be negligible.
3	***Vessels fill their capacity between 50 and 100% each month,***	*Based on the qualitative data from interviews that most companies drive captains to come back with full vessels at every fishing trip.* In reality vessels would be as close to full as possible, but the random draw helps to simulate some of the vagaries of fishing that changes in CPUE cause. Additionally, companies indicated that they catch their entire quota in a year as far as possible, thus later versions of the model will need to closer approach this reality and incorporate changes in CPUE in the monetary cost of fishing.
4	***TAC and % quota are the only explicit limiting factors on quantity of fish caught, while other vagaries of fishing e.g. catchability, interaction between fuel price and distance to trawling grounds are ignored.***	This follows the prototyping approach of building the simplest prototype first. Industry indicated that TAC and quota were the single biggest limiting factors that they also had no control over. Thus it was essential to capture these in the first prototype.
5	***Fishing trips can be summed on a monthly basis,***	This simplifies the time-step of the model. The time step was selected to be compatible with OSMOSE ecosystem model to facilitate the possibility of future coupling. TradeMap data and DAFF data are easily available at the month level. *In reality fishing trip length and turnaround time between trips differs by vessel types and companies*
6	***Companies catch their quota uniformly throughout the year and evenly between vessels (i.e. quota weight is divided evenly among 12 months and vessels)***	In reality companies indicated that they tried to spread their catch evenly throughout the year to ensure constant fish supply to clients and keep employees in work.
7	***All vessels are active at all time steps***	This is simplified from reality in such a way that vessel function is still achieved, keeping the prototype as simple as possible. In reality not all vessels are active at all times, leading to vessel decommissioning through time.
8	***Numbers for fresh fish and freezer trawlers are an accurate representation of the industry***	It was seen as essential to split fresh and frozen fish at all levels of the industry to answer the questions.
9	***Other fishing sectors of hake (e.g. longline or inshore trawl) have no effect on the fishing fleet, companies or clients in the model***	In reality this is not true, but since offshore trawling accounts for 85% of the catch and the other sectors were less active in recent years it meant the majority of industry could be captured with only data on the major sector.
10	***A single average agent will represent the behaviour of all agents of the same breed***	This allowed companies with similar behaviour to be aggregated as single agents, allowing sensitivity analysis and monitoring of model function to be easier.
11	***Quantities of frozen product purchased by clients (international figures) represents product that was sea-frozen and not product that was caught on wet-fish vessels and later land-frozen***	In reality some of fresh product may later be frozen, but it is impossible to make reliable estimates. It is therefore better to split fresh and frozen throughout the model.
12	***Countries are a good proxy for clients; individual contracts between fishing companies and client companies are not relevant***	In reality contracts are very important for companies. But given that most of these contracts are over the long term, gross exports were assumed to be a proxy for all companies within one country.

Table 4.2 continued.

	Assumptions	Why
13	***Fish meal is ignored in the model.***	Offal and other waste has recently been reported to be taken back to shore and turned into white fish meal which is sold. This accounts only a small proportion of the fish caught. This fish meal market is also a side market and does not bear any major weight in terms of income in relation to hake exports. It is also difficult to identify any fixed quantitative estimates for revenue or volumes, although both are said to be small. It is therefore ignored for the purposes of the model.
14	***Company agents were assumed to represent the combined real world companies that fell into the classes small, medium, large or super-cluster, as defined in Chapter 2.***	Numbers of vessels, quantity of rights and processing efficiencies were aggregated for the real world companies from the same class and represented by a single agent. Real world companies from the different agent classes behaved similarly and had similar attributes, making it possible to group them.
15	***Individual countries bought from the companies at random.***	In the real world specific companies do business with other companies with whom they have contracts in specific countries. However, countries instead of companies that buy SA hake are represented in the model to sum exports. It is therefore assumed that having countries buy from companies at random will balance out. This assumption is necessary, because company-specific data on clients and contracts are confidential, while export data at the country level can easily be accessed.

2.4. Model implementation

The agent-based model *HakeSim1.0* was implemented in Netlogo v5.0.1. Companies read the demand of clients (i.e. the model input) to determine whether there was demand for fresh and frozen fish. They then 'executed' (i.e. dispatched) freezer and/or wet-fish vessels to fish, as appropriate. Once vessels had fished, companies took fish from vessels to satisfy their fresh and frozen demand. Companies then processed fish which was either fresh or frozen, according to their processing efficiency. The processing efficiency was based on an aggregate conversion factor for fresh and frozen fish types calculated from the DAFF conversion factors (Table 3.2) and based on information obtained from qualitative stakeholder data on the typical products that the different company types produced. Estimated conversion values are given in Table 4.3 (the inverse value represents conversion from whole-mass to processed product). First product-mix specific conversion factor values were calculated for every company by weighting the individual conversion factors of the different types of products (Table 3.2) according to the percentage of those product types that companies sold. Since model agents represented several small, medium, or large companies, the final processing conversion factor values given in Table 4.3 were based on the product-mix specific conversion factors averaged for all small, medium or large companies based on the size of those companies' rights shares.

There were a total of 50 vessels in the model, as described above. They have a set maximum monthly storage capacity (i.e. tonnage that they can catch) calculated as:

((% quota of agent*TAC/12)/number of vessels owned by parent company cluster) .... (4.1)

Vessel agents were owned by and therefore linked to specific company agents throughout the entire model run. They were all executed to fish by their respective (company) agents at each time step, in accordance with client demand. Fishing vessels executed a 'go-fishing' behaviour where they took a random (stochastic) draw (between 50 and 100%) of their maximum monthly storage capacity for fish (tons); the resulting randomly drawn percentage represented vessel fullness. Freezer trawlers 'landed' their catch as frozen fish and wet-fish trawlers 'landed' unfrozen (i.e. fresh) fish. They then transferred the fish to their parent companies, in the company's "buy fish" procedure, in order to meet the fresh/frozen demand of parent companies. If vessels contained excess fish beyond company demand, fish was effectively lost as vessel fish stocks were reset to zero at every time step (i.e. there was no storage of fish by vessels or companies between time-steps).

Client agents were activated in a random order to execute a "buy" procedure in the model. Once activated, they read their respective model inputs of (hake) demand and proportion of frozen fish demanded and randomly selected a company agent from which to collect fish. The selected company agent then transferred fresh and/or frozen fish to the respective client agent to satisfy its demand for fresh and frozen fish. Where necessary, the client agent continued to select company agents at random until its demand was satisfied or no company agents had any fish left to transfer.

To summarise, with the aim to adhere to international best practice, the model was built via abstraction of the real world system, in line with the objectives and question set out, and created a simplified representation of the real world (Gilbert and Terna, 2000; Starfield and Jarre, 2011), using the qualitative and quantitative data described in Chapters 2 and 3 and stakeholder and expert consultation, to guide parameterization and development.

The model behaviour was then calibrated with/validated against observations in the real world to improve/determine the quality of the model output relative to its objectives (Gilbert and Terna, 2000; Farmer and Foley, 2009; Starfield and Jarre, 2011). Models were analysed, tested – sensitivity and robustness analyses (Grimm and Railsback, 2005), and used to draw some conclusions about the system they were investigating. They attempted to best answer the research question through hypothesis testing.

Table 4.3: Conversion factors for small, medium and large clusters based on DAFF conversion factors that were weighted according to confidential, qualitative information companies provided on their product mix and the relative size of company rights. The value for small clusters can equally be applied to the super-cluster.

	conversion factor	inverse
Small	1.46	0.68
Medium	1.81	0.55
Large	1.68	0.60

3. <u>Results and Discussion</u>

3.1. Model testing

Throughout development of the model, testing of varying inputs and examining outputs and model behaviour was constantly carried out, as was debugging, as each new procedure was added. Procedures were tested individually and agent monitors and plots were checked. Basic procedures were also replicated in Microsoft Excel to verify the outputs of each procedure at the agent level.

Once the model prototype was fully functional and all procedures were coded basic *ad hoc* testing was carried out to ascertain that the model was running. This involved using extreme values as an input to the basic model interface, such as making countries have zero or extremely high values of demand, creating situations where there would be all frozen or all fresh fish in the model to determine whether any erratic behaviour could be observed. This in essence involved debugging.

Following this a full sensitivity analysis was carried out to determine whether any erroneous behaviour remained in the model.

3.2. Sensitivity analysis

First, in order to optimize time and computer power, the optimum number of model runs, i.e. the minimum number of runs that would sufficiently capture the variation of outputs, was determined. To achieve this 100, 200, 500, 1000 and 2000 replicate model runs were performed for each of the major input variables (TAC, domestic and Spanish demand for fish, domestic and Spanish proportion of frozen fish, large company cluster fresh and frozen processing efficiencies, and quotas of large, medium and small clusters and the super-cluster) for a normal, zero and double normal input value. Both the coefficient of variation (CV) and the standard deviation (SD) were calculated for each corresponding output. These were assessed to determine at which number of model runs the CV and SD of outputs stabilized. It was found that CV and SD of all outputs at 100 runs sufficiently captured the variation (CV and SD), for input variable values tested (Table 4.4). Therefore for all subsequent model testing the standard of 100 replicate runs was used as the optimum number of replicate runs in relation to computing time and stable outputs.

Table 4.4: The standard deviation (StdDev) and coefficient of variation (CV) of all model outputs for standard (*in italics*) and low and high extreme domestic demand inputs, for different numbers of replicate model runs. Outputs do not differ significantly between different numbers of replicate runs.

number of runs	domestic demand (tons)	StdDev of world_fresh_fish_caught	StdDev of world_frozen_fish_caught	StdDev of world_all_fish_caught	StdDev of world_fresh_stock_processed	StdDev of world_frozen_stock_processed	StdDev of world_stock_processed	StdDev of world_fresh_fish_wasted	StdDev of world_frozen_fish_wasted	StdDev of world_all_fish_wasted	StdDev of world_frozen_demand	StdDev of world_fresh_demand	StdDev of world_client_demand	StdDev of world_frozen_fish_bought	StdDev of world_fresh_fish_bought	StdDev of world_all_fish_bought	StdDev of world_frozen_fish_unsold	StdDev of world_fresh_fish_unsold	StdDev of world_all_fish_unsold	StdDev of world_active_frozen_vessels	StdDev of world_active_fresh_vessels
100	**0**	333.75	379.81	711.20	176.56	308.97	484.13	157.19	70.97	227.24	2860.59	1260.90	4121.49	308.97	176.56	484.13	0.00	0.00	0.00	3.08	1.45
200	**0**	333.38	379.58	710.62	176.37	308.76	483.74	157.02	70.95	227.05	2860.53	1260.88	4121.40	308.76	176.37	483.74	0.00	0.00	0.00	3.08	1.45
500	**0**	333.12	379.52	710.31	176.23	308.74	483.58	156.89	70.92	226.90	2860.49	1260.86	4121.35	308.74	176.23	483.58	0.00	0.00	0.00	3.08	1.45
1000	**0**	333.23	379.62	710.52	176.29	308.80	483.71	156.94	70.95	226.98	2860.48	1260.86	4121.34	308.80	176.29	483.71	0.00	0.00	0.00	3.08	1.45
2000	**0**	333.03	379.46	710.16	176.18	308.68	483.48	156.85	70.91	226.86	2860.47	1260.85	4121.33	308.68	176.18	483.48	0.00	0.00	0.00	3.08	1.45
100	***15174***	***333.11***	***379.57***	***710.35***	***176.22***	***308.76***	***483.60***	***156.89***	***70.94***	***226.92***	***4165.69***	***1329.59***	***5495.29***	***308.76***	***176.22***	***483.60***	***0.00***	***0.00***	***0.00***	***3.08***	***1.45***
200	***15174***	***333.34***	***379.48***	***710.46***	***176.34***	***308.70***	***483.64***	***157.00***	***70.91***	***226.99***	***4165.61***	***1329.57***	***5495.17***	***308.70***	***176.34***	***483.64***	***0.00***	***0.00***	***0.00***	***3.08***	***1.45***
500	***15174***	***333.07***	***379.55***	***710.30***	***176.21***	***308.75***	***483.58***	***156.87***	***70.93***	***226.89***	***4165.56***	***1329.55***	***5495.11***	***308.75***	***176.21***	***483.58***	***0.00***	***0.00***	***0.00***	***3.08***	***1.45***
1000	***15174***	***333.04***	***379.42***	***710.13***	***176.18***	***308.64***	***483.45***	***156.85***	***70.91***	***226.85***	***4165.54***	***1329.54***	***5495.08***	***308.64***	***176.18***	***483.45***	***0.00***	***0.00***	***0.00***	***3.08***	***1.45***
2000	***15174***	***333.39***	***379.75***	***710.80***	***176.37***	***308.92***	***483.90***	***157.02***	***70.96***	***227.07***	***4165.53***	***1329.54***	***5495.07***	***308.92***	***176.37***	***483.90***	***0.00***	***0.00***	***0.00***	***3.08***	***1.45***
100	**30348**	333.57	380.40	711.64	176.46	309.44	484.52	157.11	71.09	227.28	5470.80	1398.28	6869.09	309.44	176.46	484.52	0.00	0.00	0.00	3.08	1.45
200	**30348**	332.71	379.07	709.43	176.01	308.36	482.98	156.70	70.84	226.62	5470.69	1398.25	6868.94	308.36	176.01	482.98	0.00	0.00	0.00	3.08	1.45
500	**30348**	333.66	379.88	711.21	176.51	309.02	484.16	157.14	70.99	227.22	5470.62	1398.24	6868.86	309.02	176.51	484.16	0.00	0.00	0.00	3.08	1.45
1000	**30348**	333.12	379.58	710.37	176.23	308.77	483.62	156.89	70.94	226.92	5470.60	1398.23	6868.83	308.77	176.23	483.62	0.00	0.00	0.00	3.08	1.45
2000	**30348**	332.90	379.26	709.83	176.11	308.51	483.24	156.79	70.88	226.75	5470.59	1398.23	6868.82	308.51	176.11	483.24	0.00	0.00	0.00	3.08	1.45

number of runs	domestic demand (tons)	CV of world_fresh_fish_caught	CV of world_frozen_fish_caught	CV of world_all_fish_caught	CV of world_fresh_stock_processed	CV of world_frozen_stock_processed	CV of world_stock_processed	CV of world_fresh_fish_wasted	CV of world_frozen_fish_wasted	CV of world_all_fish_waste d	CV of world_frozen_demand	CV of world_fresh_demand	CV of world_client_demand	CV of world_frozen_fish_bought	CV of world_fresh_fish_bought	CV of world_all_fish_bought	CV of world_frozen_fish_unsold	CV of world_fresh_fish_unsold	CV of world_all_fish_unsold	CV of world_active_frozen_vessels	CV of world_active_fresh_vessels
100	**0**	0.11	0.10	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.10	0.11	0.10	-	-	-	0.09	0.09
200	**0**	0.11	0.10	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.10	0.11	0.10	-	-	-	0.09	0.09
500	**0**	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.10	0.10	0.10	-	-	-	0.09	0.09
1000	**0**	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.10	0.10	0.10	-	-	-	0.09	0.09
2000	**0**	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.10	0.10	0.10	-	-	-	0.09	0.09
100	***15174***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.09***	***0.09***	***0.09***	***0.10***	***0.10***	***0.10***	-	-	-	***0.09***	***0.09***
200	***15174***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.09***	***0.09***	***0.09***	***0.10***	***0.10***	***0.10***	-	-	-	***0.09***	***0.09***
500	***15174***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.09***	***0.09***	***0.09***	***0.10***	***0.10***	***0.10***	-	-	-	***0.09***	***0.09***
1000	***15174***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.09***	***0.09***	***0.09***	***0.10***	***0.10***	***0.10***	-	-	-	***0.09***	***0.09***
2000	***15174***	***0.10***	***0.10***	***0.10***	***0.11***	***0.10***	***0.10***	***0.10***	***0.10***	***0.10***	***0.09***	***0.09***	***0.09***	***0.10***	***0.11***	***0.10***	-	-	-	***0.09***	***0.09***
100	**30348**	0.11	0.10	0.10	0.11	0.10	0.10	0.11	0.10	0.10	0.09	0.09	0.09	0.10	0.11	0.10	-	-	-	0.09	0.09
200	**30348**	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.10	0.10	0.10	-	-	-	0.09	0.09
500	**30348**	0.11	0.10	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.10	0.11	0.10	-	-	-	0.09	0.09
1000	**30348**	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.10	0.10	0.10	-	-	-	0.09	0.09
2000	**30348**	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.10	0.10	0.10	-	-	-	0.09	0.09

Subsequently, a thorough sensitivity analysis was conducted, where input variables were manipulated one by one to assess their effects on output. For each input variable in the model a range of different values was used and the changes in all model outputs were assessed relative to a standard run, i.e. a run where average values observed in the real world were used for all input variables. This was done by assessing the % change in each output relative to the % change in the input (averaged over 100 replicate runs) from the average standard run, which is used as a benchmark. That is, for example, if one input variable was increased by 50% from the input value used in the standard run it follows that corresponding outputs from the test model runs should have increased by 50% from standard, at least for TAC, which can then be used as a benchmark to assess the relative sensitivity of the model to other variables. Thus the ratio of a test run output relative to the standard run output scaled according to the variation in input would be 1. Any ratio less than 1 would indicate that the output deviated less and the model was not very sensitive to changes in that particular input variable. Any ratio greater than 1 would mean that the model was more sensitive to that particular input variable (see Figure 4.3). This ratio of actual change relative to predicted change in output was measured for every output variable for every single input variable at values of -100% (i.e. 0), -50%, (i.e. half), -30%, -20%, -10%, +10%, +20%, +30%, +50% and +100% (i.e. double) of the standard run input value. The exception to this was values that were ratios, i.e. processing efficiency and frozen relative to fresh fish ratio. These were varied as far as possible by the %'s above but within the bounds of 0 as minimum and 1 as maximum. Additionally quota (i.e. proportion of rights) inputs were varied by increasing or decreasing the quota of one company and decreasing or increasing other companies' quota in proportion to their average contribution to total quota, such that the sum of all companies quota was always 1 (i.e. all rights sum to 100%). See Appendix 4 for details of all inputs used for sensitivity analyses, including for company quota.

From Table 4.5 it is apparent that the majority of model outputs were sensitive to total allowable catch. This is unsurprising given that all of the output variables sensitive to this are measures of fish at some stage in the processing line and the quantity of fish available at each stage is based exclusively on the amount of fish that arrives into the market from fishing and the quantity of fish caught is determined by TAC. Model outputs measuring demand were not driven by TAC, which follows since demand is calculated independently of TAC in the model. In the real world companies identified TAC as an important limiting factor on their operations, since they could not catch more fish than TAC allowed regardless of demand and had no power to change or influence TAC. As such, its role as a primary driver of the model is realistic and acceptable.

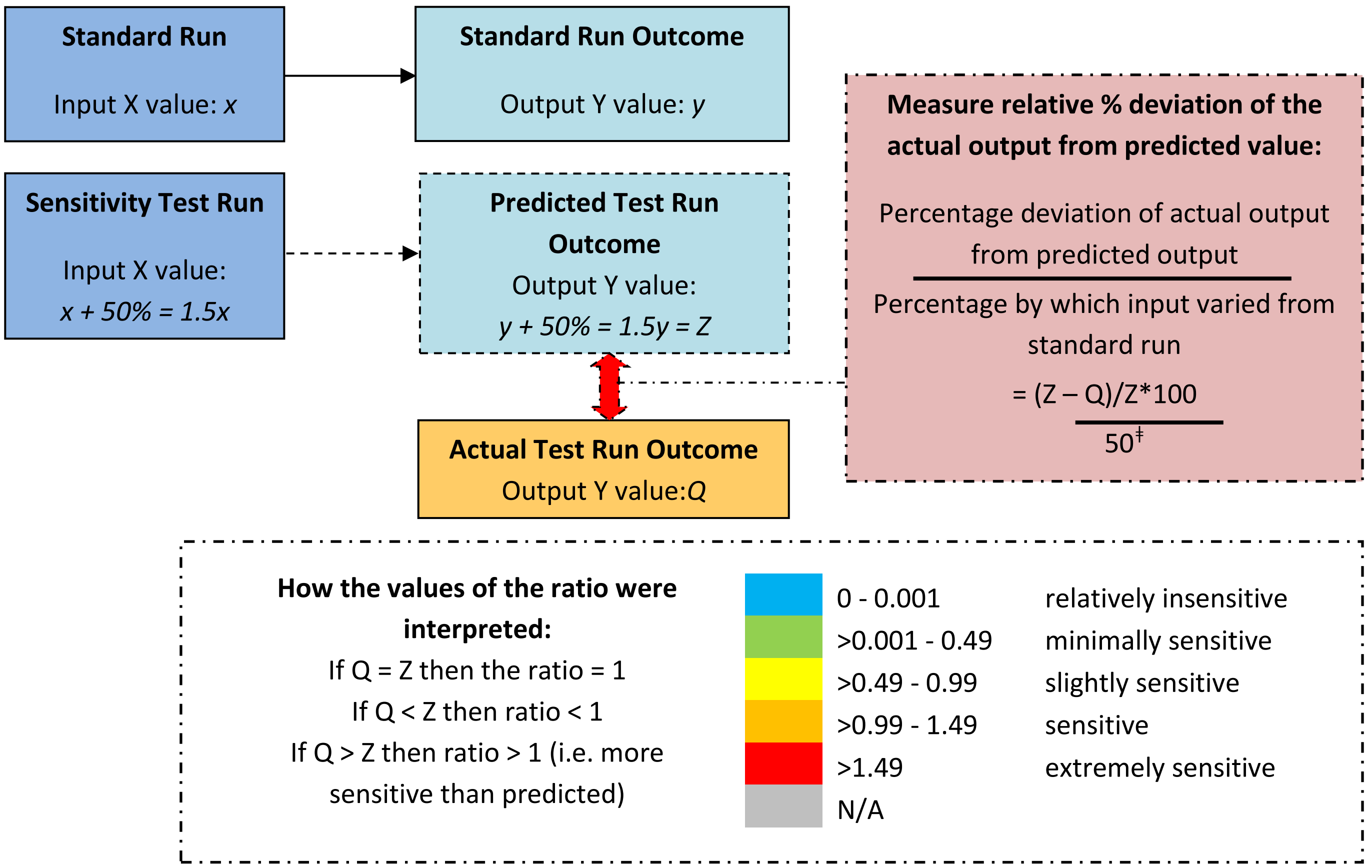

Figure 4.3: Flowchart of the calculation of the results of the sensitivity analysis, in the form of sensitivity ratios. In this example a percentage deviation of 50% from the standard run is given, but these percentage deviations in input from the standard run ranged from -100% to +100% (i.e. that is from 0 to double) in the actual sensitivity analysis. [†]The value 50 is used since the percentage variation of input from standard was 50 in this example.

Table 4.5: The input variables that were varied and the sensitivity of the resulting outputs. The maximum sensitivity for each variable was reported and can be checked against the key.

Input variable	Ave. world_fresh_fish_caught	Ave. world_frozen_fish_caught	Ave. world_all_fish_caught	Ave. world_fresh_stock_processed	Ave. world_frozen_stock_processed	Ave. world_stock_processed	Ave. world_fresh_fish_wasted	Ave. world_frozen_fish_wasted	Ave. world_all_fish_wasted
TAC	1.002	1.001	1.001	1.002	1.001	1.001	1.002	1.001	1.001
Australia demand	0.004	0.001	0.003	0.004	0.001	0.002	0.004	0.002	0.003
Domestic demand	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.004	0.006
France demand	0.004	0.002	0.003	0.004	0.002	0.003	0.004	0.002	0.003
Germany demand	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
Italy demand	0.004	0.006	0.005	0.004	0.006	0.005	0.004	0.007	0.005
Netherlands demand	0.006	0.004	0.005	0.006	0.004	0.005	0.006	0.004	0.005
Other demand	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.003	0.004
Portugal demand	0.010	0.008	0.009	0.010	0.008	0.009	0.010	0.007	0.009
Spain demand	0.009	0.007	0.008	0.009	0.007	0.008	0.009	0.008	0.009
UK demand	0.005	0.004	0.004	0.005	0.004	0.004	0.005	0.004	0.005
USA demand	0.006	0.007	0.006	0.006	0.006	0.006	0.006	0.007	0.006
Australia prop frozen	0.007	0.003	0.005	0.007	0.003	0.004	0.007	0.002	0.005
Domestic prop frozen	0.005	0.003	0.004	0.005	0.003	0.004	0.005	0.003	0.004
France prop frozen	0.010	0.009	0.009	0.010	0.009	0.009	0.010	0.009	0.009
Germany prop frozen	0.010	0.006	0.007	0.010	0.005	0.007	0.010	0.007	0.008
Italy prop frozen	0.003	0.002	0.003	0.003	0.002	0.003	0.003	0.002	0.003
Netherlands prop frozen	0.003	0.006	0.005	0.003	0.006	0.005	0.003	0.006	0.004
Other prop frozen	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.010	0.011
Portugal prop frozen	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Spain prop frozen	0.013	0.006	0.009	0.013	0.006	0.008	0.012	0.006	0.010
UK prop frozen	0.005	0.003	0.004	0.005	0.003	0.004	0.005	0.004	0.005
USA prop frozen	0.003	0.002	0.003	0.003	0.002	0.002	0.003	0.002	0.003
Large frozen efficiency	0.010	0.006	0.007	0.010	0.837	0.540	0.010	3.608	1.146
Medium frozen efficiency	0.007	0.004	0.005	0.007	0.128	0.084	0.007	0.539	0.175
Small frozen efficiency	0.008	0.008	0.008	0.008	0.028	0.021	0.008	0.092	0.032
Super-cluster frozen efficiency	0.010	0.006	0.008	0.010	0.027	0.019	0.010	0.108	0.041
Large fresh efficiency	0.007	0.004	0.005	0.893	0.003	0.322	1.003	0.004	0.687
Medium fresh efficiency	0.005	0.003	0.004	0.115	0.003	0.042	0.131	0.003	0.090
Small fresh efficiency	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.004	0.004
Super-Cluster fresh efficiency	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
large company quota high	0.758	0.627	0.688	0.762	0.643	0.686	0.753	0.558	0.691
large company quota low	0.796	0.504	0.639	0.800	0.547	0.638	0.793	0.316	0.642
large company quota medium	1.423	1.515	0.157	1.416	1.027	0.151	1.431	3.633	0.171
medium company quota high	0.143	0.132	0.137	0.145	0.131	0.136	0.140	0.138	0.140
medium company quota low	0.011	0.090	0.054	0.013	0.075	0.053	0.009	0.159	0.056
medium company quota medium	0.382	0.209	0.289	0.385	0.233	0.288	0.379	0.103	0.292
small company quota high	0.032	0.006	0.018	0.032	0.011	0.018	0.032	0.012	0.018
small company quota low	0.022	0.001	0.011	0.022	0.005	0.011	0.022	0.014	0.011
small company quota medium	0.042	0.011	0.025	0.042	0.016	0.025	0.042	0.010	0.025
super-cluster quota high	0.063	0.033	0.047	0.063	0.038	0.047	0.063	0.011	0.046
super-cluster quota low	0.043	0.029	0.035	0.043	0.031	0.035	0.043	0.018	0.035
super-cluster quota medium	0.085	0.037	0.059	0.085	0.045	0.059	0.085	0.004	0.059

Table 4.5 continued.

Input variable	Ave. world_frozen_demand	Ave. world_fresh_demand	Ave. world_client_demand	Ave. world_frozen_fish_bought	Ave. world_fresh_fish_bought	Ave. world_all_fish_bought	Ave. world_active_frozen_vessels	Ave. world_active_fresh_vessels
TAC	0.000	0.000	0.000	1.001	1.002	1.001	0.000	0.000
Australia demand	0.079	0.000	0.060	0.001	0.004	0.002	0.000	0.000
Domestic demand	0.313	0.052	0.250	0.006	0.006	0.006	0.000	0.000
France demand	0.040	0.008	0.032	0.002	0.004	0.003	0.000	0.000
Germany demand	0.030	0.018	0.027	0.007	0.007	0.007	0.000	0.000
Italy demand	0.134	0.000	0.102	0.006	0.004	0.005	0.000	0.000
Netherlands demand	0.013	0.001	0.010	0.004	0.006	0.005	0.000	0.000
Other demand	0.038	0.006	0.030	0.004	0.004	0.004	0.000	0.000
Portugal demand	0.101	0.003	0.077	0.008	0.010	0.009	0.000	0.000
Spain demand	0.191	0.762	0.329	0.007	0.009	0.008	0.000	0.000
UK demand	0.037	0.145	0.063	0.004	0.005	0.004	0.000	0.000
USA demand	0.025	0.005	0.020	0.006	0.006	0.006	0.000	0.000
Australia prop frozen	0.079	0.248	0.000	0.003	0.007	0.004	0.000	0.000
Domestic prop frozen	0.313	0.982	0.000	0.003	0.005	0.004	0.000	0.000
France prop frozen	0.040	0.124	0.000	0.009	0.010	0.009	0.000	0.000
Germany prop frozen	0.030	0.093	0.000	0.005	0.010	0.007	0.000	0.000
Italy prop frozen	0.134	0.420	0.000	0.002	0.003	0.003	0.000	0.000
Netherlands prop frozen	0.013	0.042	0.000	0.006	0.003	0.005	0.000	0.000
Other prop frozen	0.038	0.119	0.000	0.011	0.011	0.011	0.000	0.000
Portugal prop frozen	0.101	0.316	0.000	0.006	0.006	0.006	0.000	0.000
Spain prop frozen	0.191	0.597	0.000	0.006	0.013	0.008	0.000	0.000
UK prop frozen	0.037	0.115	0.000	0.003	0.005	0.004	0.000	0.000
USA prop frozen	0.025	0.078	0.000	0.002	0.003	0.002	0.000	0.000
Large frozen efficiency	0.000	0.000	0.000	0.837	0.010	0.540	0.000	0.000
Medium frozen efficiency	0.000	0.000	0.000	0.128	0.007	0.084	0.000	0.000
Small frozen efficiency	0.000	0.000	0.000	0.028	0.008	0.021	0.000	0.000
Super-cluster frozen efficiency	0.000	0.000	0.000	0.027	0.010	0.019	0.000	0.000
Large fresh efficiency	0.000	0.000	0.000	0.003	0.893	0.322	0.000	0.000
Medium fresh efficiency	0.000	0.000	0.000	0.003	0.115	0.042	0.000	0.000
Small fresh efficiency	0.000	0.000	0.000	0.003	0.003	0.003	0.000	0.000
Super-Cluster fresh efficiency	0.000	0.000	0.000	0.002	0.002	0.002	0.000	0.000
large company quota high	0.000	0.000	0.000	0.643	0.762	0.686	0.000	0.000
large company quota low	0.000	0.000	0.000	0.547	0.800	0.638	0.000	0.000
large company quota medium	0.000	0.000	0.000	1.027	1.416	0.151	0.000	0.000
medium company quota high	0.000	0.000	0.000	0.131	0.145	0.136	0.000	0.000
medium company quota low	0.000	0.000	0.000	0.075	0.013	0.053	0.000	0.000
medium company quota medium	0.000	0.000	0.000	0.233	0.385	0.288	0.000	0.000
small company quota high	0.000	0.000	0.000	0.011	0.032	0.018	0.000	0.000
small company quota low	0.000	0.000	0.000	0.005	0.022	0.011	0.000	0.000
small company quota medium	0.000	0.000	0.000	0.016	0.042	0.025	0.000	0.000
super-cluster quota high	0.000	0.000	0.000	0.038	0.063	0.047	0.000	0.000
super-cluster quota low	0.000	0.000	0.000	0.031	0.043	0.035	0.000	0.000
super-cluster quota medium	0.000	0.000	0.000	0.045	0.085	0.059	0.000	0.000

0 - 0.001	relatively insensitive
0.001 - 0.49	minor sensitivity (less than predicted)
0.49 - 0.99	slightly sensitive (less than predicted)
0.99 - 1.49	sensitive (as or slightly more than predicted)
1.49 or more	extremely sensitive
N/A	

For the most part model outputs were relatively insensitive or minimally sensitive to changes in demand. The exception to this was a slight sensitivity of average world fresh demand to Spain's demand. For changes in proportion of frozen fish purchased by country, model outputs were all relatively insensitive or minimally sensitive, apart from a two instances: average world fresh fish demanded was slightly sensitive to proportion of frozen fish purchased by the domestic and Spanish markets. It is unsurprising that Spain and the domestic market had a large effect on model outputs since these are the two largest clients (Chapter 3) and therefore have the largest effect on fish purchased in the entire model world.

The processing efficiency of frozen fish by the *large* company cluster appeared to be important for a number of outputs. Average (monthly) world stock of processed frozen fish and of fish in general (held by companies), and average world stock of frozen and all fish bought were slightly sensitive to this input variable, while the average value of world fish wasted was sensitive and world frozen fish wasted was extremely sensitive to this input. Other output variables were relatively insensitive or minimally sensitive to it. This was unsurprising since the quantity of processed fish produced from fish that were caught and the resulting quantity of waste is contingent upon the processing efficiency. On the contrary, all outputs were relatively insensitive or minimally sensitive to the processing efficiency of frozen fish of small, medium and super-clusters, with the exception of the average world fish wasted output which was slightly sensitive to the frozen processing efficiency of the medium company cluster. The reason for this is that the large company cluster constitutes more than 50% of fish production and it therefore has the largest single influence on processing of fish. This is followed by the medium company cluster that contributes 22.5% and therefore has some influence, while the other clusters are alone quite small and therefore have very little influence on their own.

Companies processing efficiency of fresh fish proved to be largely unimportant, with only the average world stock of fresh, processed fish, of fish wasted and fresh fish bought being slightly sensitive, and average world fresh fish wasted being sensitive to the fresh processing efficiency of the large company cluster. Again this is unsurprising since the majority of the world stock of processed fish is made up of frozen fish (most client countries demand a higher proportion of frozen fish on average, i.e. proportion frozen much greater than 0.5 on average) and therefore changing the processing efficiency of fresh fish is likely to have less of an effect on world processed fish stocks and only really influence the fresh product line. The large cluster is the one that deals predominantly with fresh fish, while the small clusters and super-cluster are exclusively frozen-fish-oriented.

Most output variables were slightly sensitive, sensitive or extremely sensitive to changes in large company cluster quota. Only world demands for fish, fish unsold and the average number of vessels were relatively insensitive to large company cluster quota. On the other hand, model outputs seemed relatively insensitive or minimally sensitive to changes in medium, small and the super-cluster's quotas. It therefore appears that changes in large company quota were significant in the model world. Given that large companies held the largest share of the quota it is not entirely unexpected. However, it is interesting that changes in the smaller clusters had no real effect. This would have implications for the model system should large company (cluster) quota be divided up amongst other company clusters.

3.3. Reality checking

To test whether the model was really performing as expected and did not have any significant bugs or erroneous behaviour a number of basic scenarios were run (see Appendix 4, Tables A4.8-4.10, for details of model inputs). These were based on real world values (Appendix 4, Tables A4.1 and A4.2), and were run to see whether the model produced similar patterns to those observed in the real world. As happened in reality, the quantities of fresh and frozen hake demanded by different countries were left fixed but the demand of the largest importer (Spain) was changed over time from fresh to frozen, and the converse hypothetical scenario of a switch to all fresh fish was also examined, as well as some other variations. The effects of these changes were measured at the system level. Similarly, Spanish overall demand was varied while the proportions of fresh to frozen fish were varied through time. Finally, scenarios of changes in TAC were examined. For all scenarios the realistic increase or decrease scenarios were based on the true range of values (i.e. min and max) for the period 2004/5 – 2011 for proportions of frozen fish and demand for all fish, and 2003 – 2013 for TAC.

In all cases the model was run 100 times using the BehaviorSpace function of NetLogo 5.0.1. The output values were recorded at every time step. For each scenario the averages of the 100 runs were calculated and are presented in Figures 4.4 – 4.6.

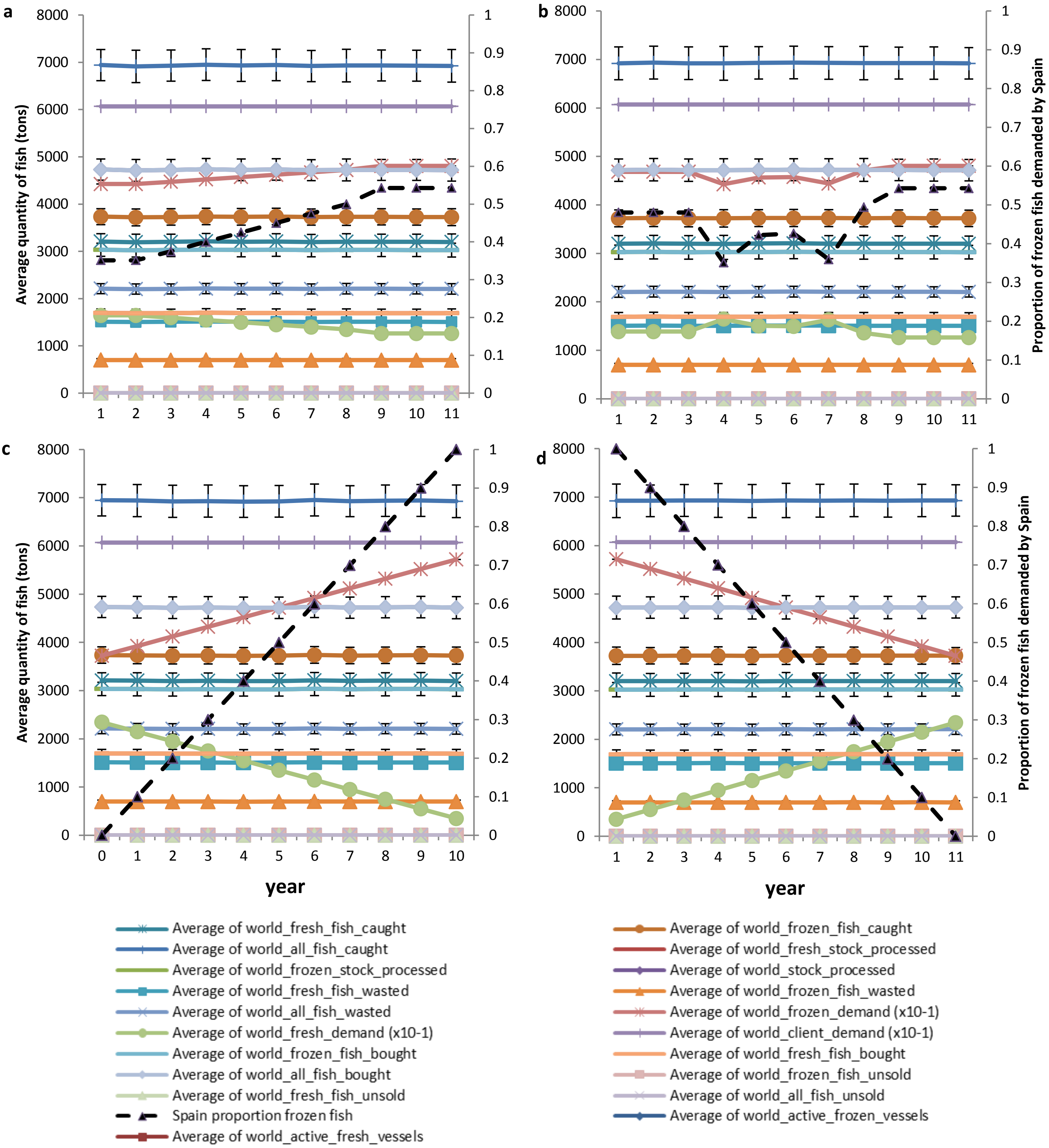

Figure 4.4: The outputs from year 0 to 10 resulting from the average of 100 model runs from scenarios of changes in the proportion of frozen fish demanded by Spain. These are a) the real world limits of Spain's % frozen fish, b) the real values of Spain's % frozen fish, c) a drastic scenario of change from all fresh to all frozen fish through time, and d) from all frozen to all fresh fish (see Appendix 4, Table A4.8).

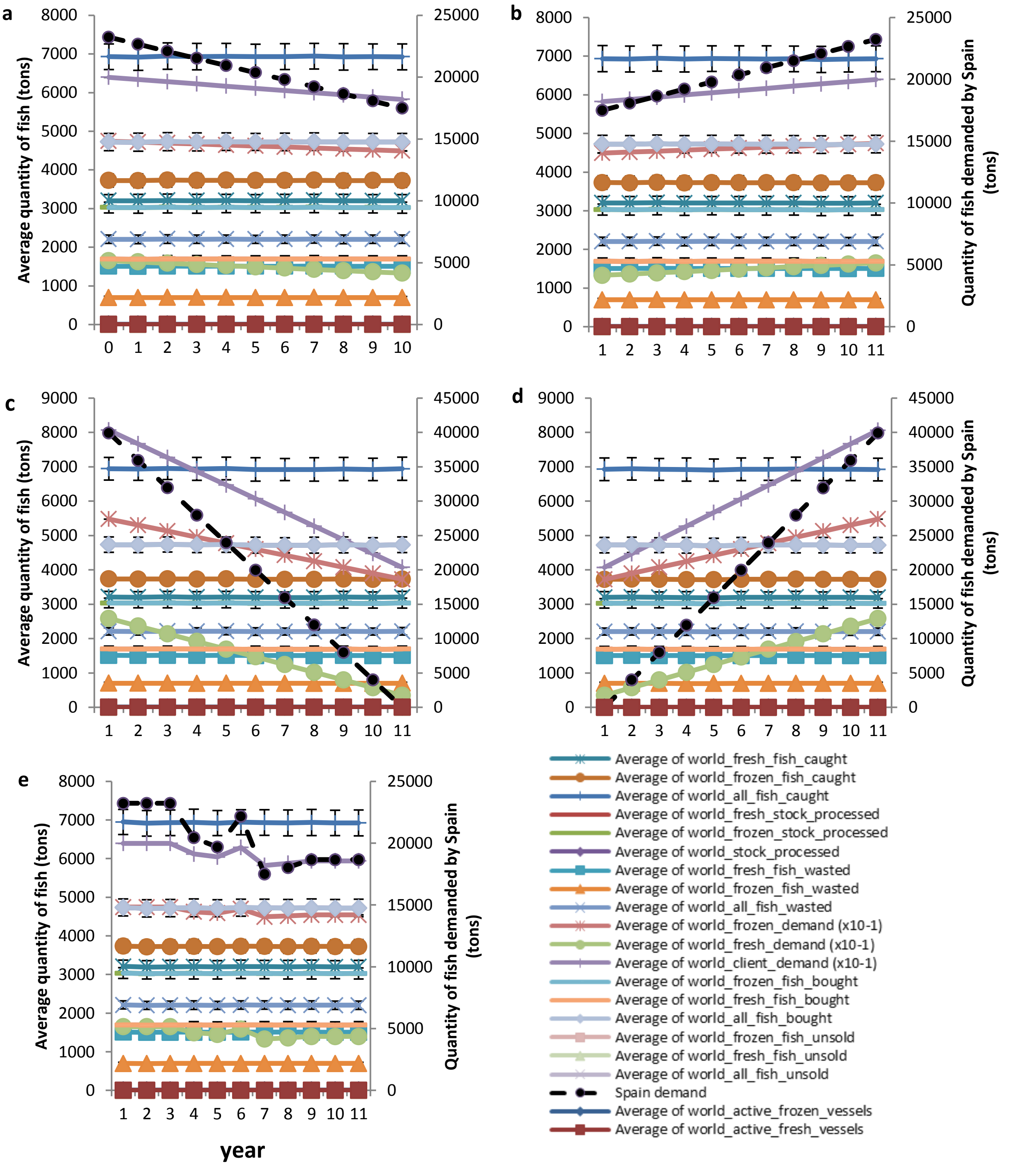

Figure 4.5: The outputs from year 0 to 10 resulting from the average of 100 model runs from scenarios of changes in the quantity of all fish demanded by Spain. These are a) a realistic decrease and b) a realistic increase based on Spain's real-world demand range, c) a hypothetical demand decrease and d) a hypothetical increase for Spain from 0 to double normal demand, and e) the real time series for Spain's demand change through time (see Appendix 4, Table A4.9).

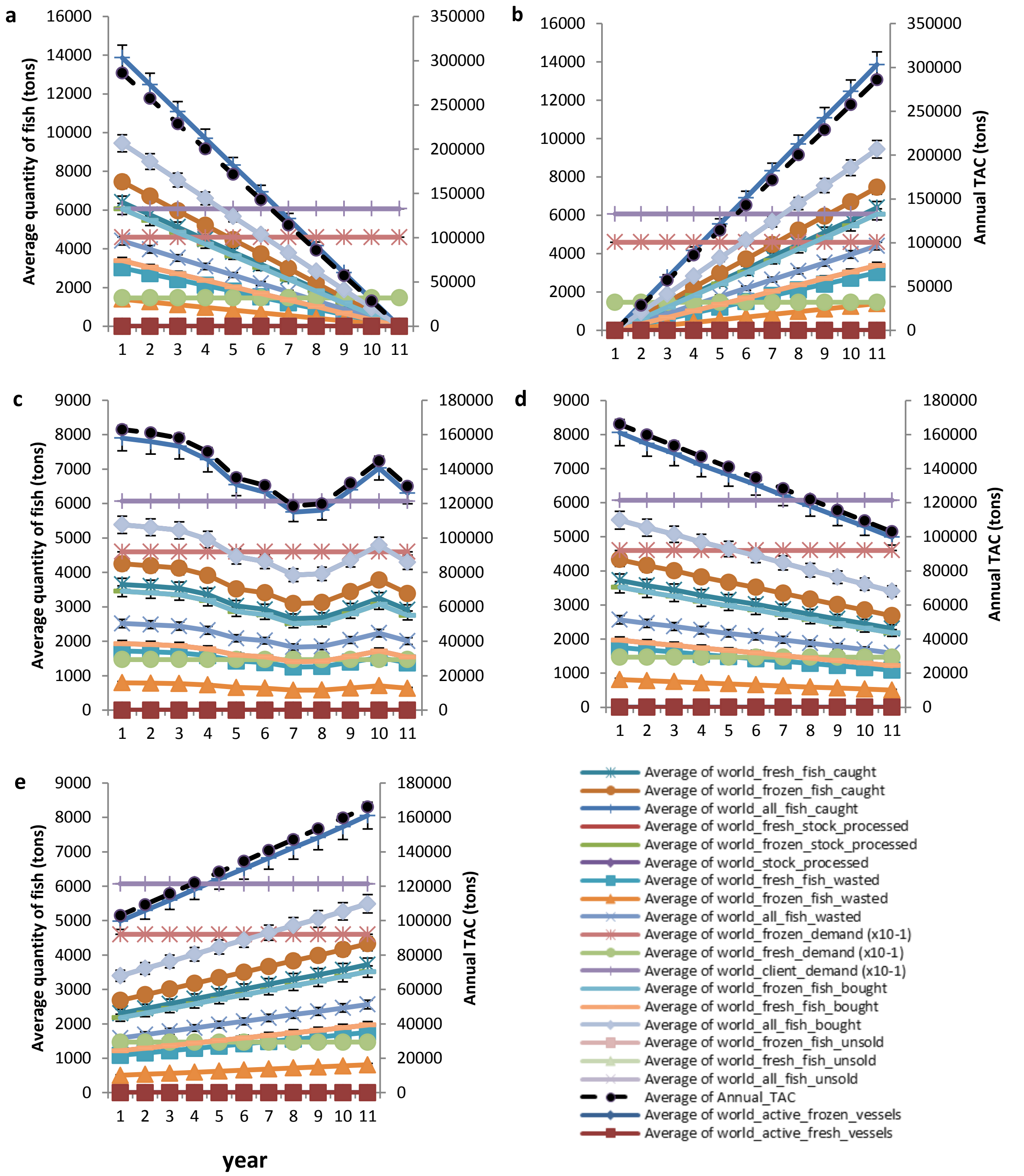

Figure 4.6: The outputs from year 0 to 10 resulting from the average of 100 model runs from scenarios of changes in hake Total Allowable Catch (TAC). These are a) a hypothetical TAC decrease and b) a hypothetical TAC increase from 0 to double average normal TAC, c) the real TAC time series, and d) a TAC decrease and e) TAC increase based on the realistic range of TAC values (see Appendix 4, Table A4.10).

For all scenarios (Figures 4.4 – 4.6) the outputs responded as would be expected from the inputs given. This indicates that the model is performing as expected and does not have any significant bugs or errors. However, it also indicates that this prototype version of the model is lacking in interesting emergent behaviour and that its behaviour is largely imposed. There are two main conclusions that can be drawn from this: i) the first prototype of the model has been soundly built, does not contain any significant errors or problems and, therefore, provides an excellent and solid foundation for building future prototypes upon, and ii) that this version of the model requires some major changes through the prototyping approach to provide more meaningful and realistic behaviours and outputs.

4. Summary

4.1. Summary of model results

To summarise the first model prototype was successfully developed in Netlogo 5.0.1 and was found to be fully functional and free of significant errors and problems. The prototype was found to be sensitive to TAC and large company quota, but relatively insensitive or only slightly sensitive to many of the inputs. There was not a great deal of stochasticity introduced in the model, since the only random procedures in this version of the model were fishing which used a random draw procedure and client purchasing which used a random draw of company identity numbers. As such, there was not much variability in the results. Sensitivity analyses and testing of the model revealed that it was quite predictable, since the structure for this prototype was also largely imposed. A number of strong assumptions were also made in this version. This indicated that there was a need for development of a more realistic model prototype and that this development could follow the prototyping approach recommended by Starfield and Jarre (2011), because the first prototype was soundly built and its overall structure was sufficiently realistic. In the next prototype the area that needs to be incrementally improved is the behaviour of agents and, therefore, the model.

4.2. Further developments in the modelling process

A quick glance back at Figure 4.1 will point out that it was not possible to capture all of the real-world drivers in the model in this prototype, but these factors do represent possible future areas for further model development and testing. More of these drivers could be explicitly represented through an improvement of model behaviour.

One possible way to include more drivers is to change the way that vessels operate, allowing more vessel-level drivers, such as running costs, to be included (Figure 4.1). In order to do this though, vessels might need to operate in a more realistic fashion. At present vessels execute a fishing behaviour at the command of companies; all vessels are executed in all time steps (barring that there is a demand for fresh or frozen fish) and the only difference between vessels is whether they transfer fresh or frozen hake to companies. In the real world not all vessels are active all of the time, and there has been a trend of declining vessel numbers through time (see Chapter 2). Vessels also vary, for example, in the volume of fish that they can hold, the days at sea for a single trip (i.e. number of trips per month), fuel consumption and therefore running costs, and their age. Thus the assumption that vessels are used equally both in terms of time and to capture quota could have a significant effect on the way that fish volumes are incorporated into the model. Given that TAC and quota were two of the factors that most influenced the model and that the way these two variables operate is through the 'fishing' behaviour of vessels, the next logical step is to test whether changes in the way vessels function in the model affects the overall model functioning.

The way forward is therefore first to conduct an assumption analysis of assumptions 6 and 7 (Table 4.1) – that all vessels are active at all times steps and that companies divide their quota evenly between all vessels – and thereby indirectly allow assumptions 3 and 8 to also be tested. This will therefore form the focus of the next chapter. The next interesting question that could be addressed following this would be to address assumption 1 – that money is not involved in the transfer of fish. Since TAC and quota have been so important to the first version of the model and these were suggested as being particularly important drivers during industry consultation (Chapter 2), it seems reasonable to assume that the other drivers such as fuel price, exchange rate and international market value for white fish that consultation also indicated as being particularly important indeed are so. In order to be able to assess this actual money, in addition to the present 'frozen' and 'fresh fish' *currencies*[13], needs to be introduced to the model. Since much of the financial equations,

[13] To recap, 'currency' in this sense is a modelling term for some unit that is exchanged between different agents or entities in the model and is not currency in the monetary sense. In this version of the model the only model currency is hake (measured in tons), but in *HakeSim 3.0* an additional 'currency' is added, which is actual money (Rands and Euros), see Chapter 6.

particularly related to cost, operate through vessel running cost this can only be done once the optimum structure and behaviour of vessels is determined through the vessel assumption analysis.

In conclusion, the prototyping approach of Starfield and Jarre (2011) implemented in the building and thorough testing of this first prototype has been an extremely useful exercise and has provided a solid model foundation upon which to build and a clear direction for subsequent model development.

CHAPTER 5:

THE ASSUMPTION ANALYSIS

Chapter 5: The assumption analysis

1. Introduction

Vessel numbers have been decreasing in the offshore trawl industry through time. This reduction in fleet size has become more apparent since the onset of long term rights (LTR) in 2006. After the introduction of LTR an initiative to reduce effort creep was undertaken by the industry itself. In 2008 the trawling industrial bodies (including the offshore trawling industry association SADSTIA – South African Deep Sea Trawling Industry Association) together with Marine and Coastal Management[14] introduced a supplementary input control (vessel effort limitation) to the existing total allowable catch output control (Powers *et al.*, 2010). Consultation with industry further suggested that through time the most efficient vessels were more commonly used. The less efficient vessels were used less often to harvest the surplus catch and ensure that the allocated fishing quota was used. This occurred, for example, in years where total allowable catch (TAC) was high, or in years where catch per unit effort (CPUE) was low possibly because fish stocks were depressed. When vessels were infrequently used and represented an unjustified (maintenance) cost to the company they were retired. With the effort limitations imposed in 2008, the incentive to reduce excess capacity increased and more vessels were retired.

What this means is that i) not all fishing vessels are active all of the time, and ii) some vessels are used in preference to others. It also means, by implication, that the fleet size of companies and the industry is not fixed. Furthermore, CPUE in a particular year represents how much effort vessels have to exert to catch a given quantity of fish (i.e. it is the quantity of fish caught per unit time by a vessel). In other words, from a single CPUE it is possible to estimate for a given level of effort by a given vessel, the quantity of fish caught and consequently how full a vessel will be on a fishing trip. By extension, CPUE can be used to calculate the number of vessels that need to be active to catch a company's quota in a given period of time. Additionally, in the real world, the quantity of fish caught in a given time (and therefore the CPUE) is indirectly affected by environmental stochasticity. Although much literature on the effects of environmental stochasticity or variability on hake and similar species exists internationally, in South Africa an ecosystem risk assessment (ERA) process that involved relevant stakeholders found that there was uncertainty relating to natural mortality and variability in recruitment in hake (Nel *et al.*, 2007). This was again highlighted in the follow up to this

[14] Marine and Coastal Management no longer exists and management of fisheries has passed to the South African Department of Agriculture, Forestry and Fisheries (DAFF).

ERA process as an important area to improve (Petersen *et al.*, 2010). As such, the exact way that environmental variability affects hake (*M. capensis* and *paradoxus*) catch is not well understood, for the South African fishery. But it can be viewed as adding to hake recruitment stochasticity that filters through to the quantity of hake that is available to be caught. These real world observations were temporarily ignored by making a series of strong assumptions in the first prototype of the model (Chapter 4). It was necessary to have built this simple prototype to fully understand and test the model function before adding further complexity. This helped to avoid a 'black box' first model version that was complex but not well understood.

With a well-understood and fully tested first model version, its assumptions can be incrementally relaxed to test their effects and increase the level of realism in the model. As such, the next step in model development is to determine whether the use of i) a fixed fleet size, ii) a preferential ranking system for vessel usage and iii) CPUE along with environmental stochasticity determining vessel catch, affect the model in such a way as to produce more realistic behaviour and outcomes. To do this an assumption analysis is to be carried out in this chapter that tests the effects of relaxing assumptions 3, 6, 7 and 8 from Table 4.1.

Assumptions are created whenever something is omitted when creating a simplified, purpose-built model of the real world (Starfield and Jarre, 2011). There are two kinds of assumptions: core or behavioural assumptions which are about the main causes proposed by a theory and concern the behaviour of an individual entity; and peripheral assumptions, which are about minor causes of the process or system being studied and these include heuristic and negligibility assumptions (Lam, 2010). The importance of an assumption is determined by the category into which it falls (Lam, 2010). Core behavioural assumptions for example often underpin the mechanistic explanations of a model and it is therefore important to test them (Tsang, 2006).

Assumption analyses should be an important part of model development. Pelletier and Mahévas (2005) state that models for policy-related applications should be designed to allow for the inclusion of various combinations of policy designs, parameter values and model assumptions to ensure that the models are not overly dependent on any parameter value or model assumption. A sound design and thorough sensitivity analysis cover the first two points, but an assumption analysis is essential to ensure that model behaviour is not overly dependent on any one assumption. Assumption testing or analysis can involve examining whether observations from the real world are commensurate with the assumptions made (Tsang, 2006). Starfield and Jarre (2011) explain that a thorough assumption analysis is as important as a sensitivity analysis and should involve testing key assumptions through making basic modifications to the model to determine how each assumption might affect the models' results. Two common ways of testing assumptions include process analysis, where statistical evidence is gathered for the mediating process that involves the assumptions, and direct inquiry, where qualitative or quantitative data obtained for the real world are used to initially inspect the realism of the behavioural assumption (Lam, 2010).

In order to carry out the assumption analyses on the *HakeSim* model and test the effect of relaxing some of the assumptions made in the first prototype, a few incrementally complex versions of the model are built. In the first model version to be tested in this chapter, the effect on model behaviour of relaxing the assumption that the number of vessels companies own is fixed, is examined by testing model behaviour/outputs with different vessel numbers (i.e. different company fleet compositions) as inputs.

Next, using vessel numbers representative of industry's fleet for 2012, as well as other company fleet compositions, the effect of relaxing the assumption that all vessels are active at every time step and that quota is evenly divided amongst vessels will be tested. This will be achieved through building a model in which *not* all vessels operate at all time steps and, thus, in which quota is unequally distributed according to the vessels randomly selected to catch the allowance of fish. Vessels will be chosen by company agents in the model according to a rank that is randomly assigned in the model initialization. This idea is based on the fact that in the real world companies, in the event of having a sufficiently large fleet, would send out more efficient vessels in preference to less efficient vessels. Over time less efficient vessels that are used less would be retired, where excess capacity exists. These vessels would only be replaced in the event of a need for additional capacity. Therefore, in the second assumption analysis prototype to be tested only sufficient vessels will be used every month (time-step) so as to make up the quota of the company (divided by 12 months) and the remainder of vessels will be left unused. Finally, the effect of relaxing the assumption that vessels are 50-100% full each month will be examined through the introduction of CPUE and a proxy for environmental uncertainty in hake recruitment and catchability (i.e. *stochasticity of catching fish*) which both determine the amount of fish that a vessel catches each month.

The aim of this chapter is, therefore, to produce these new, incrementally complex model prototypes and compare them with the previous simple model version (described in Chapter 4), in order to determine whether (and how) relaxing the assumptions 3, 6, 7 and 8 made in that version would make a significant difference to the functioning and realism of the model.

2. Methods

2.1. The conceptual framework and design of the new model prototypes

The conceptual framework and design of the following model versions is exactly the same as that of the first model version, ***HakeSim 1.0***, presented in Chapter 4, barring the new modifications to the design described below (see also Figure 5.1) and the conceptual reasoning behind these that was adopted following observation of the real world, as outlined in the introduction. All prototypes of the model were again implemented in Netlogo v5.0.1.

For the first assumption analysis, a second model prototype was built that tested the effect of relaxing the assumption that *fleet size is fixed*. In this model prototype, named ***HakeSim 2.1 Fleet Flexibility Prototype***, additional inputs were included into the model that allowed the size and composition of every company agent's fleet to be manipulated. Additional monitors were added, as detailed in Table 5.1. Vessel numbers were set to be representative for the industry for 2012, and in all cases dual vessels were treated as freezer trawlers. All other inputs, monitors, outputs and assumptions made for *HakeSim 1.0* and described in Chapter 4, including that all vessels were active at all time steps, remained.

For the second assumption analysis, *HakeSim 2.1* was further modified to simultaneously test the relaxation of two assumptions (since one modification dealt with both assumptions). These two assumptions were that i) *companies catch quota (% of TAC) evenly among vessels* and ii) *all vessels are active at every time step*. Through the addition of new procedures to the model company agents preferentially chose some vessels over others to fish based on a vessel rank that was randomly assigned during the model initialization. The ranking (i.e. order of vessels) was fixed for the entire model run. Based on rank, each company incrementally sent out one vessel after another to fish, starting with vessels ranked first, until all quota was caught, at which point they ceased to send vessels. Vessels could only catch fish up to a maximum storage capacity in each time step. This was

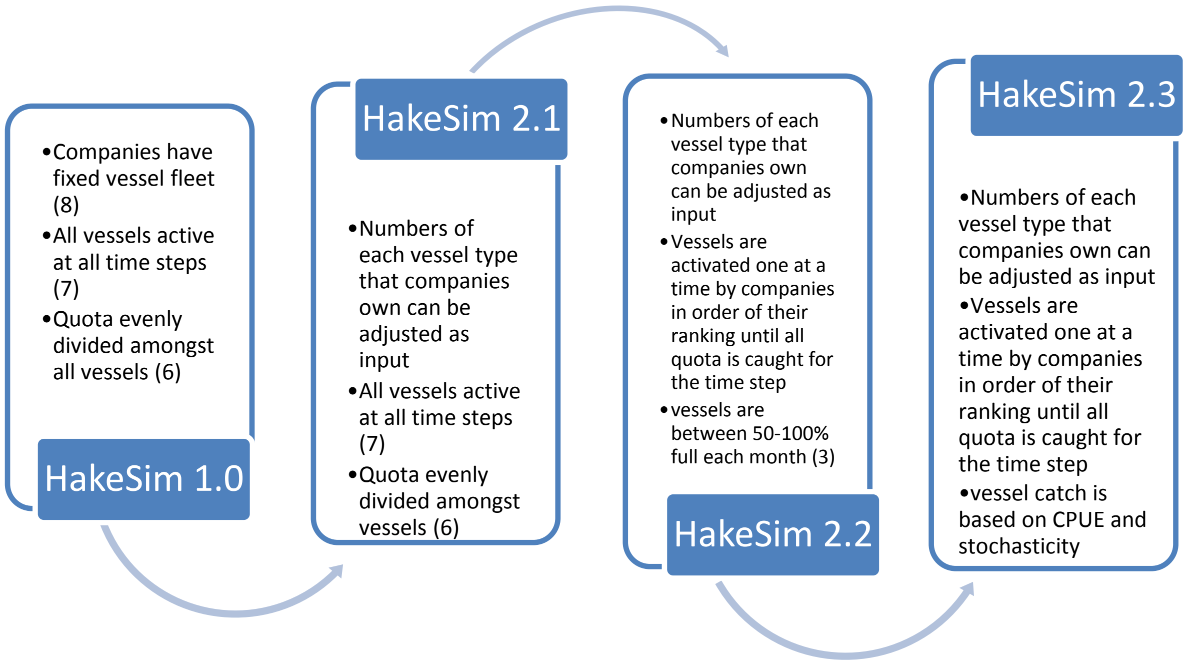

Figure 5.1: The development of *HakeSim* used in systematically testing the relaxation of assumptions that were made in *HakeSim 1.0*; assumption 8 is tested in *HakeSim 2.1* followed by 6 and 7 in *2.2* and 3 in *2.3*.

arbitrarily set as per Table 5.2, which differed from the previous model versions where the maximum storage capacity of a vessel was based on a company's monthly quota divided by the number of vessels that belonged to it (see Chapter 4 and equation 4.1). Therefore, in this model version, ***HakeSim 2.2 Preferential Vessel Use,*** both assumptions i) and ii) were removed in an attempt to create a more realistic structure for the model.

Finally, in ***HakeSim 2.3 Environmental Effects***, the effect of relaxing the assumption that *vessels are arbitrarily between 50 and 100% full each month* (i.e. assumption 3), was tested. This was done through the addition of CPUE and *stochasticity of catching fish* coefficient (as a substitute for environmental variability/uncertainty) input variables to the model interface and through changing vessel maximum capacity to reflect real vessel capacity averages (Table 5.3). It was also achieved through the addition of a new procedure to the model, which ultimately determined how full vessels were (i.e. how much fish they caught) each month. To determine which of a selection of possible equations that calculate the quantity of fish that vessels catch each month was to be used, a number of different equations and their effects on vessel catch were independently implemented and tested in Microsoft Excel. In all cases the equations included three essential variables that were incorporated from the corresponding model inputs: the maximum vessel capacity (specific to freezer trawler, factory freezer and wet-fish trawler vessels), CPUE and some stochasticity value. Note that these equations below were implemented individually by each active vessel in the model, meaning that the vessel's type determined its capacity. Both CPUE and stochasticity were read by individual vessels and affected the catch quantity on individual monthly vessel fishing trips. The three equations were:

$$QFC = MVC * \frac{(\text{random } (SC)) + (CPUE * (100 - SC))}{100} \quad \text{........ (5.1)}$$

$$QFC = MVC * ((\text{random } 100 * CPUE)/100) \quad \text{........ (5.2)}$$

$$QFC = MVC * [(CPUE - (CPUE*SC)) + ((\text{random } (2*CPUE*SC*100))/100)] \quad \text{........ (5.3A)}$$

$$QFC = MVC * (CPUE \pm (CPUE*\text{random } (SC))) \quad \text{........ (5.3B)}$$

Where QFC is the quantity of fish caught by one (active) vessel on a single fishing trip (i.e. in one monthly, time-step), MVC is the maximum vessel capacity for fish, SC is the *stochasticity of catching fish* and CPUE is catch per unit effort. In all equations CPUE is a value between 0 and 1 and 'random' represents a random draw between 0 and the numerical value of the variable that follows[15]. Equation 5.1 represents an additive scenario where SC is a value between 0 and 100, such that SC and CPUE together make up a maximum value of 100. In this case the greater the SC, the more important randomness is to determining the vessel's catch of fish in a single fishing trip and the less important the CPUE. In Equation 5.2 stochasticity (via random draw of 100) interacts with CPUE and the stochasticity is implicit but not directly regulated as a model input. In this case there is a multiplicative effect where CPUE is multiplied by a random draw of a maximum 100 such that catch is always less than but reaches the maximum of the CPUE input into the model. Equation 5.3A is a more complex scenario, where SC is a value between 0 and 1. The equation is written in a complex manner because of the nature of implementing it into code for the model, but a simpler (and equivalent) representation of it is given as equation 5.3B. In these equations the catch of fish made by a single active vessel in one fishing trip (remembering from Chapter 4 that one fishing trip is

[15] Note that Netlogo 5.0.1 uses the Mersenne Twister (MersenneTwisterFast class by Sean Luke) for random number generation. The random number generator can be seeded with the same number to ensure that runs are repeatable, or if left without a given seed Netlogo will select seeds at random based on the date and time. Because of the fact that seed numbers are used in the random number generator, the 'random' numbers that Netlogo produces are done so via a deterministic processes and are therefore actually pseudo-random numbers. Random numbers come from a uniform distribution.

equivalent to the total fish caught in a single monthly time-step) is equivalent to the vessel capacity for fish multiplied by the CPUE where the CPUE can deviate up or down by the proportion dictated by a random draw of a maximum of the SC. For example, if the CPUE were 0.5 and the SC were 0.2 (i.e. a 20% stochastic effect *on* the CPUE), then the quantity of fish caught would be determined as the maximum vessel capacity (for fish) multiplied by a proportion between 0.4 and 0.6, i.e. where the CPUE deviates by 20% up or down from its input value. To clarify, this means that the fullness of a vessel is determined by CPUE and the *stochasticity of catching fish*. This is based on the idea that each vessel catch is dependent on the 'catchability' of fish. CPUE is one measure of this, but there is also some environmental variability that can affect individual catches. This variability is a form of uncertainty, and can be captured simplistically by a random number (i.e. making the variability a stochastic process). A CPUE of 1 indicates that vessels will on average be 100% full and 0 indicates empty. An SC of 1 means that a vessel's fullness in a single trip can deviate by 100% from the CPUE, while 0 indicates that the vessel fullness will deviate by 0% from the CPUE. The single catch by a vessel (i.e. a single, monthly 'fishing trip') is determined by the proportional fullness and the maximum capacity of the vessel for fish.

After carefully examining outputs of the quantity of fish caught by a vessel for different stochasticity and CPUE values through independent implementations in Microsoft Excel (see Figure 5.2), equation 5.3 was selected as the most suitable and it was implemented into code in the model. The model was then carefully tested. The reason for the selection was that equation 5.3 provided the possibility to incorporate a known level of randomness and to adjust the relative importance of CPUE and stochasticity and still have no fish caught when CPUE was 0. Equation 5.1 provided a very similar scenario except in instances where CPUE was equivalent to 0. When CPUE was equal to 0, fish was still caught by the vessel due to some random draw of the SC. This was unrealistic, as in the real world if CPUE were equal to zero there would be no fish to catch. Equation 5.2 always produced outputs that were lower catches than the value of CPUE multiplied by vessel capacity, which was unrealistic, as in the real-world environmental uncertainty can sometimes be favourable, increasing catches beyond expectation. It was therefore rejected as a possibility.

The effects of incrementally relaxing each of the assumptions 3, 6, 7 and 8, as made in *HakeSim 1.0*, Chapter 4, on the realism of model behaviour and output were then determined by comparing its function and sensitivity with the newer prototypes *HakeSim 2.1, 2.2 and 2.3* of the model where the assumptions were relaxed.

Table 5.1: New inputs and monitors introduced into *HakeSim 2.1, 2.2and 2.3,* and which are found in all subsequent prototypes of the model.

New	Type	Agent(s) it applies to	Brief description
Input variables			
number of factory freezer trawlers	number	all companies	*the number of large factory freezer trawlers a company owns*
number of freezer trawlers	number	all companies	*the number of smaller freezer stern trawlers a company owns*
number of wet-fish trawlers	number	all companies	*the number of fresh fish stern trawlers a company owns*
CPUE	proportion of 1	all vessels	*the catch per unit effort, unitless, relative, transformed scale of 0 to 1*
stochasticity of catching fish	proportion of 1	all vessels	*level of randomness by which CPUE varies; proxy for environmental uncertainty*
Monitors			
number of vessels	number	all companies	*the sum of all vessels owned by all company agents in model*
number of wet-fish vessels	number	all companies	*the sum of all fresh fish stern trawlers owned by all company agents in model*
number of freezer trawlers	number	all companies	*the sum of all freezer stern trawlers owned by all company agents in model*
number of factory freezer trawlers	number	all companies	*the sum of all factory freezer trawlers owned by all company agents in model*
large company number of vessels	number	large company	*the sum of all vessels owned by the large company agent in the model*
medium company number of vessels	number	medium company	*the sum of all vessels owned by the medium company agent in the model*
small company number of vessels	number	small company	*the sum of all vessels owned by the small company agent in the model*
super-cluster company number of vessels	number	super-cluster company	*the sum of all vessels owned by the super-cluster company agent in the model*

Table 5.2: The arbitrary capacity that was assigned to vessels prior to the availability of better data. Figures were based on preliminary qualitative information from the consultation phase.

	fish	capacity (tons)
Factory freezer trawlers	frozen	200
Freezer stern trawlers	frozen	50
Wet-fish stern trawlers	fresh	30

Table 5.3: Average vessel traits from the real world calculated for the offshore demersal hake trawling fleet for the time period 2010 - 2013, determined from consolidating and cross-verifying government and industry data, courtesy of South African Deep Sea Trawling Industry Association (SADSTIA) and Department of Agriculture, Forestry and Fisheries (DAFF). Where applicable, average values were used for vessels in the model world, for *HakeSim 2.3* and later versions. Average maximum hake per month was used as a vessel maximum capacity value and register power was used to calculate fuel usage in later model versions. Dual vessels were not represented in the model; instead their numbers were captured as freezer vessels.

Vessel type	Statistics from the entire fleet	Build Year	Age at 2013 (years)	Vessel Length (m)	Vessel Weight (Gross Register Tons)	Crew (numbers of men)	Register Power (HP)	Number of landings per year	Average amount of hake per landing (tons)	Minimum hake landing of the year (tons)	maximum hake landing of the year (tons)	Standard deviation of whole hake caught in landings (tons)	Average amount of hake per landing as % of the maximum landing	minimum hake landing of the year as % of the maximum landing	maximum hake per month (tons)	average hake per month
Dual	***Min***	1962	51	21.5	185.7	16.0	552.0	11.0	33.6	2.9	48.7	10.1	37.8	5.9	44.6	30.8
	Max	2007	6	61.0	811.7	50.0	1798.9	52.0	80.4	53.7	127.3	28.8	80.5	42.2	551.7	348.5
	Average	1980	33	40.6	461.6	26.7	1159.3	22.1	52.8	20.4	83.4	18.2	64.7	21.7	153.9	97.5
Factory	***Min***	1970	43	48.4	684.3	42.0	1199.7	3.0	154.1	14.1	222.2	39.7	47.8	3.6	55.5	38.5
	Max	1992	21	72.1	2504.0	76.0	4524.1	10.0	1066.2	979.2	1222.7	277.1	87.2	80.1	1018.9	888.5
	Average	**1982**	**31**	**61.7**	**1637.0**	**58.4**	***2886.0***	**8.0**	**560.3**	**331.9**	**742.8**	**147.8**	**70.4**	**38.3**	***495.2***	**373.5**
Freezer	***Min***	1961	52	24.0	257.4	15.0	780.2	2.0	11.7	1.0	21.5	9.9	25.5	1.1	3.6	2.0
	Max	2002	11	57.3	852.0	45.0	1769.4	21.0	226.1	154.2	264.6	43.9	85.4	58.3	463.0	395.6
	Average	**1979**	**34**	**38.5**	**446.1**	**27.6**	***1125.8***	**11.9**	**81.0**	**45.6**	**122.3**	**24.1**	**60.5**	**30.7**	***121.4***	**80.4**
Wet-fish	***Min***	1973	40	20.4	154.0	15.0	500.0	2.0	6.5	0.0	15.6	5.8	41.3	0.2	2.6	1.1
	Max	2003	10	47.5	1215.0	32.0	2990.6	66.0	81.3	44.4	115.7	31.1	83.2	55.4	636.6	447.4
	Average	**1989**	**24**	**40.5**	**612.0**	**25.2**	***1800.4***	**37.5**	**52.2**	**17.9**	**76.4**	**15.3**	**67.1**	**23.0**	***238.5***	**162.8**

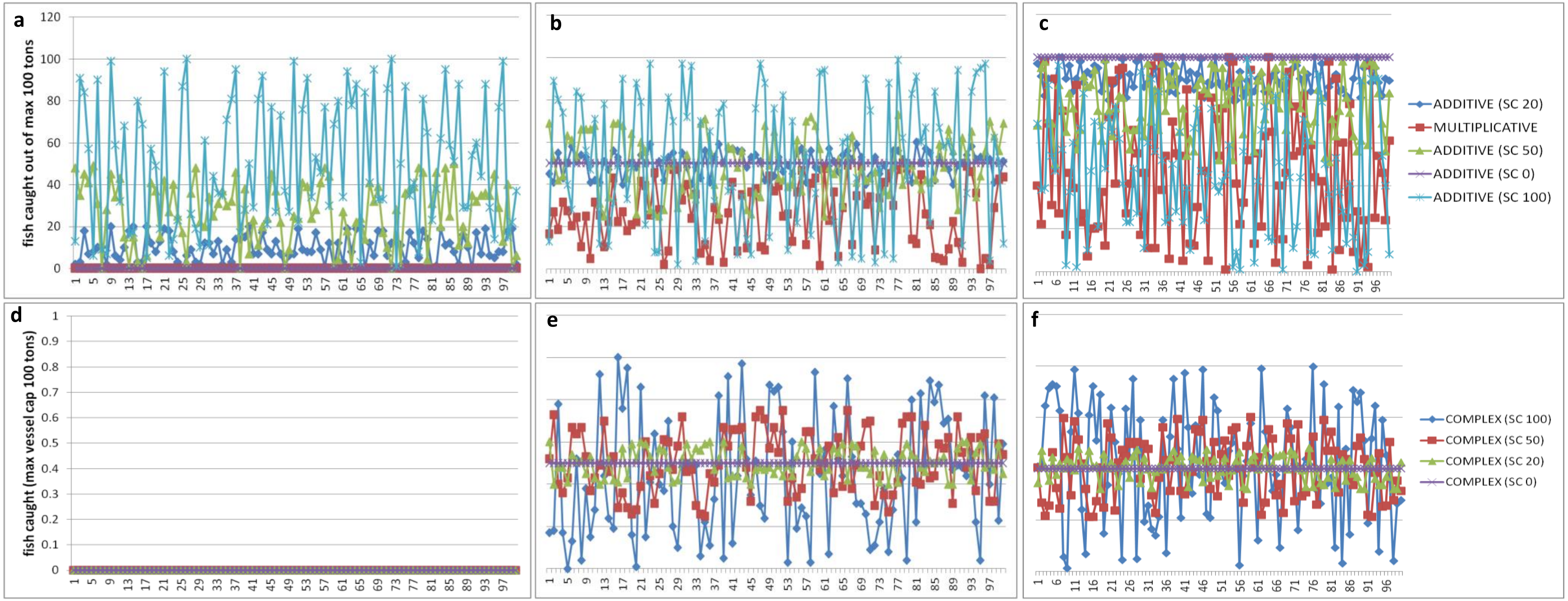

Figure 5.2: Outputs of fish caught from the independent implementation of equations 5.1, 5.2 and 5.3 in Microsoft Excel. Additive refers to equation 5.1, multiplicative to equation 5.2 and complex to equation 5.3. Outputs of fish caught (y-axis) are given for each of 100 replicates (x-axis); each replicate represents a single random number draw. The same equations were applied for different SC (stochasticity of catching fish) values 0, 20, 50 or 100%, and for different catch per unit effort values: 0 (a & d), 0.5 (b & e) and 1 (c and f). Implementations of equation 5.3 (d, e, f) produced the most realistic catches of fish.

3. Results & Discussion

3.1. Model testing

For each prototype version of the model as each new procedure or variable was added there was ongoing testing, which involved varying inputs and examining associated outputs and model behaviour, and debugging. Each procedure was tested and agent monitors and plots were inspected. In order to achieve this, new monitors were also added as described in Table 5.1. To verify the outputs of each procedure at the agent level, basic procedures that were newly added were also replicated and computed in Microsoft Excel. Basic *ad hoc* testing was employed on fully functional model prototypes where all new procedures were coded and running. This typically involved using normal and extreme input values and running the model in a step-wise manner to ascertain whether there was any erratic behaviour. If any was observed, thorough debugging and continued step-wise testing of the model was carried out.

Following this, sensitivity analyses were conducted on each of the model prototypes to ascertain that there was no erratic behaviour. These sensitivity analyses also served to compare behaviours between model prototypes to determine the effects of relaxing some of the core assumptions made in the previous model prototype and whether relaxing the assumptions might produce more realistic model behaviour.

3.2. Sensitivity analyses of the different versions

Sensitivity analyses were conducted in exactly the same manner as described in Chapter 4, e.g. 100 runs per input value run in Netlogo v5.0.1 using the BehaviorSpace tool, for each of the model versions (i.e. *HakeSim 1.0, 2.1, 2.2* and *2.3*). However, since the sensitivity analyses conducted in the present chapter serve a mainly comparative purpose a slightly less rigorous approach was adopted, in the sense that only a lower extreme value and an upper extreme value were used for each of the input parameters, as opposed to the more detailed input range that was used in Chapter 4. A full list of the input values used for the model runs can be found in Appendix 5. For *HakeSim 2.3* a transformed CPUE value (on a unitless scale from 0 to 1) based on the average of the time series from 1978 to 2012 was used for standard runs (see Appendix 5, Table A5.1). For each model version, outputs for every single input value test were then assessed relative to the standard run outputs and a sensitivity index was calculated, as per the approach of Chapter 4. The sensitivity results were then compared between model versions as follows.

All model versions remained relatively insensitive or showed minor sensitivity to the demand of international or domestic markets and there was almost no variation between the outputs of the various model prototypes (Table 5.5). This is not undesirable behaviour, since the hake industry reported during consultation that in the real world there was always a demand for South African hake from their customers and that the market would take as much fish as they could supply. Changes made to the procedures in the model that affected how and which vessels were sent fishing in the two updated model prototypes appear to have not altered the way that demand affected the model, which is desirable as vessel behaviours should not affect client behaviour in the model. It would have been unexpected for vessel-related company behaviour to have had any impact on the way that demand affects the model.

On the other hand, the different model prototypes behaved slightly differently for the same quota (i.e. proportion of rights) inputs (Table 5.6). In *HakeSim 1.0* all model outputs except world demand and world vessel numbers were slightly sensitive to quota changes. In *HakeSim 2.1, 2.2* and *2.3,* the output of demand was still insensitive to quota changes, but other outputs differed in their sensitivity to quota. *HakeSim 2.1, 2.2* and *2.3* had most outputs slightly sensitive to an increase in large company quota and fresh fish was slightly sensitive to a decrease in large company quota whereas frozen fish was less sensitive. This was not surprising given that the large company in a standard average run accounted for 70% of the wet-fish vessels in the model and 42% of all modelled vessels. Thus changes in total vessel numbers, and especially wet-fish vessel numbers, as a result of changes to the large company quota and therefore the number of its vessels it sent fishing, would have had a big impact on many outputs in the model, in the latter case on fresh fish quantities throughout the model. *HakeSim 2.1* showed little sensitivity to any other quota changes. *HakeSim 2.2* and *2.3* differed from the two earlier prototypes in that they had active frozen and fresh fish vessel numbers that were more sensitive to changes in quota, particularly to large and medium company quota changes, although sensitivity was still only slight. In *2.2* and *2.3* frozen fish quantities also displayed more sensitivity to lowering of medium company quota. This was probably explained by the fact that the medium company agent held 59% of all frozen fish vessels in the model, which meant that changes in its quota had a big impact on the number of frozen fish vessels that were active and supplying frozen fish into the model. The fact that *HakeSim 2.2* (and subsequent prototype *2.3*) had vessel numbers that were sensitive to quota resulted from *2.2's* company behaviour to selectively send vessels to fish until all quota was caught. Therefore, it was as expected that when quota was changed, the number of vessels needed to catch quota would also change. That is because, in the real world quota directly affects the quantity of fish that can be caught, and therefore processed and sold. This model behaviour was therefore more realistic than the earlier two model versions, *HakeSim 1.0* and *2.1*.

Most outputs of all model versions were insensitive or showed only minor sensitivity to companies' processing efficiencies of fresh fish, with only slight sensitivity seen for fresh fish outputs in respect to changes in large company processing efficiency (Table 5.7). *HakeSim 2.1, 2.2* and *2.3* were slightly less sensitive to this input than *HakeSim 1.0*, but in all cases sensitivity was close to negligible. Similarly, for all three model versions minor or negligible sensitivity of most outputs to changes in company processing efficiency of frozen fish was observed (Table 5.8). The exception to this was that world frozen fish wasted was extremely sensitive and world fish processed and bought was sensitive or slightly sensitive to changes in large company processing efficiency and had some sensitivity to that of the medium company agent, particularly for *HakeSim 2.2 and 2.3*. This was unsurprising since the large company agent held around half of all quota in the model, and therefore processed more fish than any of the other agents alone, and it was followed by the medium agent in the volume of quota that it held.

For all model versions the proportion of frozen fish purchased by international or domestic markets appeared to have little effect on all model outputs, with the exception of directly altering world demand. There were no important differences in model versions for this parameter (Table 5.9). Conversely, most outputs of all the model versions were sensitive to total allowable catch (Table 5.10), apart from demand which was unaffected by TAC, as was to be expected since the two were affected by separate inputs. Of interest, though, *HakeSim 2.2* and 2.3 differed from the other two earlier model versions. Firstly the number of active vessels output was sensitive to changes in TAC, which was not the case for versions *1.0* and *2.1,* as per their design. Secondly, for both versions *1.0* and *2.1*, outputs were sensitive to both increases and decreases in TAC, while for *HakeSim 2.2* (and subsequently *2.3*) model outputs were only sensitive to decreases in TAC, while they were relatively insensitive to increases in TAC. This was an interesting finding, since it indicated that at some level fleet capacity (i.e. the total capacity of all vessels in the companies' fleets) becomes limiting and any additional increases in TAC cannot be caught. This was a much more realistic behaviour than either of the earlier versions where the model was highly sensitive to increases in TAC. In the real world if

TAC was increased to an extreme at some point vessel capacity of the existing fleet would become limiting and more vessels would need to enter the fleet to be able to catch the surplus.

The sensitivity of the model versions to changes in fleet structure was assessed for *HakeSim 2.1, 2.2* and *2.3* (Table 5.11). This cannot be done for *HakeSim 1.0* because the capacity to change fleet structure did not exist in this version. Overall *HakeSim 2.2* (and consequently *2.3*) evidenced greater sensitivity but also more nuanced sensitivity to changes in fleet composition than *2.1*. Firstly changing the number of freezer trawlers in the entire model (i.e. "all companies' max/min freezer vessels") had an important effect on frozen fish throughout the model in *2.2*, since outputs of frozen fish at every level from catch through to sale displayed sensitivity to changes in numbers of freezer trawlers, while fresh fish did not. Whereas, in *HakeSim 2.1* most outputs were sensitive to declines but not to increases in freezer trawler numbers, and there was no distinction between fresh and frozen fish outputs. This reflected the structural differences between the model versions. In *2.2* changes in freezer trawler numbers directly affected the numbers of vessels that companies could send out to catch quota. Since vessel capacity was limited the maximum amount of frozen fish that could be caught, assuming TAC was not limiting, was equal to the number of frozen vessels multiplied by the maximum capacity of these vessels. In *2.1*, though, if vessel numbers were increased the same amount of quota was divided evenly amongst these vessels, meaning each caught less, but all fish was still caught, while if vessel numbers were decreased to zero (minimum) then there were no vessels to evenly divide the quota amongst, meaning the quantity of frozen fish caught would have been zero. The exact same explanation also holds true for wet-fish vessels in the two model versions: *HakeSim 2.1* only showed sensitivity at minimum (zero) wet-fish vessel numbers, but not at the maximum extreme, while *HakeSim 2.2.*had only fresh fish outputs affected by changes in total wet-fish vessel numbers in the model.

The sensitivity of *HakeSim 2.2* was indicative of a model behaviour that was much more realistic: changes in wet-fish vessel numbers affected the ability of companies to catch fresh fish and thus the amount of fresh fish in the system, just as freezer vessels affected the quantities of frozen fish. Comparing the sensitivity of outputs of *HakeSim 2.2* and *2.3* they were almost identical. However, *HakeSim 2.3* was less sensitive to increasing the vessel fleet for all companies to maximum and increasing the freezer vessel numbers for all companies to maximum. This was due to the fact that in *HakeSim 2.3* vessel maximum capacity was increased to real vessel values, which were significantly larger than the arbitrary values assigned in the earlier model version. This meant that the maximum capacity of fish that a company's entire fleet can capture (represented by vessel numbers) was less of a limiting factor in *HakeSim 2.3*. This model version retained some sensitivity to lower vessel numbers, since decreasing vessel numbers in the extreme decreases the capacity of companies to be able to catch fish, thereby affecting the quantity of fish entering the model and all fish-related outputs.

A further demonstration of the more realistic behaviour of versions *2.2* and *2.3* was that fresh fish variables displayed slight sensitivity to changes in the number of vessels owned by the large company, which in the standard average run holds 70% of wet-fish vessel numbers. Similarly frozen fish outputs indicated some response to changes in the overall numbers of vessels held by the medium company which in a standard run accounted 59% of freezer vessel numbers in the model.

Finally, most outputs of *HakeSim 2.3* were sensitive to CPUE (Table 5.12). This was because CPUE had a direct effect on the quantity of fish caught by the vessels and consequently, the quantities of fish at all later stages of processing and sale. This was a realistic observation, since CPUE was identified during consultation as one of the major factors affecting the industry in the real world.

Table 5.4: Criteria for judging sensitivity analyses

(blue)	0 - 0.001	relatively insensitive
(green)	0.001 - 0.49	minor sensitivity (less than predicted)
(yellow)	0.49 - 0.99	slightly sensitive (less than predicted)
(orange)	0.99 - 1.49	sensitive (as or slightly more than predicted)
(red)	1.5 or more	extremely sensitive
(grey)	N/A	

Table 5.5: Sensitivity of model outputs (shown along the top) to extreme values for each of three market demand inputs (shown down), for each of the model prototypes. Input and output names are as per their definitions in Chapter 4.

		Ave. world_fresh_fish_caught	Ave. world_frozen_fish_caught	Ave. world_all_fish_caught	Ave. world_fresh_stock_processed	Ave. world_frozen_stock_processed	Ave. world_stock_processed	Ave. world_fresh_fish_wasted	Ave. world_frozen_fish_wasted	Ave. world_all_fish_wasted	Ave. world_frozen_demand	Ave. world_fresh_demand	Ave. world_client_demand	Ave. world_frozen_fish_bought	Ave. world_fresh_fish_bought	Ave. world_all_fish_bought	Ave. world_active_frozen_vessels	Ave. world_active_fresh_vessels
	Domestic demand	0.0062	0.0055	0.0058	0.0063	0.0058	0.0060	0.0062	0.0043	0.0056	0.3133	0.0517	0.2500	0.0058	0.0063	0.0060	0.0000	0.0000
	Spain demand	0.0091	0.0070	0.0080	0.0091	0.0068	0.0076	0.0091	0.0078	0.0087	0.1907	0.7616	0.3288	0.0068	0.0091	0.0076	0.0000	0.0000
HakeSim 1.0	Other countries demand	0.0039	0.0037	0.0038	0.0039	0.0039	0.0039	0.0039	0.0031	0.0036	0.0381	0.0061	0.0303	0.0039	0.0039	0.0039	0.0000	0.0000
	Domestic demand	0.0007	0.0007	0.0007	0.0006	0.0007	0.0006	0.0007	0.0008	0.0007	0.3133	0.0517	0.2500	0.0007	0.0006	0.0006	0.0000	0.0000
	Spain demand	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.1907	0.7616	0.3288	0.0001	0.0001	0.0001	0.0000	0.0000
HakeSim 2.1	Other countries demand	0.0002	0.0002	0.0002	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0381	0.0061	0.0303	0.0002	0.0001	0.0002	0.0000	0.0000
	Domestic demand	0.0004	0.0000	0.0001	0.0005	0.0000	0.0001	0.0003	0.0001	0.0001	0.3133	0.0517	0.2500	0.0000	0.0005	0.0001	0.0000	0.0000
	Spain demand	0.0003	0.0009	0.0008	0.0004	0.0009	0.0008	0.0002	0.0010	0.0007	0.1907	0.7616	0.3288	0.0009	0.0004	0.0008	0.0000	0.0000
HakeSim 2.2	Other countries demand	0.0003	0.0002	0.0002	0.0003	0.0001	0.0001	0.0002	0.0003	0.0003	0.0381	0.0061	0.0303	0.0001	0.0003	0.0001	0.0000	0.0000
	Domestic demand	0.0009	0.0010	0.0009	0.0007	0.0010	0.0009	0.0011	0.0009	0.0010	0.3133	0.0517	0.2500	0.0010	0.0007	0.0009	0.0002	0.0000
	Spain demand	0.0012	0.0018	0.0006	0.0009	0.0018	0.0009	0.0014	0.0017	0.0011	0.1907	0.7616	0.3288	0.0018	0.0009	0.0009	0.0002	0.0000
HakeSim 2.3	Other countries demand	0.0006	0.0017	0.0007	0.0010	0.0017	0.0010	0.0007	0.0015	0.0009	0.0381	0.0061	0.0303	0.0017	0.0010	0.0010	0.0002	0.0000

Table 5.6: Sensitivity of model outputs (shown along the top) to extreme values for different quota allocation to company inputs (shown down), for each of the model prototypes. Input and output names are as per their definitions in Chapter 4. L, M, S and SC stand for large, medium, small and super-cluster companies.

		Ave. world_fresh_fish_caught	Ave. world_frozen_fish_caught	Ave. world_all_fish_caught	Ave. world_fresh_stock_processed	Ave. world_frozen_stock_processed	Ave. world_stock_processed	Ave. world_fresh_fish_wasted	Ave. world_frozen_fish_wasted	Ave. world_all_fish_wasted	Ave. world_frozen_demand	Ave. world_fresh_demand	Ave. world_client_demand	Ave. world_frozen_fish_bought	Ave. world_fresh_fish_bought	Ave. world_all_fish_bought	Ave. world_active_frozen_vessels	Ave. world_active_fresh_vessels
HakeSim 1.0	L company quota high	0.7575	0.6274	0.6876	0.7616	0.6434	0.6858	0.7530	0.5580	0.6913	0.0000	0.0000	0.0000	0.6434	0.7616	0.6858	0.0000	0.0000
	L company quota low	0.7965	0.5035	0.6389	0.7999	0.5468	0.6376	0.7926	0.3157	0.6417	0.0000	0.0000	0.0000	0.5468	0.7999	0.6376	0.0000	0.0000
	M company quota high	0.1429	0.1322	0.1371	0.1454	0.1307	0.1360	0.1402	0.1384	0.1396	0.0000	0.0000	0.0000	0.1307	0.1454	0.1360	0.0000	0.0000
	M company quota low	0.0112	0.0904	0.0538	0.0134	0.0747	0.0527	0.0087	0.1586	0.0562	0.0000	0.0000	0.0000	0.0747	0.0134	0.0527	0.0000	0.0000
	S company quota high	0.0320	0.0065	0.0183	0.0320	0.0106	0.0183	0.0320	0.0116	0.0182	0.0000	0.0000	0.0000	0.0106	0.0320	0.0183	0.0000	0.0000
	S company quota low	0.0219	0.0012	0.0108	0.0219	0.0047	0.0108	0.0220	0.0138	0.0107	0.0000	0.0000	0.0000	0.0047	0.0219	0.0108	0.0000	0.0000
	SC company quota high	0.0627	0.0326	0.0465	0.0627	0.0376	0.0466	0.0627	0.0114	0.0465	0.0000	0.0000	0.0000	0.0376	0.0627	0.0466	0.0000	0.0000
	SC company quota low	0.0426	0.0288	0.0352	0.0425	0.0312	0.0353	0.0428	0.0182	0.0350	0.0000	0.0000	0.0000	0.0312	0.0425	0.0353	0.0000	0.0000
HakeSim 2.1	L company quota high**	0.6616	0.5647	0.6103	0.7564	0.5899	0.6493	0.5655	0.4587	0.5332	0.0000	0.0000	0.0000	0.5899	0.7564	0.6493	0.0000	0.0000
	L company quota low	0.5477	0.3364	0.4359	0.7942	0.4046	0.5436	0.2980	0.0494	0.2227	0.0000	0.0000	0.0000	0.4046	0.7942	0.5436	0.0000	0.0000
	M company quota high	0.1461	0.1362	0.1409	0.1413	0.1339	0.1365	0.1509	0.1459	0.1494	0.0000	0.0000	0.0000	0.1339	0.1413	0.1365	0.0000	0.0000
	M company quota low	0.0950	0.1490	0.1236	0.0103	0.1243	0.0837	0.1807	0.2530	0.2026	0.0000	0.0000	0.0000	0.1243	0.0103	0.0837	0.0000	0.0000
	S company quota high	0.0087	0.0096	0.0010	0.0320	0.0030	0.0095	0.0149	0.0373	0.0217	0.0000	0.0000	0.0000	0.0030	0.0320	0.0095	0.0000	0.0000
	S company quota low	0.0023	0.0125	0.0055	0.0215	0.0071	0.0031	0.0171	0.0354	0.0226	0.0000	0.0000	0.0000	0.0071	0.0215	0.0031	0.0000	0.0000
	SC company quota high	0.0353	0.0139	0.0240	0.0627	0.0216	0.0363	0.0075	0.0186	0.0004	0.0000	0.0000	0.0000	0.0216	0.0627	0.0363	0.0000	0.0000
	SC company quota low	0.0301	0.0204	0.0250	0.0434	0.0242	0.0311	0.0167	0.0045	0.0130	0.0000	0.0000	0.0000	0.0242	0.0434	0.0311	0.0000	0.0000
HakeSim 2.2	L company quota high**	0.3422	0.8057	0.7100	0.2640	0.7930	0.7204	0.4149	0.8532	0.6825	0.0000	0.0000	0.0000	0.7930	0.2640	0.7204	0.8908	0.3418
	L company quota low	0.6959	0.2831	0.3683	0.7656	0.2945	0.3592	0.6310	0.2405	0.3925	0.0000	0.0000	0.0000	0.2945	0.7656	0.3592	0.2069	0.6957
	M company quota high	0.2273	0.1478	0.1642	0.2222	0.1421	0.1531	0.2319	0.1691	0.1936	0.0000	0.0000	0.0000	0.1421	0.2222	0.1531	0.1201	0.2272
	M company quota low	0.2181	0.4906	0.4343	0.2353	0.5104	0.4726	0.2021	0.4169	0.3333	0.0000	0.0000	0.0000	0.5104	0.2353	0.4726	0.5862	0.2174
	S company quota high	0.0306	0.0290	0.0293	0.0320	0.0294	0.0297	0.0293	0.0274	0.0282	0.0000	0.0000	0.0000	0.0294	0.0320	0.0297	0.0298	0.0306
	S company quota low	0.0440	0.0940	0.0837	0.0005	0.0811	0.0700	0.0845	0.1422	0.1197	0.0000	0.0000	0.0000	0.0811	0.0005	0.0700	0.0690	0.0435
	SC company quota high	0.0600	0.0544	0.0556	0.0627	0.0556	0.0565	0.0574	0.0502	0.0530	0.0000	0.0000	0.0000	0.0556	0.0627	0.0565	0.0541	0.0600
	SC company quota low	0.0431	0.1319	0.1135	0.0004	0.1138	0.0981	0.0836	0.1993	0.1542	0.0000	0.0000	0.0000	0.1138	0.0004	0.0981	0.1379	0.0435
HakeSim 2.3	L company quota high**	0.3416	0.8028	0.5919	0.2634	0.7899	0.6109	0.4143	0.8509	0.5569	0.0000	0.0000	0.0000	0.7899	0.2634	0.6109	0.8835	0.3418
	L company quota low	0.6959	0.2832	0.4719	0.7656	0.2945	0.4547	0.6311	0.2409	0.5036	0.0000	0.0000	0.0000	0.2945	0.7656	0.4547	0.1822	0.6957
	M company quota high	0.2272	0.1482	0.1843	0.2222	0.1424	0.1696	0.2319	0.1695	0.2115	0.0000	0.0000	0.0000	0.1424	0.2222	0.1696	0.1148	0.2272
	M company quota low	0.2174	0.4894	0.3651	0.2349	0.5091	0.4159	0.2012	0.4162	0.2714	0.0000	0.0000	0.0000	0.5091	0.2349	0.4159	0.5733	0.2174
	S company quota high	0.0306	0.0290	0.0297	0.0320	0.0294	0.0303	0.0293	0.0274	0.0287	0.0000	0.0000	0.0000	0.0294	0.0320	0.0303	0.0297	0.0306
	S company quota low	0.0414	0.0947	0.0703	0.0020	0.0817	0.0532	0.0818	0.1432	0.1019	0.0000	0.0000	0.0000	0.0817	0.0020	0.0532	0.0602	0.0435
	SC company quota high	0.0600	0.0544	0.0570	0.0627	0.0556	0.0580	0.0574	0.0502	0.0551	0.0000	0.0000	0.0000	0.0556	0.0627	0.0580	0.0538	0.0600
	SC company quota low	0.0419	0.1313	0.0904	0.0015	0.1131	0.0742	0.0823	0.1991	0.1204	0.0000	0.0000	0.0000	0.1131	0.0015	0.0742	0.1230	0.0435

Table 5.7: Sensitivity of model outputs (shown along the top) to extreme values for different company processing efficiencies for fresh fish (shown down), for each of the model prototypes. Input and output names are as per their definitions in Chapter 4. L, M, S and SC stand for large, medium, small and super-cluster companies.

		Ave. world_fresh_fish_caught	Ave. world_frozen_fish_caught	Ave. world_all_fish_caught	Ave. world_fresh_stock_processed	Ave. world_frozen_stock_processed	Ave. world_stock_processed	Ave. world_fresh_fish_wasted	Ave. world_frozen_fish_wasted	Ave. world_all_fish_wasted	Ave. world_frozen_demand	Ave. world_fresh_demand	Ave. world_client_demand	Ave. world_frozen_fish_bought	Ave. world_fresh_fish_bought	Ave. world_all_fish_bought	Ave. world_active_frozen_vessels	Ave. world_active_fresh_vessels
HakeSim 1.0	L company fresh efficiency	0.0067	0.0036	0.0050	0.8928	0.0035	0.3219	1.0026	0.0042	0.6866	0.0000	0.0000	0.0000	0.0035	0.8928	0.3219	0.0000	0.0000
	M company fresh efficiency	0.0047	0.0026	0.0036	0.1149	0.0025	0.0420	0.1307	0.0027	0.0902	0.0000	0.0000	0.0000	0.0025	0.1149	0.0420	0.0000	0.0000
	S company fresh efficiency	0.0034	0.0034	0.0034	0.0034	0.0032	0.0033	0.0033	0.0040	0.0035	0.0000	0.0000	0.0000	0.0032	0.0034	0.0033	0.0000	0.0000
	SC company fresh efficiency	0.0023	0.0023	0.0023	0.0023	0.0024	0.0023	0.0023	0.0019	0.0021	0.0000	0.0000	0.0000	0.0024	0.0023	0.0023	0.0000	0.0000
HakeSim 2.1	L company fresh efficiency	0.0003	0.0003	0.0003	0.8853	0.0003	0.3160	0.8963	0.0002	0.6248	0.0000	0.0000	0.0000	0.0003	0.8853	0.3160	0.0000	0.0000
	M company fresh efficiency	0.0003	0.0002	0.0003	0.1157	0.0003	0.0415	0.1166	0.0001	0.0813	0.0000	0.0000	0.0000	0.0003	0.1157	0.0415	0.0000	0.0000
	S company fresh efficiency	0.0005	0.0004	0.0004	0.0004	0.0004	0.0004	0.0005	0.0005	0.0005	0.0000	0.0000	0.0000	0.0004	0.0004	0.0004	0.0000	0.0000
	SC company fresh efficiency	0.0001	0.0000	0.0001	0.0001	0.0000	0.0001	0.0002	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000
HakeSim 2.2	L company fresh efficiency	0.0001	0.0004	0.0004	0.7653	0.0005	0.1046	0.7116	0.0001	0.2771	0.0000	0.0000	0.0000	0.0005	0.7653	0.1046	0.0000	0.0000
	M company fresh efficiency	0.0003	0.0002	0.0002	0.2352	0.0001	0.0324	0.2180	0.0003	0.0847	0.0000	0.0000	0.0000	0.0001	0.2352	0.0324	0.0000	0.0000
	S company fresh efficiency	0.0000	0.0004	0.0003	0.0001	0.0004	0.0003	0.0001	0.0007	0.0004	0.0000	0.0000	0.0000	0.0004	0.0001	0.0003	0.0000	0.0000
	SC company fresh efficiency	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
HakeSim 2.3	L company fresh efficiency	0.0016	0.0024	0.0006	0.7646	0.0026	0.2616	0.7141	0.0019	0.4802	0.0000	0.0000	0.0000	0.0026	0.7646	0.2616	0.0002	0.0000
	M company fresh efficiency	0.0009	0.0013	0.0003	0.2340	0.0014	0.0805	0.2194	0.0009	0.1474	0.0000	0.0000	0.0000	0.0014	0.2340	0.0805	0.0000	0.0000
	S company fresh efficiency	0.0008	0.0012	0.0003	0.0010	0.0012	0.0005	0.0007	0.0011	0.0001	0.0000	0.0000	0.0000	0.0012	0.0010	0.0005	0.0006	0.0000
	SC company fresh efficiency	0.0012	0.0027	0.0009	0.0009	0.0028	0.0015	0.0016	0.0025	0.0002	0.0000	0.0000	0.0000	0.0028	0.0009	0.0015	0.0003	0.0000

Table 5.8: Sensitivity of model outputs (shown along the top) to extreme values for different company processing efficiencies for frozen fish (shown down), for each of the model prototypes. Input and output names are as per their definitions in Chapter 4. L, M, S and SC stand for large, medium, small and super-cluster companies.

		Ave. world_fresh_fish_caught	Ave. world_frozen_fish_caught	Ave. world_all_fish_caught	Ave. world_fresh_stock_processed	Ave. world_frozen_stock_processed	Ave. world_stock_processed	Ave. world_fresh_fish_wasted	Ave. world_frozen_fish_wasted	Ave. world_all_fish_wasted	Ave. world_frozen_demand	Ave. world_fresh_demand	Ave. world_client_demand	Ave. world_frozen_fish_bought	Ave. world_fresh_fish_bought	Ave. world_all_fish_bought	Ave. world_active_frozen_vessels	Ave. world_active_fresh_vessels
HakeSim 1.0	L frozen efficiency	0.0096	0.0059	0.0074	0.0097	0.8369	0.5402	0.0096	3.6081	1.1463	0.0000	0.0000	0.0000	0.8369	0.0097	0.5402	0.0000	0.0000
	M frozen efficiency	0.0066	0.0038	0.0051	0.0066	0.1278	0.0844	0.0066	0.5388	0.1746	0.0000	0.0000	0.0000	0.1278	0.0066	0.0844	0.0000	0.0000
	S frozen efficiency	0.0085	0.0078	0.0081	0.0085	0.0283	0.0212	0.0085	0.0922	0.0317	0.0000	0.0000	0.0000	0.0283	0.0085	0.0212	0.0000	0.0000
	SC frozen efficiency	0.0103	0.0062	0.0081	0.0103	0.0270	0.0189	0.0104	0.1085	0.0414	0.0000	0.0000	0.0000	0.0270	0.0103	0.0189	0.0000	0.0000
HakeSim 2.1	L frozen efficiency	0.0022	0.0015	0.0019	0.0027	0.8087	0.5212	0.0018	3.3939	1.0264	0.0000	0.0000	0.0000	0.8087	0.0027	0.5212	0.0000	0.0000
	M frozen efficiency	0.0020	0.0025	0.0023	0.0019	0.1185	0.0755	0.0020	0.5117	0.1563	0.0000	0.0000	0.0000	0.1185	0.0019	0.0755	0.0000	0.0000
	S frozen efficiency	0.0001	0.0005	0.0003	0.0005	0.0334	0.0213	0.0002	0.1430	0.0432	0.0000	0.0000	0.0000	0.0334	0.0005	0.0213	0.0000	0.0000
	SC fozen efficiency	0.0008	0.0009	0.0009	0.0010	0.0395	0.0258	0.0007	0.1617	0.0485	0.0000	0.0000	0.0000	0.0395	0.0010	0.0258	0.0000	0.0000
HakeSim 2.2	L frozen efficiency	0.0014	0.0021	0.0020	0.0014	0.2922	0.2519	0.0014	1.0982	0.6712	0.0000	0.0000	0.0000	0.2922	0.0014	0.2519	0.0000	0.0000
	M frozen efficiency	0.0024	0.0031	0.0030	0.0022	0.5134	0.4433	0.0026	1.8978	1.1579	0.0000	0.0000	0.0000	0.5134	0.0022	0.4433	0.0000	0.0000
	S frozen efficiency	0.0007	0.0009	0.0009	0.0011	0.0822	0.0711	0.0003	0.3020	0.1843	0.0000	0.0000	0.0000	0.0822	0.0011	0.0711	0.0000	0.0000
	SC fozen efficiency	0.0012	0.0003	0.0005	0.0012	0.1136	0.0979	0.0013	0.4246	0.2598	0.0000	0.0000	0.0000	0.1136	0.0012	0.0979	0.0000	0.0000
HakeSim 2.3	L frozen efficiency	0.0012	0.0010	0.0000	0.0012	0.2967	0.1954	0.0012	1.0996	0.3600	0.0000	0.0000	0.0000	0.2967	0.0012	0.1954	0.0003	0.0000
	M frozen efficiency	0.0079	0.0030	0.0020	0.0065	0.5047	0.3354	0.0091	1.8926	0.6120	0.0000	0.0000	0.0000	0.5047	0.0065	0.3354	0.0021	0.0000
	S frozen efficiency	0.0008	0.0024	0.0009	0.0007	0.0841	0.0553	0.0009	0.3019	0.0992	0.0000	0.0000	0.0000	0.0841	0.0007	0.0553	0.0002	0.0000
	SC fozen efficiency	0.0015	0.0016	0.0018	0.0014	0.1157	0.0759	0.0015	0.4228	0.1391	0.0000	0.0000	0.0000	0.1157	0.0014	0.0759	0.0004	0.0000

Table 5.9: Sensitivity of model outputs (shown along the top) to extreme values of proportion frozen hake demanded by each of three markets (shown down), for each of the model prototypes. Input and output names are as per their definitions in Chapter 4.

		Ave. world_fresh_fish_caught	Ave. world_frozen_fish_caught	Ave. world_all_fish_caught	Ave. world_fresh_stock_processed	Ave. world_frozen_stock_processed	Ave. world_stock_processed	Ave. world_fresh_fish_wasted	Ave. world_frozen_fish_wasted	Ave. world_all_fish_wasted	Ave. world_frozen_demand	Ave. world_fresh_demand	Ave. world_client_demand	Ave. world_frozen_fish_bought	Ave. world_fresh_fish_bought	Ave. world_all_fish_bought	Ave. world_active_frozen_vessels	Ave. world_active_fresh_vessels
HakeSim 1.0	Domestic prop frozen	0.0047	0.0033	0.0039	0.0047	0.0032	0.0037	0.0047	0.0034	0.0043	0.3133	0.9816	0.0000	0.0032	0.0047	0.0037	0.0000	0.0000
	Spain prop frozen	0.0125	0.0060	0.0090	0.0126	0.0061	0.0084	0.0125	0.0056	0.0103	0.1907	0.5974	0.0000	0.0061	0.0126	0.0084	0.0000	0.0000
	Other prop frozen	0.0113	0.0106	0.0109	0.0114	0.0108	0.0110	0.0113	0.0098	0.0108	0.0381	0.1192	0.0000	0.0108	0.0114	0.0110	0.0000	0.0000
HakeSim 2.1	Domestic prop frozen	0.0143	0.0166	0.0155	0.0136	0.0166	0.0155	0.0151	0.0168	0.0156	0.3133	0.9816	0.0000	0.0166	0.0136	0.0155	0.0000	0.0000
	Spain prop frozen	0.0001	0.0000	0.0000	0.0001	0.0001	0.0000	0.0001	0.0000	0.0001	0.1907	0.5974	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000
	Other prop frozen	0.0049	0.0029	0.0039	0.0046	0.0026	0.0033	0.0053	0.0043	0.0050	0.0380	0.1190	0.0000	0.0026	0.0046	0.0033	0.0000	0.0000
HakeSim 2.2	Domestic prop frozen	0.0081	0.0029	0.0006	0.0070	0.0007	0.0004	0.0091	0.0112	0.0033	0.3133	0.9816	0.0000	0.0007	0.0070	0.0004	0.0000	0.0000
	Spain prop frozen	0.0003	0.0004	0.0003	0.0004	0.0004	0.0003	0.0001	0.0006	0.0003	0.1907	0.5974	0.0000	0.0004	0.0004	0.0003	0.0000	0.0000
	Other prop frozen	0.0020	0.0072	0.0062	0.0005	0.0072	0.0061	0.0044	0.0075	0.0063	0.0380	0.1190	0.0000	0.0072	0.0005	0.0061	0.0000	0.0000
HakeSim 2.3	Domestic prop frozen	0.0212	0.0048	0.0123	0.0188	0.0055	0.0100	0.0233	0.0022	0.0164	0.3133	0.9816	0.0000	0.0055	0.0188	0.0100	0.0148	0.0000
	Spain prop frozen	0.0010	0.0005	0.0002	0.0005	0.0007	0.0006	0.0015	0.0011	0.0010	0.1907	0.5974	0.0000	0.0007	0.0005	0.0003	0.0005	0.0000
	Other prop frozen	0.0341	0.0352	0.0035	0.0327	0.0348	0.0118	0.0355	0.0369	0.0118	0.0381	0.1192	0.0000	0.0348	0.0327	0.0118	0.0126	0.0000

Table 5.10: Sensitivity of model outputs (shown along the top) to extreme values of Total Allowable Catch (TAC; shown down), for each of the model prototypes. Input and output names are as per their definitions in Chapter 4.

		Ave. world_fresh_fish_caught	Ave. world_frozen_fish_caught	Ave. world_all_fish_caught	Ave. world_fresh_stock_processed	Ave. world_frozen_stock_processed	Ave. world_stock_processed	Ave. world_fresh_fish_wasted	Ave. world_frozen_fish_wasted	Ave. world_all_fish_wasted	Ave. world_frozen_demand	Ave. world_fresh_demand	Ave. world_client_demand	Ave. world_frozen_fish_bought	Ave. world_fresh_fish_bought	Ave. world_all_fish_bought	Ave. world_active_frozen_vessels	Ave. world_active_fresh_vessels
HakeSim 1.0	TAC	1.0022	1.0009	1.0008	1.0022	1.0008	1.0008	1.0021	1.0010	1.0009	0.0000	0.0000	0.0000	1.0008	1.0022	1.0008	0.0000	0.0000
HakeSim 2.1	TAC	1.0018	1.0019	1.0019	1.0020	1.0019	1.0019	1.0017	1.0016	1.0017	0.0000	0.0000	0.0000	1.0019	1.0020	1.0019	0.0000	0.0000
HakeSim 2.2	TAC - 100%	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	TAC + 100%	0.0002	0.0003	0.0002	0.0002	0.0004	0.0003	0.0001	0.0002	0.0002	0.0000	0.0000	0.0000	0.0004	0.0002	0.0003	0.0000	0.0000
HakeSim 2.3	TAC - 100%	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	TAC + 100%	0.0007	0.0010	0.0009	0.0008	0.0010	0.0009	0.0007	0.0010	0.0008	0.0000	0.0000	0.0000	0.0010	0.0008	0.0009	0.0311	0.0000

Table 5.11: Sensitivity of model outputs (shown along the top) to extreme values of different fleet combinations (shown down), for only three model prototypes. Input and output names are as per their definitions in Table 5.1, and Table 4.1 above. L, M, S and SC stand for large, medium, small and super-cluster companies and max and min refer to maximum and minimum, respectively. In this case either the entire fleet, freezer vessel or wet-fish vessel numbers are maximized or minimized for all companies or individual company agents.

		Ave. world_fresh_fish_caught	Ave. world_frozen_fish_caught	Ave. world_all_fish_caught	Ave. world_fresh_stock_processed	Ave. world_frozen_stock_processed	Ave. world_stock_processed	Ave. world_fresh_fish_wasted	Ave. world_frozen_fish_wasted	Ave. world_all_fish_wasted	Ave. world_frozen_demand	Ave. world_fresh_demand	Ave. world_client_demand	Ave. world_frozen_fish_bought	Ave. world_fresh_fish_bought	Ave. world_all_fish_bought	Ave. world_active_frozen_vessels	Ave. world_active_fresh_vessels
HakeSim 2.1	All companies max freezers	0.2489	0.2585	0.2540	0.2396	0.2561	0.2502	0.2583	0.2689	0.2615	0.0000	0.0000	0.0000	0.2561	0.2396	0.2502	1.0000	0.0000
	All companies min freezers	0.8424	0.6403	0.7355	0.7234	0.6344	0.6662	0.9630	0.6649	0.8728	0.0000	0.0000	0.0000	0.6344	0.7234	0.6662	1.0000	0.0000
	All companies max wetfish	0.2314	0.1738	0.2009	0.2124	0.1735	0.1874	0.2507	0.1748	0.2277	0.0000	0.0000	0.0000	0.1735	0.2124	0.1874	0.0000	1.0000
	All companies min wetfish	1.0000	0.7443	0.8647	1.0000	0.7506	0.8396	1.0000	0.7175	0.9145	0.0000	0.0000	0.0000	0.7506	1.0000	0.8396	0.0000	1.0000
	All companies max fleet size	0.0001	0.0550	0.0292	0.0001	0.0521	0.0336	0.0002	0.0673	0.0205	0.0000	0.0000	0.0000	0.0521	0.0001	0.0336	1.0000	1.0000
	All companies min fleet size	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	L company max vessels	0.0002	0.0238	0.0127	0.0002	0.0241	0.0156	0.0003	0.0225	0.0070	0.0000	0.0000	0.0000	0.0241	0.0002	0.0156	0.2069	0.6957
	L company min vessels	0.8400	0.7945	0.8160	0.8847	0.8064	0.8343	0.7947	0.7446	0.7796	0.0000	0.0000	0.0000	0.8064	0.8847	0.8343	0.2069	0.6957
	M company max vessels	0.0002	0.0099	0.0051	0.0002	0.0100	0.0063	0.0002	0.0093	0.0027	0.0000	0.0000	0.0000	0.0100	0.0002	0.0063	0.5862	0.2174
	M company min vessels	0.1116	0.1193	0.1157	0.1153	0.1211	0.1190	0.1078	0.1120	0.1091	0.0000	0.0000	0.0000	0.1211	0.1153	0.1190	0.5862	0.2174
	S company max vessels	0.0002	0.0100	0.0052	0.0004	0.0083	0.0052	0.0001	0.0168	0.0050	0.0000	0.0000	0.0000	0.0083	0.0004	0.0052	0.0690	0.0435
	S company min vessels	0.0216	0.0393	0.0310	0.0009	0.0329	0.0209	0.0445	0.0661	0.0510	0.0000	0.0000	0.0000	0.0329	0.0009	0.0209	0.0690	0.0435
	SC max vessels	0.0001	0.0117	0.0062	0.0002	0.0099	0.0064	0.0001	0.0193	0.0058	0.0000	0.0000	0.0000	0.0099	0.0002	0.0064	0.1379	0.0435
	SC min vessels	0.0252	0.0456	0.0360	0.0006	0.0383	0.0244	0.0513	0.0762	0.0589	0.0000	0.0000	0.0000	0.0383	0.0006	0.0244	0.1379	0.0435
HakeSim 2.2	All companies max freezers	0.0001	1.0013	0.7944	0.0001	1.0012	0.8637	0.0001	1.0016	0.6117	0.0000	0.0000	0.0000	1.0012	0.0001	0.8637	1.0000	0.0000
	All companies min freezers	0.0002	1.0000	0.7934	0.0003	1.0000	0.8628	0.0001	1.0000	0.6107	0.0000	0.0000	0.0000	1.0000	0.0003	0.8628	1.0000	0.0000
	All companies max wetfish	1.0002	0.0000	0.2066	0.9999	0.0001	0.1372	1.0004	0.0003	0.3897	0.0000	0.0000	0.0000	0.0001	0.9999	0.1372	0.0000	1.0000
	All companies min wetfish	1.0000	0.0001	0.2065	1.0000	0.0000	0.1372	1.0000	0.0005	0.3890	0.0000	0.0000	0.0000	0.0000	1.0000	0.1372	0.0000	1.0000
	All companies max fleet size	0.9999	1.0005	1.0004	0.9999	1.0004	1.0003	0.9999	1.0010	1.0006	0.0000	0.0000	0.0000	1.0004	0.9999	1.0003	1.0000	1.0000
	All companies min fleet size	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	L company max vessels	0.6970	0.2829	0.3685	0.7666	0.2942	0.3591	0.6324	0.2408	0.3933	0.0000	0.0000	0.0000	0.2942	0.7666	0.3591	0.2069	0.6957
	L company min vessels	0.6956	0.2830	0.3682	0.7653	0.2944	0.3591	0.6308	0.2405	0.3924	0.0000	0.0000	0.0000	0.2944	0.7653	0.3591	0.2069	0.6957
	M company max vessels	0.2176	0.4905	0.4341	0.2348	0.5101	0.4723	0.2015	0.4173	0.3333	0.0000	0.0000	0.0000	0.5101	0.2348	0.4723	0.5862	0.2174
	M company min vessels	0.2172	0.4903	0.4339	0.2344	0.5101	0.4722	0.2011	0.4169	0.3329	0.0000	0.0000	0.0000	0.5101	0.2344	0.4722	0.5862	0.2174
	S company max vessels	0.0432	0.0953	0.0846	0.0002	0.0823	0.0710	0.0835	0.1440	0.1205	0.0000	0.0000	0.0000	0.0823	0.0002	0.0710	0.0690	0.0435
	S company min vessels	0.0432	0.0946	0.0840	0.0002	0.0817	0.0705	0.0836	0.1428	0.1197	0.0000	0.0000	0.0000	0.0817	0.0002	0.0705	0.0690	0.0435
	SC company max vessels	0.0432	0.1328	0.1143	0.0005	0.1146	0.0988	0.0839	0.2006	0.1552	0.0000	0.0000	0.0000	0.1146	0.0005	0.0988	0.1379	0.0435
	SC company min vessels	0.0438	0.1318	0.1136	0.0003	0.1136	0.0981	0.0843	0.1994	0.1546	0.0000	0.0000	0.0000	0.1136	0.0003	0.0981	0.1379	0.0435
HakeSim 2.3	All companies max freezers	0.0018	0.3433	0.1871	0.0016	0.3435	0.2273	0.0019	0.3424	0.1131	0.0000	0.0000	0.0000	0.3435	0.0016	0.2273	0.4954	0.0000
	All companies min freezers	0.0012	1.0000	0.5422	0.0011	1.0000	0.6597	0.0013	1.0000	0.3257	0.0000	0.0000	0.0000	1.0000	0.0011	0.6597	1.0000	0.0000
	All companies max wetfish	1.0018	0.1638	0.3692	1.0018	0.1701	0.2282	1.0017	0.1403	0.6287	0.0000	0.0000	0.0000	0.1701	1.0018	0.2282	0.2630	1.0000
	All companies min wetfish	1.0000	0.0012	0.4566	1.0000	0.0013	0.3391	1.0000	0.0009	0.6731	0.0000	0.0000	0.0000	0.0013	1.0000	0.3391	0.0311	1.0000
	All companies max fleet size	1.0012	0.0866	0.4108	1.0008	0.0962	0.2767	1.0016	0.0508	0.6579	0.0000	0.0000	0.0000	0.0962	1.0008	0.2767	0.1612	1.0000
	All companies min fleet size	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	L company max vessels	0.0008	0.0806	0.0434	0.0006	0.0838	0.0551	0.0010	0.0686	0.0217	0.0000	0.0000	0.0000	0.0838	0.0006	0.0551	0.1367	0.0000
	L company min vessels	0.0005	0.0020	0.0013	0.0004	0.0021	0.0015	0.0006	0.0017	0.0010	0.0000	0.0000	0.0000	0.0021	0.0004	0.0015	0.0583	0.0000
	M company max vessels	0.0008	0.2832	0.1533	0.0006	0.2946	0.1942	0.0010	0.2408	0.0780	0.0000	0.0000	0.0000	0.2946	0.0006	0.1942	0.4926	0.0000
	M company min vessels	0.0012	0.0367	0.0194	0.0011	0.0381	0.0248	0.0012	0.0313	0.0094	0.0000	0.0000	0.0000	0.0381	0.0011	0.0248	0.1340	0.0000
	S company max vessels	0.0009	0.0385	0.0205	0.0007	0.0334	0.0218	0.0010	0.0578	0.0182	0.0000	0.0000	0.0000	0.0334	0.0007	0.0218	0.0517	0.0000
	S company min vessels	0.0008	0.0089	0.0044	0.0005	0.0078	0.0050	0.0011	0.0129	0.0035	0.0000	0.0000	0.0000	0.0078	0.0005	0.0050	0.0107	0.0000
	SC max vessels	0.0008	0.0566	0.0304	0.0007	0.0489	0.0321	0.0008	0.0853	0.0273	0.0000	0.0000	0.0000	0.0489	0.0007	0.0321	0.1116	0.0000
	SC min vessels	0.0013	0.0280	0.0158	0.0012	0.0239	0.0162	0.0014	0.0433	0.0151	0.0000	0.0000	0.0000	0.0239	0.0012	0.0162	0.0547	0.0000

Table 5.12: Sensitivity of model outputs (shown along the top) to extreme values of catch per unit effort (CPUE) and stochasticity of catching fish. Only the results for *HakeSim 2.3* are shown, since this is the only model prototype that includes these two parameters as model inputs.

		Ave. world_fresh_fish_caught	Ave. world_frozen_fish_caught	Ave. world_all_fish_caught	Ave. world_fresh_stock_processed	Ave. world_frozen_stock_processed	Ave. world_stock_processed	Ave. world_fresh_fish_wasted	Ave. world_frozen_fish_wasted	Ave. world_all_fish_wasted	Ave. world_frozen_demand	Ave. world_fresh_demand	Ave. world_client_demand	Ave. world_frozen_fish_bought	Ave. world_fresh_fish_bought	Ave. world_all_fish_bought	Ave. world_active_frozen_vessels	Ave. world_active_fresh_vessels
HakeSim 2.3	**CPUE**	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000	1.0000	1.0000	1.0000	0.0311	0.0000
	Stochasticity of catching fish	0.0032	0.0791	0.0444	0.0034	0.0821	0.0553	0.0031	0.0679	0.0243	0.0000	0.0000	0.0000	0.0821	0.0034	0.0553	0.0044	0.0000

4. Summary

If all of the above results are considered collectively, it becomes apparent that *HakeSim 2.3* had a much more realistic behaviour than the other model versions. *HakeSim 1.0* and *2.1* were not very different from each other in behaviour, suggesting that while average vessel numbers were used in 2.1 the assumption (8, see Table 4.1) that vessel fleet structure did not have a significant effect on the model held true in the early prototype. But *HakeSim 2.1* showed some sensitivity to changes in fleet structure (vessel number) inputs, suggesting it might be an important variable. Additionally, when considering the more complex prototypes *HakeSim 2.2 and 2.3*, a variable fleet structure did have a significant impact on model performance, as was evidenced by the sensitivity of the outputs of *HakeSim 2.2* and *2.3* to changes in fleet structures. Having the ability to alter fleet structure in the model will allow for a different series of questions to be asked of later prototypes and might confer a significant advantage in terms of the flexibility of analyses that could be conducted with the model prototype that will include monetary model currency. It also leaves the possibility to continue to run the model with the fixed fleet structure or modify it easily as desired. This ability will therefore be retained in future model versions.

The assumptions (6 and 7, see Table 4.1) that *companies divide quota evenly between vessels* and that *all vessels are active at all time steps* had a significant effect on model behaviour. In *HakeSim 2.2* where these assumptions were relaxed, i.e. where company agents had the potential to preferentially send some vessels fishing rather than others and to only send fishing as many vessels as necessary to catch their quota, much more realistic model behaviour was achieved. This was not surprising given that in the real world this reflects how focused on efficiency the fishery was. Furthermore, *HakeSim 2.3* had the same behaviour as *2.2* but additionally captured CPUE, a factor identified as important to industry, and to which the model was sensitive. It will therefore allow the testing of a greater variety of scenarios in later model versions, where CPUE may be especially important for financial variables through its influence on per vessel catch and consequently vessel running costs. Given this much more realistic and interesting behaviour of the model that will better allow questions about the real world industry to be answered, *HakeSim 2.3* will be used in preference to the alternate versions *2.2*, *2.1* and *1.0* for further model development.

As suggested by Starfield and Jarre (2011), the first model prototype after having been subjected to a thorough sensitivity analysis and assumption analysis has led to a plan of how to advance the model to the next prototype through improving on the existing one. In the next phase of model development *HakeSim 2.3* will be modified to incorporate monetary model currency to allow for testing questions about the importance of fuel price and exchange rate for the fishing industry.

CHAPTER 6:

THE FULL PROTOTYPE OF HAKESIM – FROM FISH TO EXPORTS

Chapter 6: The full prototype of *HakeSim* – from fish to exports

1. Introduction

Building on the work of the previous model versions, this chapter takes the model to the final full prototype, *HakeSim 3.0* which incorporates monetary values as a model currency in addition to fresh and frozen fish. This will allow some of the original questions on the trade-offs between total allowable catch (TAC), catch per unit effort (CPUE), fuel price, exchange rate and market factors such as price and demand, to be addressed.

Some further questions and ideas emerged during the data collection, stakeholder consultation and data analysis phases and the model further attempts to speak to these. These new ideas emerged as a result of iterating through the model development cycle, where new questions and hypotheses emerged from the analysis of early model prototypes and communication of the results with stakeholders. Some of these new ideas and hypotheses are tested in the scenarios at the end of the chapter.

In Chapter 2 it emerged that companies were shown to have different business strategies. These different strategies presumably involve trade-offs in profit and risk, and this idea is to be tested. Another important trend that was highlighted in the Chapter 2 was that the industry has downsized its fleet through time, particularly since the start of Medium and Long Term Rights Allocation (MTRA and LTRA) processes. This was said to be partially to reduce *excess* effort, presumably to increase economic efficiency (decrease maintenance costs etc.) and also further to maintain an industry-led effort restriction. Industry also suggested that freezer trawling was less costly than catching fresh fish (particularly under higher fuel prices), and that was part of the reason for the switch through time to more frozen product, as was observed in the export data trends (Chapter 3). As such, much of the reduced vessel numbers were accounted for by retired wet-fish vessels, as seen in the industry fleet structure trends (Chapter 2). Industry suggested, that this allowed them to maintain profitability in the face of rising fuel (and other) costs. The hypothesis that fleet size and composition (i.e. quantity of fresh to freezer vessels) has an effect on company profitability and risk is also to be tested. Both of these hypotheses are tested through mean variance economic analyses, which allows the examination of profit versus deviation in profit (i.e. financial risk) to be assessed for different strategies and fleet sizes.

Other important factors that were identified as drivers of company behaviour and profitability in the industry were fuel price, exchange rate, market factors and CPUE. Understanding the interactions between these variables was another important question to address. It is hypothesized, based on interviews with companies that fuel price is the single biggest cost to industry and as fuel price increases profitability will decrease until at some point fuel price will cause companies to make a loss. Secondly, favourable exchange rates and high market value of product might buffer against the losses made by high fuel costs by increasing the revenue from fish. While high CPUE (under unchanged distribution of the fish) might reduce the amount of fuel needed to catch a given quantity of fish, thereby reducing total fuel used and thereby total fuel costs. Companies identified that the exchange rate adds complexity by simultaneously affecting international fuel price (priced in US$) and Rand value equivalent of exported product, this interactive effect is to be explored.

Companies reported that there could be temporal mismatches between TAC and CPUE due to a lag in stock assessment models incorporating CPUE into hake population predictions and therefore TAC recommendations[16]. This could cause a de-synchronization in investment; in other words, while TAC remains low or average and CPUE is high companies require fewer vessels to catch their quota and they disinvest in (i.e. sell or retire) vessels, but if CPUE drops and TAC is high companies will have insufficient vessel numbers to catch their allotted quota and would need to rapidly re-invest (i.e. purchase) new vessels to catch their quota, which would take at least one year to purchase a second hand vessel or two years to have a new vessel built. This was identified as a possible concern to companies because they wish to demonstrate that they have the capability to catch their allotted annual quota for future rights allocations. Companies may have the incentive to maintain a larger fleet size solely to buffer against such mismatches in TAC and CPUE and ensure that they have the capacity to catch their allotted quota. The hypothesis that TAC and CPUE mismatches have consequences for profitability of companies and for the ability to catch their quota is tested. The effect of TAC and CPUE mismatches on different fleet sizes is also examined.

[16] That is to say, in simplest terms, that the stock assessment models used in the Operational Management Procedure employed by government use past time series of CPUE to project future TACs and this can occasionally result in a mismatch between projected hake populations and therefore TAC and actual hake populations and therefore CPUE. Although reasons for mismatches may be more complex than this.

2. <u>Methods</u>

In this chapter, following the rapid prototyping approach described in Chapter 4, monetary model currency and associated inputs and processes are added to produce a full prototype model, *HakeSim 3.0*. The model is then implemented using Netlogo v5.0.1.

2.1. Conceptual framework & design

HakeSim 3.0 builds upon the previous model versions and therefore has the same underlying conceptual framework and design described in Chapters 4 and 5. This version is, however, more complex and attempts to capture more of the known drivers for the real world offshore demersal hake trawling industry by i) adding a new model currency, ii) increasing the number of input parameters to the model (Figure 6.1), and iii) incorporating a variety of more complex procedures (sub-models). The model retains the model 'currency' of fresh and frozen fish at all levels (vessels, companies, clients, global variables). Money, South African Rands (ZAR) and Euros, is added as a new 'currency' in the model. To capture aspects of the two existing 'currencies' in the model, there are distinct model inputs of monetary values for the different vessel types and the different fish types (fresh or frozen), where applicable. This allows differences in, for example, running costs for different vessel types and different values obtained for fresh versus frozen product to be captured as different inputs. These price differences in turn have consequences for company profit. The new parameters allow the capture of financial aspects of the industry such as sales values, operating costs for companies and vessels, fuel price, foreign exchange value (Rand/Euro) and values paid for hake by countries (i.e. 'price paid per ton').

Structural and functional aspects of the model resemble earlier prototypes: there are eleven client agents, and four companies that can each own a variably-sized vessel fleet. Vessels take the form of wet-fish stern trawlers that land fresh fish, and freezer stern trawlers or factory freezer trawlers, which land frozen fish. Each of these three agent classes has the same traits and input variables as described in detail in the previous chapters. But they have also been assigned additional attributes and model inputs that allow for money to be captured in the model (see Table 6.1 for a full list of new inputs).

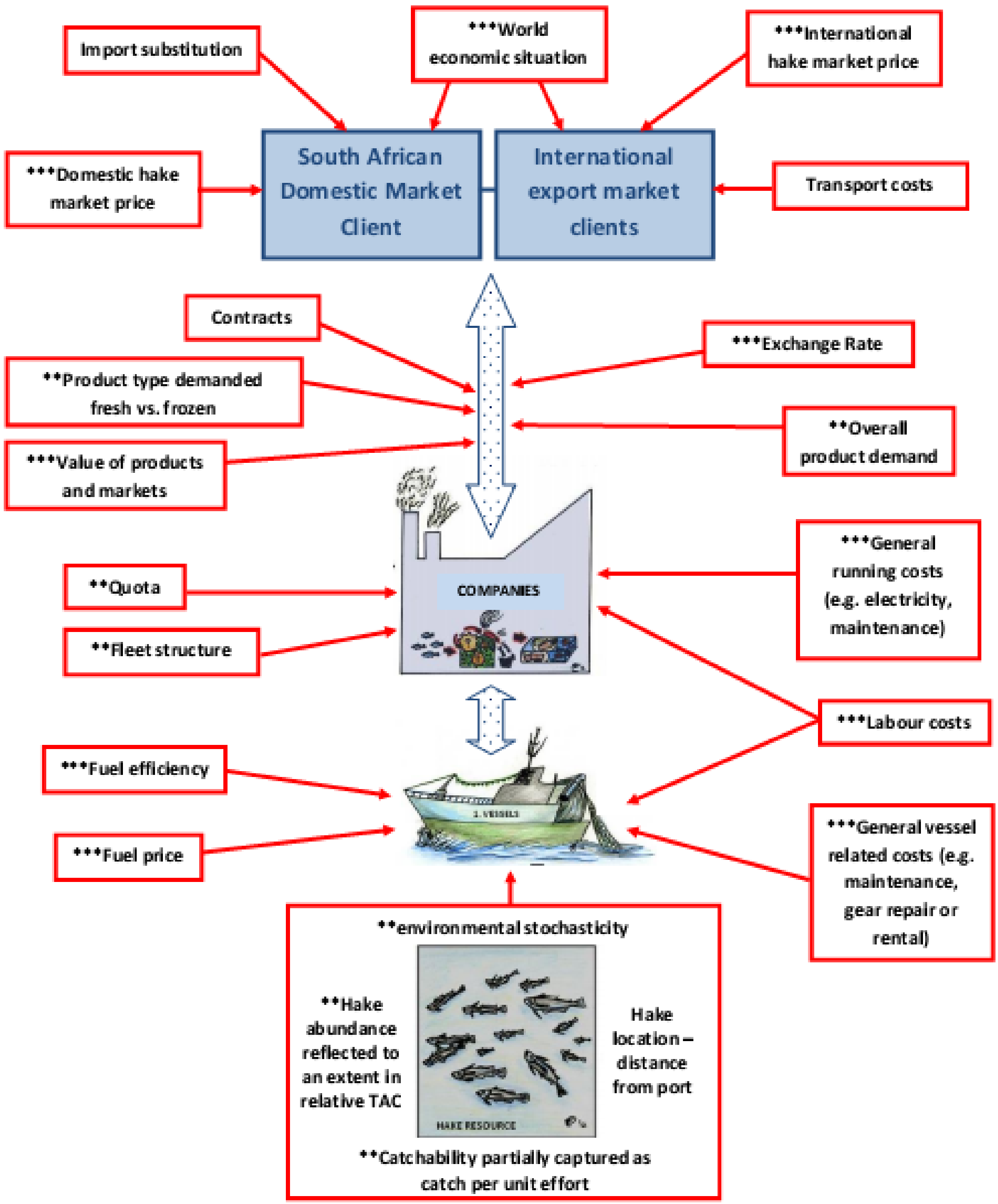

Figure 6.1: A variety of external drivers known to affect the offshore demersal hake trawling industry in South Africa. Parameters newly captured in *HakeSim 3.0* are marked * and those still captured from earlier model versions as **. Illustrations by Rachel Cooper.**

Table 6.1: List of all new inputs and monitors introduced in *HakeSim 3.0* in addition to inputs and outputs of previous versions.

	Type	Agent(s) it applies to	Brief description
Input variables			
fuel cost of factory freezer trawlers	ZAR	factory freezer vessels	*cost of fuel used monthly by an active vessel, = fuel usage * fuel price*
fuel cost of freezer trawlers	ZAR	freezer vessels	*cost of fuel used monthly by an active vessel, = fuel usage * fuel price*
fuel cost of wet-fish trawlers	ZAR	wet-fish vessels	*cost of fuel used monthly by an active vessel, = fuel usage * fuel price*
cost of active factory freezer vessels per month	ZAR	factory freezer vessels	*monthly cost of an active vessel, = fuel cost + other vessel costs*
cost of active freezer vessels per month	ZAR	freezer vessels	*monthly cost of an active vessel, = fuel cost + other vessel costs*
cost of active wet-fish vessels per month	ZAR	wet-fish vessels	*monthly cost of an active vessel, = fuel cost + other vessel costs*
fuel price	ZAR	entire model	*price per litre of fuel, input monthly*
fuel usage of factory freezer trawlers	L/month	factory freezer vessels	*quantity of fuel used by an active vessel in a month*
fuel usage of freezer trawlers	L/month	freezer vessels	*quantity of fuel used by an active vessel in a month*
fuel usage of wet-fish trawlers	L/month	wet-fish vessels	*quantity of fuel used by an active vessel in a month*
Exchange Rate	Euro/Rand	entire model	*foreign exchange rate*
monthly cost to L company per vessel	ZAR	large company	*costs to company based on the total number of vessels owned*
monthly cost to M company per vessel	ZAR	medium company	*costs to company based on the total number of vessels owned*
monthly cost to S company per vessel	ZAR	small company	*costs to company based on the total number of vessels owned*
monthly cost to SC company per vessel	ZAR	super-cluster company	*costs to company based on the total number of vessels owned*
price paid for fresh hake	Euros/ton	Clients	*price paid per ton of fresh hake by clients (markets)*
price paid for frozen hake	Euros/ton	Clients	*price paid per ton of frozen hake by clients (markets)*
Monitors			
world cost of active wet-fish vessels	ZAR	companies	*sum of costs of all active wet-fish vessels for all companies in one time step*
world cost of active frozen vessels	ZAR	companies	*sum of costs of all active frozen fish vessels for all companies in one time step*
world frozen fish sold value	ZAR	companies	*sum value of all frozen fish sold by all companies in one time step*
world fresh fish sold value	ZAR	companies	*sum value of all fresh fish sold by all companies in one time step*
world all fish sold value	ZAR	companies	*sum value of all fish sold by all companies in one time step*
world all fish bought value	ZAR	Clients	*sum value of all fish bought by all clients in one time step*
world fresh fish bought value	ZAR	Clients	*sum value of all fresh fish bought by all clients in one time step*
world frozen fish bought value	ZAR	Clients	*sum value of all frozen fish bought by all clients in one time step*
world company short term costs	ZAR	companies	*all costs incurred by company in one time step*
world company profit	ZAR	companies	*all profit (i.e. fish sold value - costs) by company in one time step*
world uncaught quota	tons	companies	*all quota that was allocated to company that was not caught by vessels*

Table 6.2: Fuel used by vessels on a monthly basis, calculated on the basis of daily fuel use for a single horsepower unit. Data from the European Union (EU) demersal trawl fleets were obtained from the STCEF online database http://datacollection.jrc.ec.europa.eu and used to estimate daily values for the SA offshore hake trawl fleet.

		daily fuel usage per single horsepower (L)		fuel usage per month (L)	
vessel type	**vessel engine size (HP)**	**industry***	**EU***	**industry***	**EU***
Wet-fish stern trawlers	1800.4	3.2	1.57	127228.3	62470.1
Freezer stern trawlers	1125.8	3.2	1.57	79556.5	39062.9
Factory freezer trawlers	2886	3.2	1.57	203944.0	100138.2

Vessels have different maximum capacities for fish, as specified in Chapter 5, and different sized engines (i.e. register power Table 5.3). They therefore have different running costs and catch costs per landed ton of fresh/frozen fish. Engine size is an important part of the running cost of a vessel catching fish. Fuel consumption per vessel type is therefore calculated based on engine size (Table 6.2). This relies on the simplifying assumption that fuel usage is directly related to engine size and ignores other factors, such as vessel shape, that can also affect usage; i.e. fuel usage is assumed to be related to engine size (HP) rather than vessel type. Unfortunately, although these assumptions are simplifying, in the absence of perfect data (since real business data on this are of a highly confidential nature and not publically available) this is the best possible estimate. To calculate a monthly fuel usage per vessel, it is further assumed that vessels fish their maximum number of permit days (265 days) in one year, and that the annual fuel usage is spread evenly across the 12 months of the year, not completely unreasonable based on the results of company interviews. The use of 265 fishing days will also provide a final fuel usage based on the idea that a vessel is active the entire month it is out fishing, which active vessels are assumed to be in the model. The South African industry-based estimate of fuel consumed *per horsepower* is used for standard runs. The fuel usage of a vessel (L) is accordingly:

$$\text{Fuel usage per month (L)} = \frac{\text{vessel engine size (HP)*daily fuel usage (L/HP.day)* 265 fishing days per year}}{\text{12 months per year}} \qquad \text{........... (6.1)}$$

The fuel cost of an active vessel for a one month time-step is then calculated as:

Vessel fuel cost (ZAR) = fuel usage per month (L) * fuel price (ZAR/L) .... (6.2)

An active vessel accrues additional costs to fuel, such as crew salaries and wages and additional variable costs directly related to fishing effort, catching or landing fish. These additional vessel costs have also been described for the European demersal trawling fleet and were used to produce an average per vessel cost (see Table 6.3). The total cost for an active vessel (ZAR) is calculated accordingly as:

Active vessel cost = vessel fuel cost + additional vessel costs .... (6.3)

Not only active vessels represent a cost to companies. All vessels that a company owns, as well as a company's base running expenses, accrue a monthly cost. These company costs (CC, estimated in Table 6.3) can include repairs and maintenance to all vessels and facilities and non-variable costs like rent of business premises. A total monthly cost (ZAR) to a company is therefore calculated as:

Total cost to company = (no. active vessels * active vessel cost) + (no. vessels owned * CC) .... (6.4)

The numbers of active vessels and total vessels owned as well as their estimated costs are differentiated into wet-fish, freezer, and factory freezer vessels in the model.

Companies also make revenue from their hake sales to balance against the costs. At each time step company agents calculate the total revenue from all sales as the sum of frozen and fresh hake sales values. Income from commercial bycatch or through other streams are ignored.

Table 6.3: Estimates of monthly vessel running costs that are based on data from the EU demersal trawl fleet were obtained from the STCEF online database http://datacollection.jrc.ec.europa.eu. Data were manipulated to a daily cost per vessel and this was then scaled to a monthly value based on the 265 permit days of the South African fleet, assuming an even cost distribution across 12 months of the year. Values are given in ZAR based on the average Euro/ZAR exchange rate for the 2008 - 2012 period (appended Table A6.2) that the EU data represents. * company related costs – costs borne by company irrespective of whether vessel goes fishing and ** vessel costs – costs only incurred for active fishing vessels.**

	monthly cost per vessel (ZAR)			
	Average	**Minimum**	**Maximum**	**Std Dev**
Crew wages & salaries **	239,206	161,670	309,773	52,495
other variable costs**	144,155	95,626	188,694	33,840
vessel costs (ZAR)	***383,361***	***257,296***	***498,467***	***86,336***
repair & maintenance***	87,451	61,619	103,537	16,156
other non-variable costs***	79,215	53,860	101,255	20,990
Company costs (ZAR)	***166,666***	***115,479***	***204,792***	***37,146***

Total revenue of company = VF + VW .... (6.5)

VF = sum for all clients of (quantity of frozen hake sold to client * pp of client * XR) .... (6.6)

VW = sum for all clients of (quantity of fresh hake sold to client * pp of client * XR) .... (6.7)

Where VF is the value (ZAR) of all frozen hake sold, and VW the value (ZAR) of all fresh hake sold, by a company in one time-step, pp is price paid by client for fresh or frozen hake (Euros/ton), and the XR is the foreign exchange rate of Euro to Rands (see Appendix 6, Table A6.2 for rates). The quantity of hake available to sell is dependent on the amount of hake caught by a company on all of its vessels in that one time step, (which is itself dependent on things such as company's quota, total allowable catch and catch per unit effort, as per previous model versions) and on the fresh and frozen hake processing efficiencies of that company. Price paid by individual clients is input in the model and, is based on real world time series of price paid (Euros/ton) for fresh and frozen hake, as determined in the Chapter 3 (see also Appendix 6, Tables A6.3 and A6.4).

Finally, (accounting) profits are calculated for individual companies based on the balance between the total revenue and the total short term costs, in each time step. (Note that opportunity costs, amortization costs and capital depreciation are ignored in these calculations.) Longer term calculations of nett profit which might be paid to shareholders are not calculated in the model. This is due to the fact that long term costs such as, capital (re-)investments, are difficult to estimate for different companies and may represent costs that do not occur at fixed intervals or have fixed values. Thus the profit estimated is a shorter term, gross accounting profit. The monthly profit (ZAR) is calculated in the model as:

Company profit = Total revenue of company - Total cost to company .... (6.8)

In the production of this model prototype, and in producing the above series of behaviours and inputs, a number of assumptions are made. These include some of the assumptions from previous model versions, along with new assumptions introduced (Table 6.4).

During the implementation of the above model design in Netlogo 5.0.1, ongoing debugging and testing of the model is carried out. The model is thoroughly analysed, tested – sensitivity and robustness analyses carried out (Grimm and Railsback, 2005), and used to draw some conclusions about the system. The model behaviour is also calibrated with/validated against observations in the real world to improve/determine the quality of the model output relative to its objectives (Gilbert and Terna, 2000; Farmer and Foley, 2009; Starfield and Jarre, 2011).Through the use of a range of scenarios based on the real world, the original research questions and interesting questions that emerged during the development of earlier model prototypes and stakeholder consultation, are examined through hypothesis testing. Finally some insights on possible further scenarios for testing and areas for future expansion and development of the model are identified. These are discussed in the concluding chapter.

3. Results & discussion

3.1. Model testing

With the addition of each new procedure, the model was debugged and tested by varying inputs and examining outputs and model behaviour. Procedures were independently tested and some of the basic procedures were also independently implemented in Microsoft Excel to verify their outputs. Agent monitors and plots were also thoroughly scrutinized.

Ad hoc testing was then completed on the final model prototype, in order to test that the model was functioning. Extreme values were used as inputs to the basic model interface, such as extremely low or high fuel prices, unrealistic vessel numbers, all frozen or fresh fish situations, and zero values for inputs, to determine whether the model behaved erratically.

A full sensitivity analysis was subsequently undertaken to verify that no erroneous behaviour remained in the model. Scenario analyses were also conducted to examine whether the model had interesting and realistic behaviours.

Table 6.4: A list of the assumptions made in *HakeSim 3.0* and explanations of why these assumptions were made.

	Assumptions	Why
1	***Other fishing sectors of hake (e.g. longline or inshore trawl) have no effect on the fishing fleet, companies or clients in the model***	In reality this is not true, but since offshore trawling accounts for 85% of the catch and the other sectors were less active in recent years it meant the majority of industry could be captured with only data on the major sector.
2	***There is no storage of fish (either fresh or frozen) by any agent between time steps***	Storage would complicate the prototype making it difficult to analyse trends and conduct sensitivity analyses. In the real world fish is sold relatively quickly, so storage by companies can be assumed to be negligible.
3	***Vessel fullness is dependent on CPUE and the stochasticity of catching fish;***	Based on the idea that each vessel catch is dependent on the catchability of fish. CPUE is one measure of this, but there is also some environmental stochastiicty that can affect individual catches. This stochasticity is a form of uncertainty. A CPUE of 1 indicates that vessels will on average be 100% full (i.e. at maximum capacity) and 0 indicates empty; a stochasticity of 1 indicates that a vessel catch can deviate by 100% from the CPUE, while 0 indicates that the vessel catch will deviate by 0% from the CPUE
4	***Fishing trips can be summed on a monthly basis***	Although in reality fishing trip length and turnaround time between trips differs by vessel types and companies. This simplifies the time-step of the model. The time step was selected to be compatible with OSMOSE ecosystem model to facilitate the possibility of future coupling. TradeMap data and DAFF data are easily available at the month level.
5	***Companies catch their quota uniformly throughout the year (i.e. quota weight is divided evenly among 12 months)***	In reality companies indicated that they tried to spread their catch evenly throughout the year to ensure constant fish supply to clients and keep employees in work.
6	***Vessels are sent out fishing at random***	In reality some vessels are preferentially used, and over time other less used and usually older vessels have been retired. For the present model version it is simpler to select vessels at random rather than assuming on what criteria vessel choice is made. For the fleet size at the time of consultation most companies indicated that they used most or all vessels during the year.
7	***There are only three vessel types and these have fixed size attributes such as maximum capacity for fish and engine size.***	In reality there are a few dual vessels, which have been assumed to be freezer stern trawlers. Dual vessels presented a problem to model as they can either produce fresh or frozen fish. In DAFF and industry data it was unclear how dual vessels functioned; in some cases they were sold from one company to another and changed vessel types, in other cases they changed vessel type through time. This presented a challenge to model and as such they were ignored. Vessels do have fixed maximum capacities for fish and fixed engine sizes, but they are not fixed within vessel categories. Wetfish stern trawlers, freezer stern trawlers and the larger factory freezer trawler categories do exist though, and behaviour and fish caught differs between these categories.
8	***Fuel used per vessel type based on average engine size per vessel category and a value of litres fuel used per single engine horse-power and sea day is an accurate estimate of vessel fuel usage.***	Industry suggested that this was a good ball-park estimate when providing the data and this was the best possible estimate of fuel usage that was available. Real fuel usage is confidential information for companies and was not possible to obtain.

Table 6.4 continued.

9	***Costs to companies vary proportionally with number of vessels owned***	Again no real values of cost for individual companies were available, thus an estimate based on European trawling counterparts was the best available data. Since larger companies owned more vessels it seemed logical that general running costs might increase proportionally with number of vessels owned. Also it is presumed that the more vessels owned, the greater the costs of maintaining and docking vessels. Since European fleet data was given with explicit vessel numbers it was easy to estimate a company cost per vessel from this data, making a per vessel value the easiest means of estimating cost to company for the South African example where vessel ownership was known.
10	***Quantities of frozen product purchased by clients (international figures) represents product that was sea-frozen and not product that was caught on wetfish vessels and later land-frozen***	In reality some of fresh product may later be frozen, but it is impossible to make reliable estimates. It is therefore better to split fresh and frozen throughout the model.
11	***A single average agent will represent the behaviour of all agents of the same 'breed'(i.e. subtype of agent in Netlogo)***	This allowed companies with similar behaviour to be aggregated as single agents, allowing sensitivity analysis and monitoring of model function to be easier.
12	***Fish meal is ignored in the model.***	Offal and other waste has recently been reported to be taken back to shore and turned into white fish meal which is sold. This accounts only a small proportion of the fish caught. This fish meal market is also a side market and does not bear any major weight in terms of income in relation to hake exports. It is also difficult to identify any fixed quantitative estimates for revenue or volumes, although both are said to be small. It is therefore ignored for the purposes of the model.
13	***Company agents were assumed to represent the combined real world companies that fell into the classes small, medium, large or supercluster, as defined in Chapter 2.***	Numbers of vessels, quantity of rights and processing efficiencies were aggregated for the real world companies from the same class and represented by a single agent. Real world companies from the different agent classes behaved similarly and had similar attributes, making it possible to group them.
14	***Individual countries bought from the companies at random.***	In the real world specific companies do business with other companies with whom they have contracts in specific countries. However, countries instead of companies that buy SA hake are represented in the model to sum exports. It is therefore assumed that having countries buy from companies at random will balance out. This assumption is necessary, because company-specific data on clients and contracts is confidential, while export data at the country level can easily be accessed.

3.2. Sensitivity analysis

Sensitivity analyses were conducted as described in Chapter 4. Of importance, the standard 100 replicate runs, which were the optimum number of replicate runs in relation to computing time and stable outputs per input value, were run in *HakeSim 3.0* using the Netlogo v5.0.1 BehaviorSpace tool. A full list of the input values used for each of the model tests can be found in Appendix 6. Outputs for every single input value test were then assessed relative to the standard run outputs (of *HakeSim 3.0*) and a sensitivity index was calculated, as per the approach of Chapter 4. The sensitivity results were then compiled and assessed. Criteria for judging the sensitivity index values are provided in Table 6.5.

Generally, model outputs were not very sensitive to company costs (Table 6.6). This is to be expected since most outputs (e.g. world fish demand, world fish processed, or world fish bought) are not directly related to this variable in any way. So too for the real world, economic theory says that production should not be affected by overhead costs in the short term but that it will be affected by variable costs like fuel (in the longer run overhead costs do matter). Some sensitivity was expected for company cost and profit outputs, but this can only be seen for the output cost of running wet-fish vessels which showed some sensitivity to their fuel usage inputs. The reason for less sensitivity in company and vessel cost outputs than expected, is most likely due to the usage of an average fuel price from the 2000-2012 time series; proportional changes in the quantity of fuel used by vessels may have had less of an effect on cost to companies at the fuel cost used (ZAR4.11). These same proportional changes in fuel usage would be expected to have more of an effect on cost at a higher average fuel price. In other words, fuel efficiency of vessels was expected to interact synergistically with fuel price (and catch per unit effort) changes to affect cost to companies. That is, at high fuel costs and low CPUE changes in vessel efficiency would be expected to have more significance for company costs and hence profits. The other possibility is that the fuel used by vessels was underestimated. Unfortunately, without having access to (proprietary/confidential) real time series of fuel usage this was impossible to verify, and the assumptions made about how representative an average of 3.2 L per horsepower per day is, must be accepted. Some sensitivity of company costs to fuel price was observed (Table 6.8), to add weight to the first explanation. During the consultation phase, as discussed in Chapter 3, companies indicated that although fuel price was the single biggest contributor to cost, it did not affect core operations of the business at the fuel price corresponding to the time of the interviews. They did state, however, that if fuel price increased substantially in the future it would increase costs to companies, squeeze profits and possibly make fishing non-viable at some point. Interactions between fuel price and other variables are explored further in the scenario analysis section.

Similar to the model prototype that *HakeSim 3.0* was built upon, most of its outputs displayed little sensitivity to the fish processing efficiency of different companies (Table 6.7). The exceptions to this were outputs of frozen/fresh fish processed and wasted, which were directly determined by how efficiently a company processed whole fish to fish products and how much it discarded. As explained in Chapter 5, fresh fish wasted, and in this model version also the total value (as a product of quantity) of fresh fish bought by clients, were affected by the processing efficiency of the large company as it was the company agent with the greatest number of wet-fish vessels in the industry. Similarly, the quantity of frozen fish wasted and total value of frozen fish bought by clients and company profit were sensitive to the value of the medium agent's frozen fish processing efficiency, since the medium agent contained a large proportion (59%) of the industry's frozen fish vessels.

All outputs of the model were sensitive to changes in fleet structures, particularly to declines in vessel numbers (Table 6.7). This is because lower vessel numbers made it difficult for companies in the model to catch their quota (as evidenced by the very high sensitivity of uncaught quota to these inputs), and therefore reduced fish volumes and income from company sales in the model. Changes in fresh and freezer vessels naturally affected fresh and frozen fish related outputs, respectively. Model outputs were slightly sensitive to changes in large company quota, due to the fact that the large company agent holds 52.9% of quota in the model and therefore has an overall influence on the catching, processing and sale of fish for the entire model world. The quantity of uncaught TAC for the entire model world was sensitive to changes in both medium and large company quota, since medium and large companies are responsible for catching three quarters of the fish in the model (as they hold 75.4 % of all quota), suggesting, that for a constant TAC, changes in quota distribution have effects on harvesting, processing and sale of fish in the model.

Almost all model outputs were sensitive to changes in catch per unit effort (CPUE, Table 6.8). Profit and uncaught quota were extremely sensitive to this input. This is to be expected as changes in CPUE affect both the quantity of fish caught and consequently supplied to all agents in the model, and the cost of catching fish for companies. During the consultation phase companies identified CPUE as a major factor affecting gross profit levels for the industry, along with total allowable catch and fuel price (see Chapter 3 for details). In the model, total vessel costs for industry were slightly sensitive to fuel price, but more sensitive to TAC. This is because, the greater the TAC the more vessels needed to catch it and therefore the greater the cost to companies and ergo the industry.

TAC, and particularly a drop in its levels, has important consequences in the model, as shown by the strong effect of a zero TAC (i.e. TAC – 100%), on all model outputs (Table 6.8). This is because TAC directly sets the level of fish available for vessels to catch, and therefore for companies to process and sell and clients to buy in the model. In the real world, companies can also import fish, but this behaviour is not captured in the model, as the model is primarily concerned with the catching and processing of local fish, which make up the bulk of hake dealt with in the real world South African industry. The only model output that was particularly sensitive to increased TAC was uncaught quota. This is due to the fact that once quota is increased beyond a certain level, it is impossible for the companies in the model to catch this entire quota with their given numbers of vessels. In this case, vessel numbers would need to be increased to be able to catch the entire TAC.

Changes in exchange rate (Euro/Rand) inputs had important consequences for outputs of the value of fish bought by clients and consequently the profit made by companies (Table 6.8). This is because the Rand value of sales is directly determined by the exchange rate in the real world, since export clients pay a Euro price for fish. It is desirable and realistic that the model exhibited this particular sensitivity.

The model outputs exhibited little sensitivity to either client demands or price paid for fish (Table 6.9), indicating that the model is more driven by the availability of fish and cost of catching fish than by selling fish. This is probably representative of the real world, where companies have indicated that there is a greater demand for fish internationally than they can satisfy (see Chapter 3). It is important to remember, though, that in the real world companies indicated that under unfavourable economic conditions, such as those in the years immediately following 2008, although there was still a demand for hake it was for lower priced product or more highly processed product. The model does not capture specific product groups through the value chain and therefore does not fully capture this.

Table 6.5: Criteria for judging sensitivity analyses.

(blue)	0 - 0.001	relatively insensitive
(green)	0.001 - 0.49	minor sensitivity (less than predicted)
(yellow)	0.49 - 0.99	slightly sensitive (less than predicted)
(orange)	0.99 - 1.49	sensitive (as or slightly more than predicted)
(red)	1.5 or more	extremely sensitive
(grey)	N/A	

Table 6.6: Sensitivity of the model outputs to various company and vessel related costs. Symbols W, F and A are abbreviations of 'wet-fish' i.e. fresh fish, frozen fish and all fish, respectively. While L, M, S and SC stand for large, medium, small and super-cluster company agents, respectively.

	Ave. world demand			Ave. world fish bought			Ave. world fish caught			Ave. world fish processed			Ave. world fish wasted			Ave. world active vessels		Ave. Cost vessels		Ave. world fish bought value			Ave. world company costs	Ave. world company profits	Ave. world uncaught quota
	F	W	A	F	W	A	W	F	A	W	F	A	W	F	A	F	W	F	W	F	W	A			
Lcompany other costs	0.000	0.000	0.000	0.002	0.002	0.000	0.002	0.001	0.000	0.002	0.002	0.000	0.003	0.000	0.002	0.003	0.003	0.002	0.003	0.001	0.004	0.002	0.070	0.051	0.001
M company other costs	0.000	0.000	0.000	0.001	0.002	0.001	0.002	0.001	0.003	0.002	0.001	0.002	0.002	0.001	0.001	0.005	0.002	0.002	0.002	0.005	0.001	0.003	0.074	0.055	0.001
S company other costs	0.000	0.000	0.000	0.001	0.003	0.002	0.003	0.001	0.001	0.003	0.001	0.001	0.003	0.002	0.002	0.005	0.003	0.004	0.003	0.002	0.002	0.002	0.010	0.010	0.002
SC company other costs	0.000	0.000	0.000	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.002	0.002	0.001	0.005	0.002	0.004	0.002	0.002	0.001	0.002	0.017	0.015	0.000
fuel used monthly factory	0.000	0.000	0.000	0.023	0.074	0.013	0.075	0.022	0.023	0.074	0.023	0.013	0.076	0.018	0.044	0.034	0.067	0.276	0.067	0.004	0.072	0.024	0.095	0.106	0.009
fuel used monhtly freezer	0.000	0.000	0.000	0.006	0.039	0.010	0.039	0.007	0.015	0.039	0.006	0.010	0.040	0.009	0.023	0.007	0.032	0.267	0.032	0.053	0.039	0.048	0.130	0.008	0.002
fuel used monthly wetfish	0.000	0.000	0.000	0.000	0.002	0.001	0.002	0.000	0.001	0.002	0.000	0.001	0.002	0.000	0.001	0.003	0.003	0.002	0.576	0.001	0.001	0.001	0.224	0.155	0.003
other costs factory freezer	0.000	0.000	0.000	0.008	0.013	0.001	0.013	0.008	0.001	0.013	0.008	0.001	0.013	0.009	0.006	0.015	0.013	0.145	0.013	0.003	0.012	0.003	0.059	0.045	0.002
other costs freezer	0.000	0.000	0.000	0.025	0.080	0.013	0.081	0.022	0.026	0.080	0.025	0.013	0.082	0.012	0.050	0.014	0.077	0.294	0.077	0.004	0.085	0.029	0.159	0.060	0.001
other costs wetfish	0.000	0.000	0.000	0.040	0.076	0.002	0.077	0.039	0.015	0.076	0.040	0.002	0.078	0.032	0.040	0.055	0.076	0.046	0.350	0.027	0.076	0.011	0.157	0.126	0.017

Table 6.7: Sensitivity of the model outputs to various company-related inputs. Symbols W, F and A are abbreviations of 'wet-fish' i.e. fresh fish, frozen fish and all fish, respectively. While L, M, S and SC stand for large, medium, small and super-cluster company agents, respectively.

	Ave. world demand			Ave. world fish bought			Ave. world fish caught			Ave. world fish processed			Ave. world fish wasted			Ave. world active vessels		Ave. Cost vessels		Ave. world fish bought value			Ave. world company costs	Ave. world company profits	Ave. world uncaught quota
	F	W	A	F	W	A	W	F	A	W	F	A	W	F	A	F	W	F	W	F	W	A			
L fresh processing efficiency	0.000	0.000	0.000	0.003	0.738	0.268	0.003	0.004	0.001	0.738	0.003	0.268	0.818	0.007	0.541	0.004	0.002	0.003	0.002	0.003	0.748	0.274	0.001	0.462	0.001
M fresh processing efficiency	0.000	0.000	0.000	0.003	0.188	0.071	0.002	0.003	0.001	0.188	0.003	0.071	0.215	0.003	0.140	0.003	0.001	0.003	0.001	0.010	0.184	0.074	0.001	0.124	0.001
SC fresh processing efficiency	0.000	0.000	0.000	0.005	0.044	0.013	0.002	0.005	0.002	0.044	0.005	0.013	0.045	0.006	0.032	0.004	0.002	0.005	0.002	0.005	0.042	0.019	0.001	0.032	0.001
S fresh efficiency	0.000	0.000	0.000	0.004	0.043	0.013	0.011	0.004	0.003	0.043	0.004	0.013	0.025	0.003	0.017	0.001	0.011	0.001	0.011	0.005	0.043	0.019	0.004	0.029	0.000
L frozen processing efficiency	0.000	0.000	0.000	0.299	0.001	0.189	0.001	0.017	0.010	0.001	0.299	0.189	0.001	1.193	0.408	0.022	0.003	0.017	0.003	0.331	0.007	0.206	0.006	0.352	0.014
M frozen efficiency	0.000	0.000	0.000	0.487	0.002	0.308	0.002	0.003	0.001	0.002	0.487	0.308	0.002	1.794	0.614	0.012	0.003	0.008	0.003	0.499	0.001	0.314	0.002	0.528	0.003
SC frozen efficiency	0.000	0.000	0.000	0.099	0.018	0.070	0.018	0.016	0.004	0.018	0.099	0.070	0.019	0.445	0.140	0.024	0.019	0.020	0.019	0.103	0.020	0.072	0.001	0.122	0.002
S frozen efficiency	0.000	0.000	0.000	0.082	0.009	0.048	0.010	0.003	0.004	0.009	0.082	0.048	0.010	0.302	0.110	0.004	0.008	0.003	0.008	0.080	0.012	0.046	0.004	0.080	0.003
vessels fleet max	0.000	0.000	0.000	0.194	0.412	0.274	0.410	0.188	0.291	0.412	0.194	0.274	0.408	0.166	0.326	0.158	0.411	0.169	0.411	0.195	0.419	0.278	0.405	0.191	1.000
vessels fleet min	0.000	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
frozen vessels max	0.000	0.000	0.000	0.426	0.102	0.233	0.103	0.417	0.176	0.102	0.426	0.233	0.105	0.382	0.061	0.384	0.103	0.396	0.103	0.427	0.099	0.233	0.229	0.237	0.619
frozen vessels min	0.000	0.000	0.000	1.000	0.050	0.615	0.051	1.000	0.513	0.050	1.000	0.615	0.051	1.000	0.308	1.000	0.051	1.000	0.051	1.000	0.048	0.614	0.515	0.682	1.757
wetfish vessels max	0.000	0.000	0.000	0.150	0.791	0.195	0.790	0.150	0.286	0.791	0.150	0.195	0.789	0.148	0.469	0.163	0.790	0.158	0.790	0.151	0.820	0.207	0.314	0.134	0.997
wetfish vessels min	0.000	0.000	0.000	0.073	1.000	0.320	1.000	0.072	0.425	1.000	0.073	0.320	1.000	0.068	0.635	0.109	1.000	0.095	1.000	0.081	1.000	0.317	0.424	0.244	1.471
L company quota high	0.000	0.000	0.000	0.765	0.297	0.594	0.301	0.779	0.557	0.297	0.765	0.594	0.305	0.831	0.485	0.863	0.302	0.832	0.302	0.777	0.282	0.594	0.483	0.670	2.852
large company quota low	0.000	0.000	0.000	0.241	0.684	0.404	0.680	0.229	0.438	0.684	0.241	0.404	0.675	0.184	0.507	0.110	0.680	0.154	0.680	0.244	0.664	0.399	0.333	0.444	1.473
mdium company quota high	0.000	0.000	0.000	0.131	0.225	0.165	0.224	0.137	0.177	0.225	0.131	0.165	0.223	0.160	0.202	0.099	0.224	0.113	0.224	0.134	0.219	0.166	0.137	0.185	0.861
medium company quota low	0.000	0.000	0.000	0.470	0.175	0.362	0.177	0.449	0.323	0.175	0.470	0.362	0.180	0.370	0.245	0.536	0.177	0.504	0.177	0.480	0.167	0.365	0.291	0.415	1.050
small company quota high	0.000	0.000	0.000	0.029	0.031	0.030	0.031	0.029	0.030	0.031	0.029	0.030	0.031	0.027	0.029	0.030	0.031	0.029	0.031	0.029	0.030	0.030	0.025	0.033	0.132
small company quota low	0.000	0.000	0.000	0.062	0.014	0.044	0.014	0.075	0.047	0.014	0.062	0.044	0.014	0.122	0.051	0.036	0.014	0.050	0.014	0.065	0.013	0.046	0.028	0.059	0.077
supercluster quota high	0.000	0.000	0.000	0.055	0.060	0.057	0.060	0.054	0.057	0.060	0.055	0.057	0.060	0.049	0.056	0.053	0.060	0.053	0.060	0.055	0.059	0.057	0.047	0.064	0.254
supercluster quota low	0.000	0.000	0.000	0.076	0.012	0.052	0.012	0.095	0.056	0.012	0.076	0.052	0.012	0.165	0.064	0.081	0.011	0.086	0.011	0.077	0.012	0.053	0.042	0.061	0.127

Table 6.8: Sensitivity of the model outputs to various 'global' (i.e. entire model) inputs. Symbols W, F and A are abbreviations of 'wet-fish' i.e. fresh fish, frozen fish and all fish, respectively.

	Ave. world demand			Ave. world fish bought			Ave. world fish caught			Ave. world fish processed			Ave. world fish wasted			Ave. world active vessels		Ave. Cost vessels		Ave. world fish bought value			Ave. world company costs	Ave. world company profits	Ave. world uncaught quota
	F	W	A	F	W	A	W	F	A	W	F	A	W	F	A	F	W	F	W	F	W	A			
CPUE	0.000	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.122	0.051	0.106	0.051	1.000	1.000	1.000	0.066	1.731	3.568
exchange rate	0.000	0.000	0.000	0.015	0.024	0.001	0.025	0.015	0.003	0.024	0.015	0.001	0.025	0.016	0.011	0.050	0.023	0.036	0.023	0.999	1.024	1.008	0.007	1.704	0.008
fuel price rand	0.000	0.000	0.000	0.009	0.004	0.004	0.005	0.009	0.002	0.004	0.009	0.004	0.005	0.007	0.001	0.032	0.012	0.534	0.590	0.039	0.002	0.025	0.465	0.276	0.024
stochasticity of catching fish	0.000	0.000	0.000	0.003	0.003	0.001	0.003	0.004	0.001	0.003	0.003	0.001	0.003	0.006	0.006	0.006	0.007	0.004	0.007	0.001	0.003	0.001	0.001	0.001	0.049
TAC -100	0.000	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.829	1.117	1.000
TAC +100	0.000	0.000	0.000	0.078	0.050	0.068	0.051	0.078	0.065	0.050	0.078	0.068	0.051	0.077	0.060	0.121	0.051	0.105	0.051	0.081	0.048	0.069	0.066	0.071	4.179

Table 6.9: Sensitivity of the model outputs to various client (i.e. market) related variables. Symbols W, F and A are abbreviations of 'wet-fish' i.e. fresh fish, frozen fish and all fish, respectively. PP stands for price paid for hake by international clients (countries).

	Ave. world demand			Ave. world fish bought			Ave. world fish caught			Ave. world fish processed			Ave. world fish wasted			Ave. world active vessels		Ave. Cost vessels		Ave. world fish bought value			Ave. world company costs	Ave. world company profits	Ave. world uncaught quota
	F	W	A	F	W	A	W	F	A	W	F	A	W	F	A	F	W	F	W	F	W	A			
domestic demand	0.313	0.052	0.250	0.002	0.004	0.002	0.004	0.002	0.003	0.004	0.002	0.002	0.004	0.003	0.003	0.009	0.004	0.007	0.004	0.010	0.015	0.011	0.005	0.016	0.000
other countries demand	0.038	0.006	0.030	0.006	0.009	0.001	0.009	0.006	0.001	0.009	0.006	0.001	0.009	0.003	0.005	0.008	0.010	0.008	0.010	0.015	0.019	0.003	0.000	0.005	0.002
Spain demand	0.191	0.762	0.329	0.006	0.004	0.002	0.005	0.006	0.001	0.004	0.006	0.002	0.005	0.006	0.001	0.009	0.005	0.008	0.005	0.001	0.050	0.019	0.002	0.031	0.001
UK demand	0.037	0.145	0.063	0.001	0.002	0.000	0.002	0.001	0.000	0.002	0.001	0.000	0.002	0.000	0.001	0.001	0.001	0.000	0.001	0.000	0.105	0.039	0.001	0.065	0.001
prop frozen domestic	0.313	0.982	0.000	0.016	0.003	0.011	0.003	0.018	0.011	0.003	0.016	0.011	0.004	0.027	0.012	0.132	0.005	0.090	0.005	0.042	0.194	0.045	0.042	0.047	0.013
prop frozen other countries	0.038	0.119	0.000	0.034	0.057	0.042	0.057	0.038	0.047	0.057	0.034	0.042	0.058	0.050	0.055	0.112	0.069	0.082	0.069	0.077	0.094	0.014	0.063	0.019	0.012
prop frozen spain	0.191	0.597	0.000	0.005	0.001	0.003	0.001	0.004	0.002	0.001	0.005	0.003	0.001	0.003	0.001	0.012	0.003	0.010	0.003	0.002	0.002	0.000	0.003	0.002	0.005
prop frozen UK	0.037	0.115	0.000	0.008	0.010	0.002	0.010	0.009	0.001	0.010	0.008	0.002	0.010	0.010	0.003	0.025	0.011	0.018	0.011	0.006	0.066	0.028	0.004	0.050	0.001
pp fresh domestic	0.000	0.000	0.000	0.041	0.070	0.000	0.071	0.040	0.012	0.070	0.041	0.000	0.072	0.036	0.035	0.027	0.072	0.032	0.072	0.053	0.074	0.061	0.014	0.112	0.008
pp fresh italy	0.000	0.000	0.000	0.014	0.003	0.008	0.003	0.017	0.008	0.003	0.014	0.008	0.004	0.028	0.007	0.069	0.008	0.049	0.008	0.008	0.005	0.007	0.018	0.024	0.004
pp fresh other countries	0.000	0.000	0.000	0.001	0.020	0.008	0.020	0.008	0.011	0.020	0.001	0.008	0.020	0.010	0.017	0.008	0.017	0.008	0.017	0.005	0.046	0.020	0.010	0.027	0.001
pp fresh spain	0.000	0.000	0.000	0.010	0.035	0.007	0.036	0.008	0.013	0.035	0.010	0.007	0.036	0.000	0.024	0.043	0.029	0.026	0.029	0.013	0.459	0.177	0.023	0.283	0.002
pp frozen domestic	0.000	0.000	0.000	0.029	0.028	0.008	0.028	0.029	0.002	0.028	0.029	0.008	0.029	0.030	0.009	0.001	0.028	0.012	0.028	0.215	0.023	0.127	0.005	0.218	0.006
pp frozen italy	0.000	0.000	0.000	0.001	0.003	0.000	0.003	0.001	0.001	0.003	0.001	0.000	0.003	0.001	0.002	0.001	0.004	0.001	0.004	0.103	0.002	0.064	0.001	0.109	0.002
pp frozen other countries	0.000	0.000	0.000	0.004	0.012	0.002	0.012	0.004	0.003	0.012	0.004	0.002	0.012	0.006	0.006	0.002	0.012	0.002	0.012	0.061	0.012	0.043	0.004	0.071	0.000
pp frozen spain	0.000	0.000	0.000	0.004	0.016	0.008	0.016	0.004	0.009	0.016	0.004	0.008	0.016	0.002	0.011	0.015	0.025	0.008	0.025	0.097	0.012	0.057	0.006	0.100	0.002

3.3. Scenario testing

To answer some of the core questions of this study, i.e. the purpose for which the model was developed, a number of scenarios were posed that were informed by real world questions and ideas. Some additional questions and scenarios that emerged from the industry consultation phase were also explored.

For all scenarios 100 replicate runs of the inputs were made in *HakeSim 3.0* using the BehaviorSpace tool of Netlogo 5.0.1.The output values were recorded at every time step.

3.3.1.Company strategy and risk

A mean-variance analysis of profit versus risk in profit was conducted on the different companies in the model under different levels of *stochasticity of catching fish*[17] (i.e. environmental uncertainty), to determine their different strategies for trading off profit against risk with different levels of uncertainty. Three levels, low (0), medium (0.5) and high (1), were used as *stochasticity of catching fish* inputs for the model and all other inputs were held constant for replicate runs. The output of profit at each time step was collected for individual companies and this was aggregated between replicate runs to determine average profit and standard deviation of profit per company, plotted in Figure 6.2. In the context of this analysis risk is defined as a calculated parameter, while uncertainty is something that cannot be quantified.

Companies had distinct strategies for trading off profit against risk. Large, followed by medium companies, made the greatest levels profit, but also had the highest risks, indicating that they had relatively more risky behaviour (i.e. they were relatively less risk-averse). On the other hand, super-cluster followed by small companies made the lowest profits, but also bore much less risk, i.e. they were relatively more risk-averse. For all companies as stochasticity levels increased, deviation in profits i.e. financial risk, also increased. Although the large company made a higher profit than its medium counterpart, large company risks changed much more drastically with uncertainty in catching fish (i.e. stochasticity) than medium company risks did. At low (0) and medium (0.5) stochasticity levels the large company had lower risks than the medium company, but at high

[17] Where *stochasticity of catching fish* is the level of randomness by which CPUE varies in the catch of each vessel in each time-step; a very broad-brush proxy for environmental uncertainty, as defined in Table 5.1.

stochasticity (1), large company risk surpassed medium company risk. The large company in the model appeared to be the most vulnerable to *stochasticity of catching fish* (a coarse proxy for environmental uncertainty) in terms of its increased risk at high stochasticity levels, but it maintained high profits. Medium companies with slightly less profit were less prone to fluctuations in risk that was associated with increased stochasticity of catching fish.

Changes in company strategy in terms of trading off profit versus risk are likely to be partially linked to quota. Large and medium companies have a larger share of quota and therefore have more access to economies of scope and scale than smaller companies, allowing them to buffer larger risks (i.e. their riskier strategies, or relatively less risk-averse strategies) through the large volumes of fish that they process and sell, allowing them to take advantage of the high profits this strategy yields. Fleet size and configuration is another very important factor that is likely to affect how companies are affected by the stochasticity or uncertainty of catching fish. This is especially true given that costs, profits and other outputs in the model were shown to be quite sensitive to changes in fleet structures. Therefore it was of interest to assess the effects of fleet size on company profit and risk.

3.3.1.The effect of fleet size on profit and risk

A mean-variance analysis of profit versus standard deviation in profit (i.e. financial risk) was conducted for different fleet sizes and configurations. This analysis was designed to help to shed light on the trend of decreasing vessel numbers through time. In this scenario analysis the model inputs were modified so that there was only a single functional company agent that represented the entire offshore demersal trawling industry. To do this all vessels and all quota were assigned to a single company agent, and all other companies were allocated zero quota and vessels. Different fleet sizes and compositions were compared using historical data of actual fleet compositions from the past (*circa* 1983, c.1995, c.2005, c.2011, c.2013) and using some hypothetical scenarios where the fleet size from 2013 was manipulated to be all fresh vessels or all freezer vessels and where total fleet size was made unrealistically small (Table 6.10).

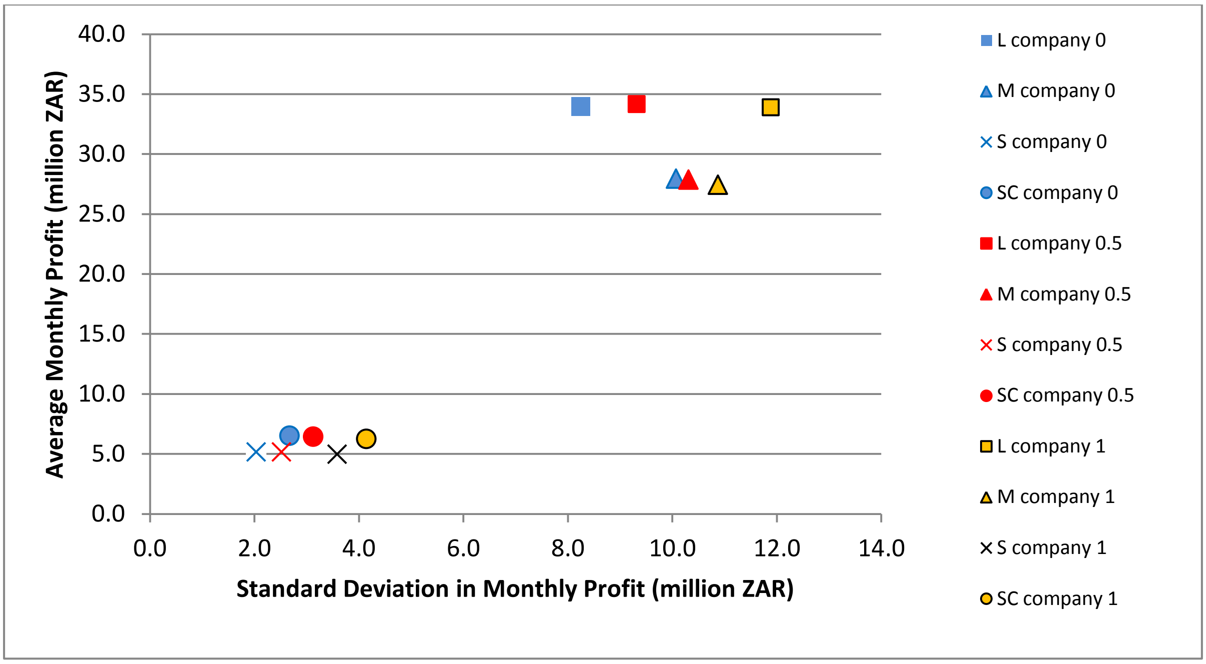

Figure 6.2: Economic mean variance analysis for model companies under different levels of stochasticity of catching fish. For each company the average monthly profit is plotted against the standard deviation in monthly profit for 100 replicate model runs of each of three scenarios: high (1), medium (0.5) and low (0) stochasticity of catching fish.

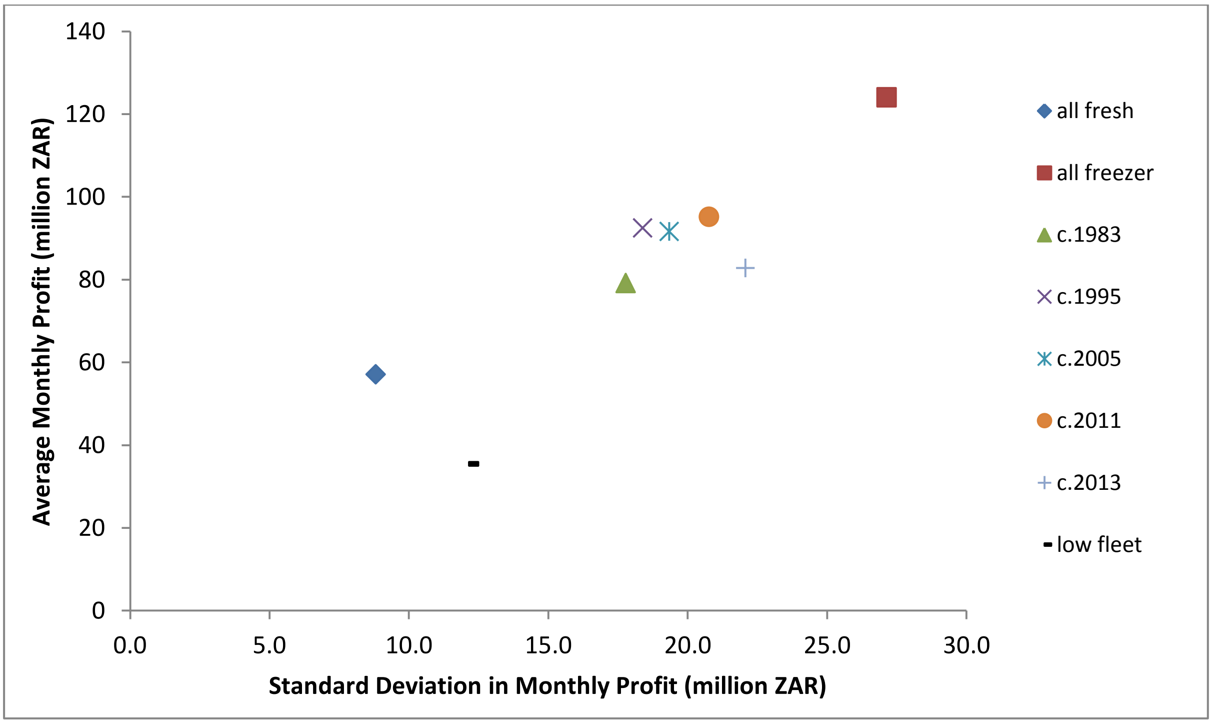

Figure 6.3: Economic mean variance analysis for company fleet size. Only one company is used to represent the entire industry and different fleet sizes and compositions from the past, as well as hypothetical scenarios, are used to assess trade-offs in profits and standard deviation in profit (i.e. financial risk) under average model conditions.

Table 6.10: Inputs of vessel numbers used in the mean variance analysis of fleet size and configuration on profit and financial risk (i.e. deviation in profit). Historical fleet composition was calculated from data courtesy of DAFF. Fleet composition for c. 2013 was based on data courtesy of DAFF and SADSTIA. The c. is an abbreviation of *circa,* meaning that these values reflect average vessel numbers for approximately the entire year, since fleet configurations sometimes change within a year.

Values in analysis	c. 1983	c. 1995	c.2005	c.2011	c. 2013	low	all freezer**	all fresh**
number of wet-fish	121	67	74	42	23	5	0	52
number of freezers*	33	20	28	17	21	5	33	0
number of factory freezers*	13	8	10	7	8	5	19	0
total	167	95	112	66	52	15	52	52

* for years other than 2013 the number of factory and freezer trawlers is approximated as only a frozen vessel value existed in the data and dual vessels numbers were divided between wet-fish and freezer trawlers.
** all freezer and all fresh use present values, but remove wet-fish or freezer vessels and give to other category

The "all freezer" fleet yielded the highest profit, but also bore the highest risk (Figure 6.3), while a fleet comprised of "all fresh" (i.e. wet-fish) vessels yielded the lowest risk and the second lowest profit. The real world fleet scenario inputs all had a mixed fleet of freezer and wet-fish vessels and presented outputs of profits and risks intermediate to "all freezer" and "all fresh" hypothetical fleet inputs, indicating that the model world reflected the real trade-off of profit against risk that real companies experience when designing their fleets. This coincides with what emerged very clearly from industry consultation. That is, in the real world companies indicated that freezer trawlers were much cheaper to run than wet-fish vessels per kg of landed fish and that frozen product could yield a higher profit to industry. However, they also indicated that the use of only freezer trawlers could significantly increase risk in the business, particularly because the sea-frozen hake market has been known to change very rapidly with prices often unexpectedly falling largely due to competition on the international market with Argentinean hake. Companies indicated that shifting entirely to freezer vessels might yield high short term profit gains, but low long-term price and market stability (see Chapter 3 for details of industry consultation). Fresh product (i.e. that landed on wet-fish vessels) has more end product options and therefore flexibility in terms of what markets it could cater to. These results provide an optimistic view of the realism of the model, since the profit-risk trade-off between fresh and freezer vessels from the real world was observed in the model.

In the real world, industry as a whole has opted for a mixed wet-fish and freezer trawled product approach, which presumably, according to industry consultation balances risks and profits. This was again observed in the model.

For scenarios of real, historical vessel numbers, all profits and risks were quite similar. Comparing these historical scenarios, the fleet from 1995 yielded a high profit for the lowest risk, while for similar profit levels the 2005 fleet bore a higher risk, which was interesting since the number of vessels in 2005 was higher than the number of vessels in 1995. In this case increased vessel numbers resulted in increased risk. The 2011 fleet made a slightly higher profit than other years, but had a slightly higher risk than the fleets from the earlier years. Given that the 2011 fleet was just above half the size of the 2005 fleet it probably represented a lower cost and given that company costs might be underestimated in the model, this likely explains the need for companies to reduce fleet size over time. Additionally, there is the effort restriction regulation, which was not fully captured in the model, and the aging nature of the fleet. All of these represent incentives to industry to reduce fleet size that were not fully captured in the model. These incentives, though, were clearly traded off against a loss in profits and an increased risk. This can be seen in the analysis since a very low fleet size represented the lowest profit to industry, but still a moderate level of risk. This would be an unfavourable situation for the industry. Indeed at no point in history has the vessel number ever dropped this low, presumably because this strategy has negative financial implications for companies and would also be a situation where catching the average allocated quota would be difficult. This fact, that industry must operate within a certain level of acceptable profit and risk, might also explain the clustered nature of fleet composition in terms of profits and risks through time.

Interestingly some verification for the careful trade-offs between risk and profit and the nature of industry to optimize fleet size to remain within a certain level of profits and risks is that 2013 fleet composition showed a reduced profit for an increased risk. This might explain the observations that i) in 2014, for the first time in about a decade, a new vessel was purchased in the industry, increasing industry's capacity for catching fish, and ii) companies leased vessels increasing their effective capacity without increasing vessel numbers in the industry.

3.3.2.The importance of fuel price

Fuel price and profitability

The effect of future increases in fuel price (estimated by diesel prices, although some ships may use different fuel types) was examined on company profitability by running a variety of scenarios with different fuel prices. Fuel price inputs to the model were varied as indicated in Table 6.11, while all other input variables were kept as per the standard run. As fuel price increased costs to all companies increased and profits decreased proportionally (Figure 6.4). At double the maximum fuel price from the 2000 – 2012 time series (max + 100%, ZAR18.783 per litre) profits of all companies dropped to 0. Beyond this price they became negative (i.e. turned into losses). These results were based on all other variables remaining at average levels. The question that follows from this then is what happens when fuel price interacts with other variables such as CPUE, exchange rate and market value of hake, given that profitability was shown to be directly influenced by fuel price and increases in fuel price alone caused model companies to become unprofitable. Companies have indicated the importance of these other variables in consultation and the trade-offs and interactions between variables. Understanding such trade-offs between these different variables is one of the central questions of this thesis. The scenarios that follow examine some possible interactions.

Table 6.11: Model inputs used in the analysis of fuel price on company profitability. The average, minimum and maximum fuel price values are indicative of those from the time series of diesel fuel prices from 2000 – 2012.Data courtesy of the offshore demersal trawling industry. Additional scenarios of max +50% to max + 200% represent percentage increases on top of the maximum fuel price from the real time series.

	Fuel price (ZAR)
Ave	4.110
Min	1.574
Max	9.392
max + 50%	14.087
max + 100%	18.783
max + 150%	23.479
max + 200%	28.175

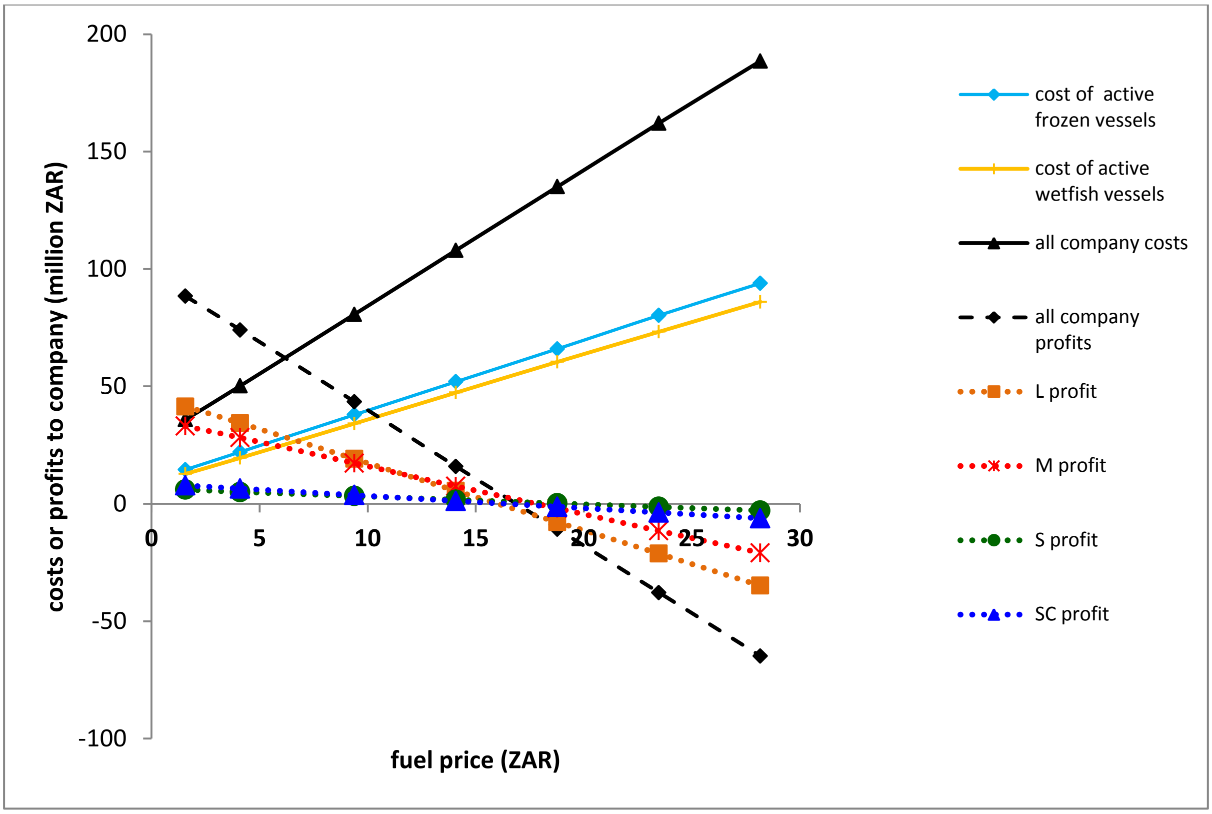

Figure 6.4: Model outputs of company profits and costs for different fuel price levels per litre of diesel. Dots represent each model output at that particular fuel price level. L, M, S and SC stand for Large, Medium, Small and Super-Cluster company, respectively and 'all company' refers to the sum of that variable for all company agents in the model. All outputs at each fuel price represent monthly (time-step) value and are averaged for the 100 replicate model runs.

Interactions between fuel price and CPUE

To examine interactions between fuel price and CPUE a number of scenarios for different levels of these variables were run (Table 6.12). Since ZAR18.783/L was found to be the fuel price at which companies switched from making a profit to making a loss (Figure 6.4), this was used as the 'high' price scenario. Since it was only double the maximum for the 2000-2012 time series it did not appear to be an unrealistically high future value for fuel.

There were clear interactions between CPUE and fuel price in determining the costs and hence profitability of companies (Figure 6.5). All companies made a loss when catch per unit effort was low, irrespective of fuel price. Fuel price however, determined how big the loss was, the higher the fuel price, the greater the loss (negative profit). This was because costs were much higher at low

CPUE than high CPUE and higher at high fuel prices than low fuel prices. When CPUE was high companies all made a profit and the lower the fuel price, the greater was the profit. CPUE had a greater overall effect on whether companies remained profitable or not. This is due to the fact that CPUE has a two-fold effect: firstly it influences the catch cost per ton - the lower the CPUE the greater the effort spent and the more fuel needed to catch the same quantity of fish, and secondly, it influences the maximum catching ability of companies – if CPUE is low and with all vessels active it may still be difficult for companies to catch all of their quota, meaning that their overall profits are likely to be reduced through lower volumes of fish available for sale.

Table 6.12: Inputs of fuel price (ZAR) per litre of diesel, catch per unit effort (CPUE) and stochasticity of catching fish as used in scenario analysis of interactions between fuel price and CPUE. Fuel price values are based on real time series for the 2000 – 2012 period, where high fuel price is double the maximum from this period (i.e. the value identified as the point where companies shift from making a profit to not) and low fuel price is the minimum from this period.

	Fuel price (ZAR/L)	CPUE*	stochasticity
Both high	18.783	1	0.5
High fuel, low CPUE	18.783	0.1	0.5
Low fuel, high CPUE	1.574	1	0.5
Both low	1.574	0.1	0.5

* a zero value for CPUE is not used as 0 means no catch at all

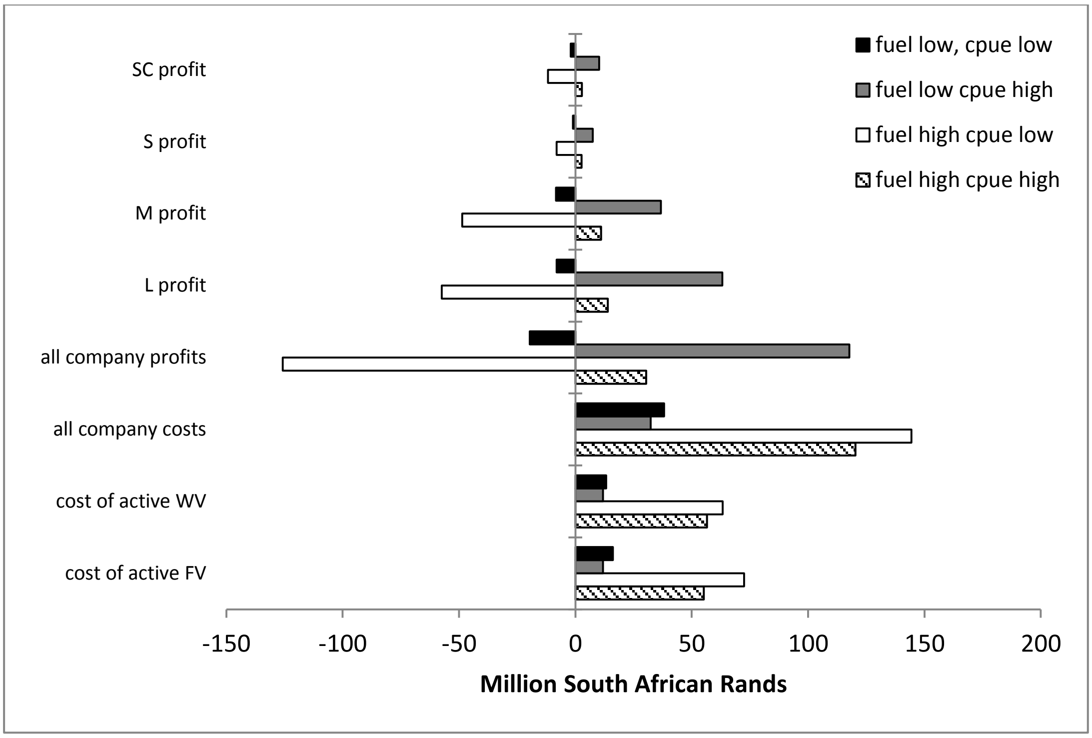

Figure 6.5: Costs and profits of companies (million ZAR) under different scenarios of fuel prices and CPUE. SC, S, M, and L stand for super-cluster, small, medium, and large companies, respectively and WV and FV stand for wet-fish and freezer vessels, respectively.

Interactions between fuel price and stochasticity

On top of the interaction between fuel price and CPUE there is another component to the certainty of catching fish which is captured in the model through the variable *'stochasticity of catching fish'*. This variable allows some uncertainty in the catching of fish (i.e. the 'environment') to be added, since the stochasticity coefficient dictates how stochastic the CPUE is for each fishing trip. It is in essence an attempt to incorporate some environmental uncertainty into the model. Scenarios of average and high stochasticity in situations where fuel price is low and high were explored (Table 6.13). Low stochasticity scenarios were not considered, since in reality there is always some environmental uncertainty in catching fish, even in ideal circumstances, thus a low stochasticity environment is uninformative for interpretation of the model results in the real world.

When fuel price was low companies made a positive profit, but when fuel price was high companies made a loss (negative profit), irrespective of stochasticity (Figure 6.6). In other words, in the model, fuel price was a more important determinant of cost and hence profit levels than stochasticity of catching fish. Increasing stochasticity, however, increased costs and thereby reduced profits. This means that uncertainty reduces potential profits in favourable conditions, and could under certain unfavourable conditions be the nail in the coffin that pushes companies to make unbearable losses.

Table 6.13: Inputs of fuel price (ZAR) per litre of diesel, catch per unit effort (CPUE) and stochasticity of catching fish as used in scenario analysis of interactions between fuel price and stochasticity. Fuel price values are based on real time series for the 2000 – 2012 period, where high fuel price is double the maximum from this period (i.e. the value identified as the point where companies shift from making a profit to not) and low fuel price is the minimum from this period.

	Fuel price (ZAR/L)	CPUE*	stochasticity
High fuel, high stochasticity	18.783	0.5	1
Low fuel, high stochasticity	1.574	0.5	1
High fuel, ave stochasticity	18.783	0.5	0.5
Low fuel, ave stochasticity	1.574	0.5	0.5

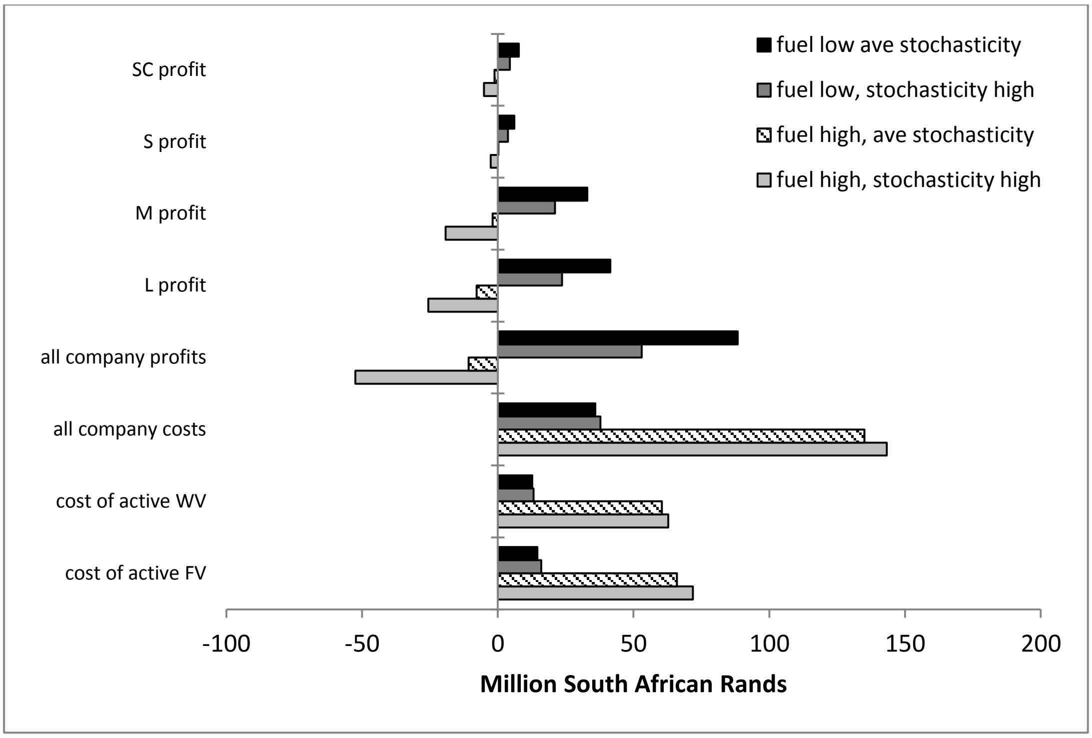

Figure 6.6: Costs and profits of companies (million ZAR) under different scenarios of fuel prices and stochasticity. SC, S, M, and L stand for super-cluster, small, medium, and large companies, respectively and WV and FV stand for wet-fish and freezer vessels, respectively.

Interactions between fuel price and exchange rate

Local fuel price and exchange rate are usually linked. In general when exchange rate increases (i.e. the South African Rand devalues), fuel price increases, since oil is priced in US dollars. But at the same time, since hake is an export market, a higher Rand value equivalent is obtained for the same Euro price of exported fish. Companies discussed this point during the consultation phase explaining that often when the exchange rate increases their (Rand) revenue increases, but so does their fuel cost. Thus profit does not always increase. To explore this in the model, scenarios of different Rand/Euro exchange rates and fuel prices were explored. This included scenarios where fuel price and exchange rate followed the same trend and cases in which fuel price changed due to changes in the oil price rather than the exchange rate (Table 6.14).

The value of fish sold increased substantially when exchange rate increased (i.e. when the Rand devalued), and the costs to companies increased when fuel price increased, but to a lesser extent

(Figure 6.7). The resulting interaction between costs and revenue determined profits for companies; i.e. at some break-even point fuel price and exchange rates would intersect and profits would be zero. When fuel price was high but exchange rate was low (i.e. scenarios where the world US $ price of oil increases substantially and the Rand is strengthened against the Euro), companies made a loss. In the opposite scenario, where fuel price was low but the exchange rate was high (i.e. scenarios where the world US $ price of oil decreases substantially and the Rand weakens against the Euro) company costs declined and the value of fish sold increased substantially, resulting in a large profit made by companies. The scenarios where fuel price and exchange rate were linked were more realistic and therefore interesting scenarios. In cases where they were linked (i.e. both high and both low), companies maintained positive profits. These profits were greater when both fuel price and exchange rate were high than when both were low. Of interest, though, the increased value of fish with a devalued Rand outweighed the increased fuel cost, leading to a positive profit. This means that companies would likely be able to maintain profitability in the face of higher fuel prices (up to a point) if the Rand was devalued. Importantly these results also suggest that exchange rate, where CPUE and other variables are average, can outweigh the effect of fuel price on profit.

Table 6.14: Inputs of fuel price (ZAR) per litre of diesel and exchange rate (Euro/Rand) as used in scenario analysis of interactions between fuel price and stochasticity. Fuel price values are based on real time series for the 2000 – 2012 period, where high fuel price is double the maximum from this period and low fuel price is the minimum from this period. A high exchange rate is double the maximum and low is the minimum of the 2003-2014 exchange rate time series from oanda.com.

	Fuel price (ZAR/L)	**Exchange Rate (Euro/Rand)**
Both high	18.783	30.031
High fuel, low exchange	18.783	7.297
Low fuel, high exchange	1.574	30.031
Both low	1.574	7.297

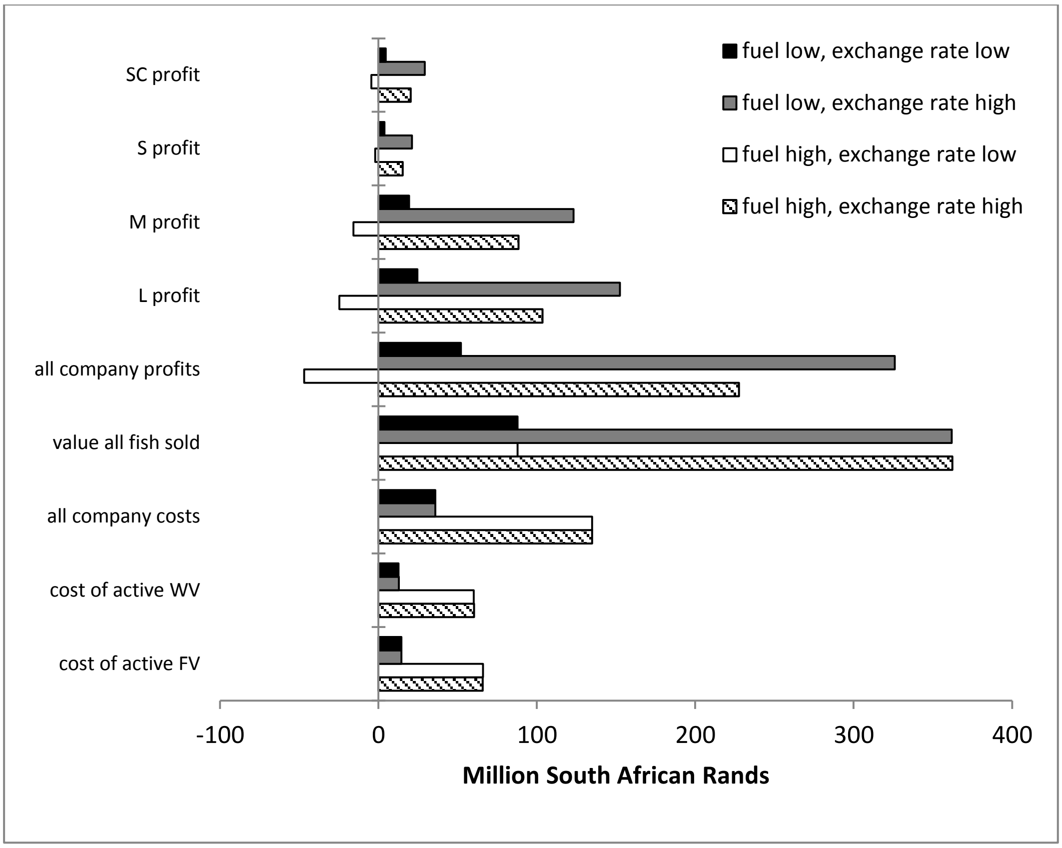

Figure 6.7: Costs and profits of companies (million ZAR) under different scenarios of fuel prices and exchange rates. SC, S, M, and L stand for super-cluster, small, medium, and large companies, respectively and WV and FV stand for wet-fish and freezer vessels, respectively.

Interactions between fuel price and market value of fish

Another question of interest is given a fixed exchange rate and an increase in world fuel prices, resulting in a higher Rand cost of fuel, to what extent would the Euro equivalent market value of fish need to increase to compensate the loss incurred by increased fuel costs. Scenarios of different price paid by countries for hake (i.e. market value of hake) with high fuel price were run to explore this (Table 6.15).

As the price paid (pp) by countries increased the value of fish sold and consequently company profit increased (Figure 6.8). For a fixed average exchange rate and the average market value of fish (i.e. average pp), a high fuel price resulted in losses being made; at (current) average conditions firms had a tight profit margin. In other words, the model suggests that should US$ fuel price increase and the international market price of hake not increase, companies would make a loss. However, even an increase of market value by 25% across the board for countries was enough to cause model companies to make a profit under high fuel price and fixed exchange rates. Any increases in international market value of hake above this further increased profits through direct increases in the value of fish sold by companies. This means that should costs like fuel increase for companies, they could make a profit by increasing the market value of their product. Companies of course have little ability to influence market value for hake, as they are price takers in the current international hake market (as described during industry consultation). They do however, have the ability to value-add their product and shift towards a product that yields a higher Euro value per ton, as this would have the same effect as increasing market value for hake. Indeed, this type of product displacement towards a higher value (and lower catch cost value) product was seen in the export data analysis where companies switched from whole fresh fish towards value added frozen product, which had a lower catch cost per ton and a higher international market value per ton.

Table 6.15: Inputs of price paid by countries for fresh and frozen hake (Euros/ton) under a scenario of high fuel price. Average scenarios represent the average market value of hake (Euro's/ton) for various countries for the period 2005-2011, as determined from data downloaded from TradeMap (see Appendix 6, Table A6.3 for details). The price paid by countries for fresh and frozen hake are simultaneously increased by a proportion of 25%, 50%, 100% and 150% above the average value in the scenarios ave+25%, ave. + 50%, ave. + 100% and ave. + 150%, respectively. The abbreviation USA is for the United States of America.

	fuel price (ZAR/L)	Domestic*	Australia	France	Germany	Italy	Netherlands	Portugal	Spain	United Kingdom	USA	Other countries
		price paid for fresh (Euros/ton)										
Average*	18.783	2315.29	5073.08	2234.64	2382.12	5564.84	2419.34	3480.52	2386.99	1858.59	5791.46	3302.23
Ave + 25%	18.783	2894.11	6341.35	2793.31	2977.65	6956.05	3024.17	4350.64	2983.74	2323.24	7239.33	4127.79
Ave + 50%	18.783	3472.93	7609.62	3351.97	3573.18	8347.25	3629.01	5220.77	3580.48	2787.88	8687.19	4953.34
Ave + 100%	18.783	4630.57	10146.16	4469.29	4764.24	11129.67	4838.67	6961.03	4773.98	3717.18	11582.92	6604.46
Ave + 150%	18.783	5788.22	12682.69	5586.61	5955.30	13912.09	6048.34	8701.29	5967.47	4646.47	14478.65	8255.57
		price paid for frozen (Euros/ton)										
Average*	18.783	2186.30	3489.87	2348.55	811.16	1882.98	1576.86	2145.50	2118.76	2233.69	2814.20	1749.70
Ave + 25%	18.783	2732.88	4362.34	2935.68	1013.96	2353.73	1971.08	2681.88	2648.45	2792.12	3517.74	2187.12
Ave + 50%	18.783	3279.45	5234.81	3522.82	1216.75	2824.48	2365.29	3218.25	3178.14	3350.54	4221.29	2624.55
Ave + 100%	18.783	4372.60	6979.75	4697.09	1622.33	3765.97	3153.72	4291.00	4237.52	4467.39	5628.39	3499.40
Ave + 150%	18.783	5465.76	8724.68	5871.37	2027.91	4707.46	3942.16	5363.76	5296.90	5584.23	7035.49	4374.25

*Average calculated from existing TradeMap time series of prices paid per ton of hake exports for the years 2005-2011 and domestic price based on the world average from the TradeMap time series.

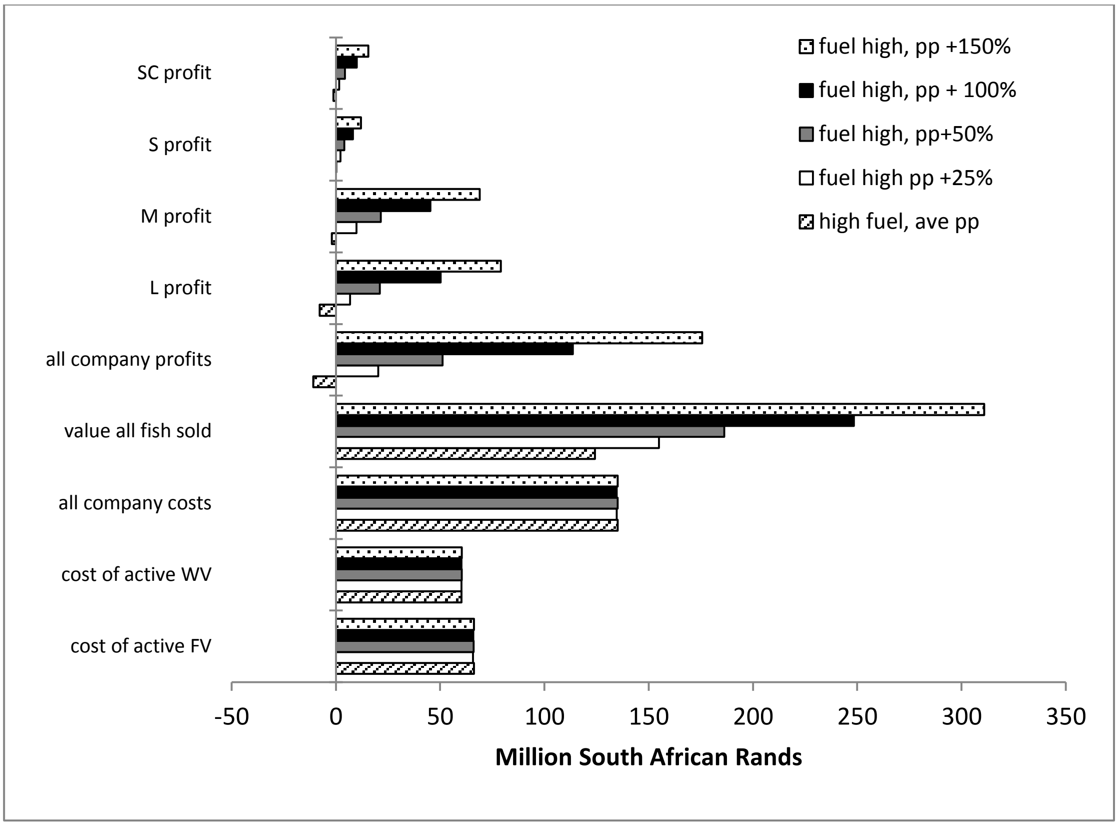

Figure 6.8: Costs and profits of companies (million ZAR) under different scenarios of price paid by countries for hake. SC, S, M, and L stand for Super-Cluster, Small, Medium, and Large companies, respectively and WV and FV stand for wet-fish and freezer vessels, respectively.

3.3.3.Interactions of TAC and CPUE with company fleets

During the consultation phase companies reported that mismatches between TAC and CPUE (i.e. TAC high and CPUE low) could make it difficult for companies to downsize their fleets or for companies with downsized fleets to catch their entire quota. It was suggested that if mismatches between TAC and CPUE occur because of time lags in CPUE being incorporated into hake population predictions and therefore TAC recommendation, that it could lead to mismatched fishing capacity (i.e. number of boats) and CPUE and consequently desynchronized investment in vessels (see Chapter 3). To test this idea the structure of the industry was modified through different initialization values to inputs (Table 6.16). Four equally sized companies were created in the model with equal shares of the quota, but with vessel numbers equal to the entire industry fleet in 2013, double this number, half this number or no vessels at all. The model was then run with different scenarios of TAC and CPUE to explore whether mismatches could affect the levels of uncaught fish and profitability for different fleet sizes (Table 6.17).

In the standard model run (Figure 6.9.a and b), where TAC and CPUE are held at an average level, all fleet sizes were profitable and each 'company' fleet caught its proportion of TAC (i.e. there were no uncaught fish, with the exception of no vessels. (Since the 'no vessels' fleet represented the null case as a control that verified that the fleet size variables were behaving as expected and because it had outputs of zero in all cases it is not discussed further.) Of all the TAC and CPUE scenarios the average input scenario yielded the maximum profit for all companies in the model (i.e. all fleet sizes). The scenario of TAC being at an extreme high and CPUE at an extreme low represented a situation where the industry made a loss regardless of fleet size. The larger the fleet, the higher the vessel running costs and costs to companies and the greater the loss. The quantity of uncaught fish in this scenario was also very high for all fleet sizes, and even increased with fleet size. In the case where TAC was at a realistic maximum and CPUE was at a realistic minimum the normal (i.e. 2013) fleet size yielded the greatest profit, followed by the half normal fleet size. A fleet of double the present size incurred the largest costs and made the least profit in this scenario. In this scenario companies with the normal fleet and double fleet size also managed to catch their entire allotted quota, while a fleet half normal size did not. In scenarios where TAC was low and CPUE was high all fleet sizes yielded a profit. Half the normal fleet size made the greatest profit and profit decreased with increasing fleet size, due to increasing maintenance costs to companies with increasing vessel numbers. When TAC was low and CPUE was high the entire allotted quota was caught regardless of fleet size.

Given these findings it seems that in all circumstances other than where TAC was high and CPUE was low, it was favourable to have a smaller fleet than the present size (2013 values) in terms of profit, since all quota could still be caught and the cost to company was lower. If no mismatches where TAC was high and CPUE was low occurred it would seem efficient then for companies to have smaller fleets, if profitability was to be considered. The only benefit of having a normal fleet size then seems to be to maximise profitability and reduce the risk of not catching the entire allotted quota when TAC is high and CPUE is low. Double the current fleet size would help to buffer even more for an extreme situation, but since a larger fleet size carries a larger cost, the logical trade-off for industry appears to be to settle for a normal fleet size, which is what they have done in the real world. In conclusion, it is also important to note that mismatches in TAC and CPUE have economic consequences for companies if they are to go out catching and ensure that they catch their quota, which companies suggested they did to ensure renewal of rights in future.

Table 6.16: Inputs used to create the four company agents during the initialization of the model.

Taking the place of: Values in analysis:	Large present industry	Medium double	Small half	Super-Cluster none
Number of wet-fish	23	46	12	0
Number of freezers	21	42	11	0
Number of factory freezers	8	16	4	0
Quota	0.25	0.25	0.25	0.25
Frozen processing efficiency	0.75	0.75	0.75	0.75
Fresh processing efficiency	0.52	0.52	0.52	0.52

Table 6.17: Scenarios of TAC and CPUE explored in the model. The standard average run used average values for all variables apart from the initialization of the company variables described in table 6.16. Mismatch of CPUE and TAC scenarios either used realistic values of maxima and minima from real time series of TAC and CPUE, courtesy of DAFF, or extreme values that were 150% of real maxima or 50% of real minima. Input of CPUE is limited to a maximum of 1, since it is a value from a transformed, unitless scale of 0-1.

	TAC (tons)	CPUE
Standard average run	143000	0.724
Realistic: TAC high, CPUE low	166000	0.376
Extremes: TAC high, CPUE low	214611	0.1
Realistic TAC low, CPUE high	103000	0.956
Extremes: TAC low, CPUE high	71537	1

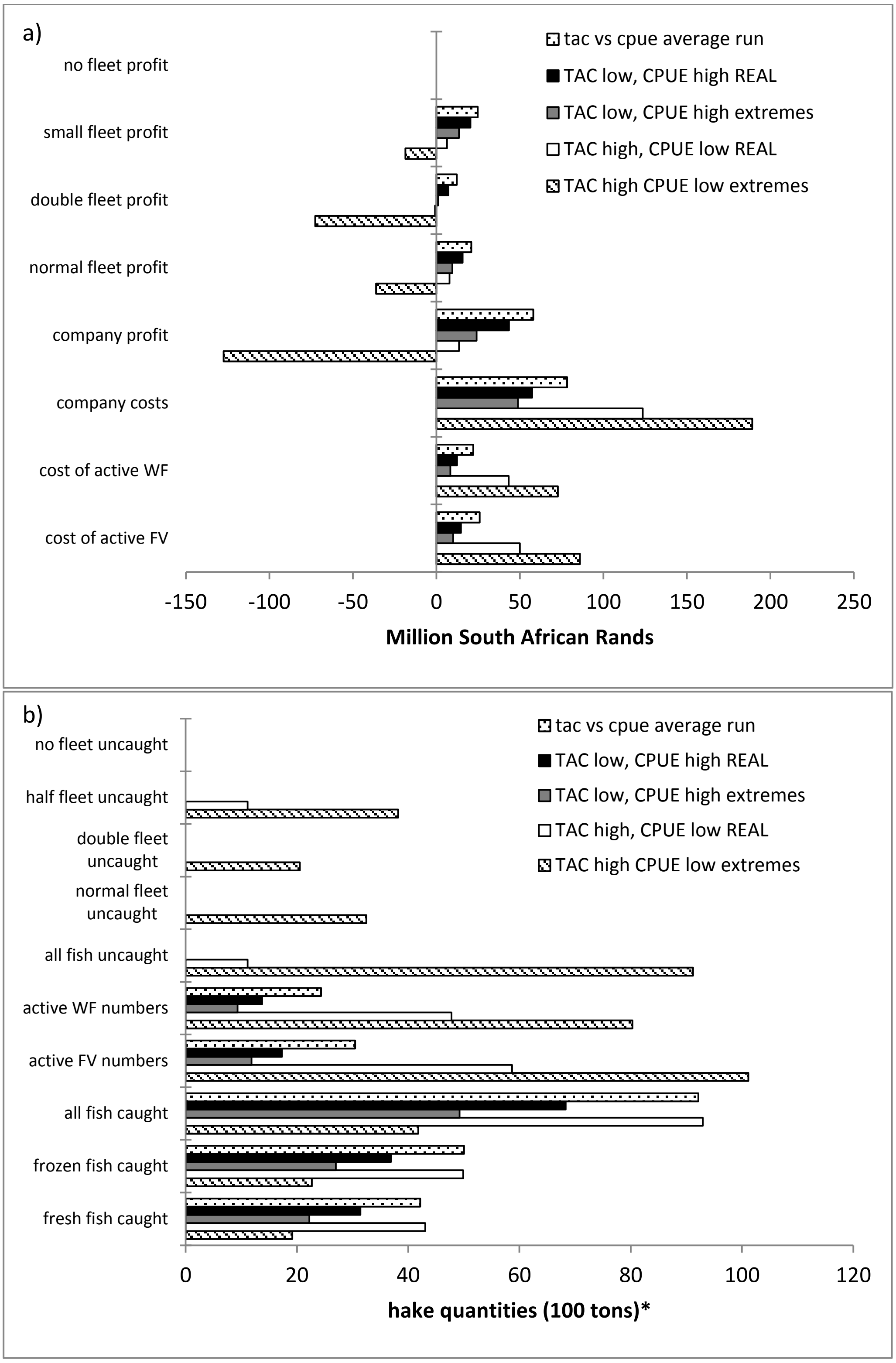

Figure 6.9: a) Costs and profits of companies (million ZAR) and b) the quantities of hake caught or (hake quota) not caught by vessels, under different scenarios of TAC and CPUE. Apart from normal, half, double and no fleet, which correspond to fleet sizes relative to the 2013 fleet size, all variables correspond to the sum of that parameter for all 'companies', i.e. fleet sizes in model. WV and FV stand for wet-fish and freezer vessels, respectively. * The scale of 9b) represents hake quantities with the exception of active WF and FV numbers as specified on left axis, which represent vessel numbers (nominal scale).

4. Summary of findings

The final version of the model behaved realistically despite imperfect parameterization. It produced some interesting outputs that coincided with real world observations, and verified hypotheses put forward following industry consultation.

From thorough sensitivity analyses, the model was found to be sensitive to changes in fleet size, the quota of large and medium companies, catch per unit effort, exchange rate and (most expectedly) situations where the TAC was reduced to zero. This indicated that the model was behaving as a good approximation for the real world, as these were all factors that were indicated as being important drivers of the industry from stakeholder consultation and expert opinion. The one exception to this was fuel price; the model showed much less sensitivity to fuel price than expected, which was explained as being due to the low average fuel price for the 2000-2012 time series. It was anticipated that fuel price would have more of an impact on costs and profits. The effect of fuel price on model outputs was later explored through scenarios of increased fuel price, which showed that increases in fuel price had important consequences for costs to company and profits, as expected.

Company strategies for trading off profit against risk were explored. It emerged that companies had different strategies of trading off risk against profit. In the model, large followed by medium companies made the highest profits, but bore the highest risks, indicating that they were less risk-averse (i.e. had relatively riskier strategies). While super-cluster followed by small companies made the lowest profits and had more risk-averse (relatively less risky) strategies. For all companies as the *stochasticity of catching fish* (i.e. a proxy for environmental uncertainty) increased, financial risk also increased. Large and medium companies can likely buffer their riskier strategies because of their economies of scope and scale. Their reward for bearing the higher risk is a much greater profit. The large company had the greatest increase in risk with increased uncertainty, but it maintained high average profits. The fact that all companies have an increased risk with increased uncertainty represents an interesting area for further exploration, since the current model version does not fully capture environmental variability but only has a crude proxy in the form of the stochasticity coefficient for catching fish.

There were clear interactions of fuel price with CPUE, stochasticity of catching fish, exchange rate and with price paid by markets to pay for hake, in the model. CPUE had a more important impact on profit than fuel price, with all companies making a loss at low CPUE irrespective of whether fuel price was high or low; the higher the cost of fuel the bigger the loss though. This could be important since companies stated that they might take these kinds of losses over the short term since catching all of their quota was their primary objective, for the purpose of both meeting their contractual (supply) agreements with clients and demonstrating to government their capacity to catch their quota which is a possible criterion for successful future rights allocations.

Conversely, changes in modelled fuel price were more important than the environmental uncertainty proxy ‘stochasticity of catching fish’. This may be partially a result of insufficiently capturing environmental variability in the model. Increasing stochasticity did, however, reduce profits for companies. This means that if uncertainty is greater than levels estimated in the model it could have more important consequences for profitability. Increases in environmental uncertainty, under certain other unfavourable model input conditions (i.e. environment and economic conditions), could tip companies from making a profit into making a loss.

Both modelled exchange rate and the price paid by countries (i.e. market value in Euro terms) were shown to buffer the effects of fuel price on profitability. In cases where fuel price and exchange rate were linked (even when both increased), profitability for companies was high. In other words, a devalued Rand is favourable (under standard CPUE and environmental conditions) for companies in terms of profitability despite its effect of also increasing fuel price. This situation might be modified though if fuel usage to catch fish were substantially increased. Similarly, for a set exchange rate, increases in fuel price (i.e. cases where the international US$ oil price increases) were buffered by as little as a 25% increase in market value of hake across the board in the model. Although real companies have no effect on international market prices (they are price takers) they can shift their product to higher value markets to buffer the effect of increased costs. Indeed this behaviour has been observed in the fishery through product displacement to frozen processed product with a lower catch cost and a higher value.

Finally, interactions between TAC and CPUE were important for company profitability in the model. When TAC was high and CPUE was low companies made a loss. In all other TAC/CPUE combinations it was favourable to have a smaller fleet than the present size (2013 values) in terms of profit, since all quota could still be caught and cost to company was lower. If no mismatches occurred where TAC was high and CPUE was low, it would seem efficient then for companies to have smaller fleets, if only profitability was to be considered. The only benefit to industry of having its actual, present fleet size must then be to maximise profitability and reduce the risk of not catching the entire allotted quota when TAC is high and CPUE is low. This may be especially true given the incentives of companies to meet contractual obligations and ensure the re-allocation of rights in future. Indeed, this corresponds to suggestions made by industry during the consultation phase.

All in all, *HakeSim 3.0* appears to model the economics of the offshore demersal hake trawl fishery adequately, and this represents the first simulation model of the SA hake fishery economics which can be used as a foundation for further work. This is discussed in the concluding chapter.

CHAPTER 7:
CONCLUSION

Chapter 7: Conclusion

1. Summary of findings

This thesis set out to lay the foundations for a study of the economics of the offshore demersal hake trawl fishery in the Southern Benguela in an interdisciplinary context. It firstly aimed to develop a principal understanding of the South African hake industry through data collection and analysis, and industry and expert consultation. Secondly it aimed to produce a prototype economic model of the South African hake fishery to gain a preliminary understanding of its structure, dynamics and the relative importance of internal and external drivers, such as industrial organization, exchange rates and fuel price. The first aim was largely achieved in Chapters 2 and 3 and the second aim in Chapters 4, 5 and 6.

Chapter 2 sought to describe the industry structure of the offshore demersal hake trawl and contextualise it within existing economic and related studies, paying particular attention to the existence and changes in company clusters, and to describe its changes through time to assist in the production and analysis of prototype models of the industry. These aims were achieved through data collection from sources such as government and through consultation with relevant stakeholders and experts. The structure of the industry for the period of study (2012-2013) was described and analysed. Rights were grouped into nine company clusters that were highly vertically integrated. There were four types of clusters: large companies, medium, small and super-cluster companies. They differed in the quantity of quota that they held, the products that they produced, and their business models. An ownership profile of these different companies was also generated and indicated that a few parent companies or investment boards have shares in a number of different fishing companies, which are therefore traded on the stock exchange. There was (and continues to be) a high level of vertical integration in the industry, with much value-adding of fish products. Product streams for hake were also identified, providing an understanding of how hake was caught on different vessel types, landed as fresh or (sea-)frozen, processed in vessels and factories and sold. The industry was described as a mature one in economic terms, with a high level of vertical integration and a fairly stable structure where the main changes were in the direction of consolidation of rights, at least within the present context of long term rights. The previous major change to the number of participants and therefore industry structure occurred when the Long Term Rights Allocation process was begun and it was suggested that some re-shuffling of structure after the rights are reviewed at the end of 2020 was probable. The vessels owned by companies were also studied. Declines in vessel numbers, particularly wet-fish stern trawler vessel (i.e. those that caught fresh fish) numbers, for the existing time series from 1978 to the present time were found. This downsizing of fleet was said to present removal of excess capacity from the fleet which incurred unnecessary extra maintenance costs, and in the years directly preceding 2013 was further driven by the establishment of an industry-led effort restriction based on the horsepower of the trawler engine in 2006. Overall, qualitative and quantitative data in Chapter 2 were in agreement and also matched some information in the existing literature, showing the strength of the data. Additionally, the findings of this chapter were published in an international, peer-reviewed journal[18]. As such, the findings of Chapter 2 were treated as reliable in providing a foundation for the production of the economic agent-based model.

Following from the structural study of Chapter 2 a greater insight was needed into the functioning of the offshore demersal hake trawl industry, particularly an understanding of the export and domestic markets for hake. Chapter 3 therefore, aimed to provide analyses of hake export data over the 2000s in as much detail as possible given their coarse resolution, to understand the relative importance of and changes in the domestic and export markets and how companies or the industry as a whole might have responded to these, and thereby to provide additional insights into the economics of the fishery in South Africa.

To accomplish this hake exports from South Africa were analysed for general trends from TradeMap data and in relation to changes in fuel price, exchange rate, total allowable catch (TAC) and qualitative information on overall market demand. Quantitative findings were taken through expert and stakeholder consultation and further qualitative data on domestic and export market behaviour were collected. Additional qualitative information on how companies coped with changes in domestic and international markets and apportioned their efforts in resource collection, processing (i.e. product streams) and sale (domestic versus international market) of hake was also collected. Quantitative and qualitative estimates suggested that export volumes of South African hake were in the order of 60-70% of the TAC, for the 2005 – 2011 period. The major export market was identified as Spain. Smaller, but still important markets (those contributing more than 500 tons of hake purchased per year) included Italy, Portugal, the United Kingdom, Germany, the Netherlands, the United States of America, Australia and France. Exports to all other countries together constituted

[18] Cooper, R., Leiman, A., and Jarre, A. 2014. An Analysis of the Structural Changes in the Offshore Demersal Hake (*Merluccius Capensis* and *M. Paradoxus*) Trawl Fishery in South Africa. *Marine Policy*, 50, Part A: 270-279. DOI: http://dx.doi.org/10.1016/j.marpol.2014.06.006.

just over 500 tons. According to industry, all hake exports from South Africa could be treated as having been caught in domestic waters, because lower export tariffs in Namibia discouraged exportation of Namibian hake through South Africa.

The general trend in export volumes of hake was away from fresh, whole prime quality hake toward frozen product, fillets and value-added (i.e. highly processed) hake, this was especially visible from 2008 (the time of the international financial crisis) onwards. This product shift was largely due to changes in the Spanish markets. There was an associated shift towards a greater reliance on freezer trawling, which was suggested to also bring with it some risks of international price instability. The ability for industry to be able to switch between fresh and frozen product was a key aspect that allowed industry to remain profitable by shifting its product stream to match international demand, reduce catch costs and therefore retain a profit margin. A product displacement was observed in export data from fresh towards frozen and increasingly value added product, which corresponded to an increased value per ton for value-added product. Industry suggested that this increased value of processed, frozen product allowed profits to be retained in a scenario of higher catch cost and changing markets. A price convergence between whole fresh and whole frozen hake, which corresponded to the product displacement, was also observed after 2008 and verified during industry consultation. Consultation with industry provided a domestic market size estimate as 30% of South African TAC plus additional import volumes equivalent to 15% of TAC. The price paid on the domestic market was also reported to be slightly lower than export premium. Decisions on whether to export or sell hake products domestically were based on the catch size mix, demand for hake, price parity, exchange rate and long term relationships with clients. A significant positive relationship was found between Rand/Euro exchange rate and annual hake export volumes.

In terms of operational decisions, companies identified catching their entire quota within effort restriction limitations as their primary objective, even if it meant bearing short term losses because of unfavourable CPUE and fuel price interactions. Companies also aimed to keep their vessels active throughout the year. CPUE, fuel price and size-mix of catch affected profitability and choice of fishing location. Once again, there was consensus between qualitative and quantitative data in this chapter providing confidence in the use of both data forms in informing model design and as model inputs.

Taking the findings of Chapters 2 and 3 then, a first prototype agent-based model was developed of the harvest and post-harvest industry of the offshore demersal hake trawl in Chapter 4. Modelling provides the next step in understanding and exploring questions surrounding the dynamics of the offshore demersal hake trawl fishery. The modelling process can also provide information that might in future be used to clarify thinking around what economic objectives could potentially be for the fishery, which could help to inform possible management strategies. The broad aim of Chapter 4 was to gain a preliminary understanding of the dynamics of the Southern African offshore demersal hake trawl fishery, which operates in the Southern Benguela, between target resource and markets with regard to its structure. That is, this prototype of the model specifically i) explored changes in international and national market demands on the quantity of resource (fish) extracted in the SA hake fishery and on overall company sales volumes or wastage, ii) explored scenarios of changes in TAC and iii) explored changes in frozen vs fresh demand of export and local markets for fish. A conceptual framework for the first model prototype was developed (i.e. the model world was designed) and the model was implemented in code in Netlogo 5.0.1. The model was thoroughly tested and sensitivity analyses and reality checking were conducted. The first model prototype was found to be fully functional and free of significant bugs and errors. It was sensitive to TAC and large company quota, but relatively insensitive or only slightly sensitive to many other inputs. The model outputs were quite simple and constrained, since the structure for this prototype was largely imposed and a number of heavy assumptions were also made in this version. This was done intentionally to provide a thorough understanding of the first prototype before adding levels of complexity to the model without creating a black box. The (rapid) prototyping approach recommended by Starfield and Jarre (2011) was adopted where a simple first prototype is built, understood and layers of complexity are incrementally added through iterations of the modelling development cycle. Because the first prototype was soundly built and its overall structure was sufficiently realistic it provided a good starting point on which to build more complex model versions.

The rapid prototyping approach was continued in Chapter 5, where a number of the assumptions made in the first prototype were incrementally relaxed and the effect of relaxing these assumptions was tested on the behaviour and realism of the model. This chapter therefore served the purpose of a thorough assumption analysis and a significant step in complexifying the model through rapid prototyping. The aim of this chapter was to produce these new, incrementally complex model prototypes and compare them with the previous simple model version in order to determine whether and how relaxing some of the assumptions made in that version would make a significant difference to the functioning and realism of the model. It was found that *HakeSim 2.3* had much more realistic behaviour than all of the other model prototypes. It represented the model version in which four major assumptions were relaxed; i) vessel numbers became flexible and represented the average fleet of the industry, ii) vessels were not active at every time step (i.e. some vessels were preferentially used over others based on a rank), iii) company quota was not evenly divided among vessels, and iv) vessel fullness became dependent on vessel maximum fish storage capacity, CPUE and *stochasticity of catching fish* (as a simplified model for environmental uncertainty). The changes made to the model not only increased realistic behaviour, but also allowed for the possibility to test the effects of changing additional factors in future model versions such as company's vessel numbers and types (i.e. fleet composition), CPUE and (environmental) *stochasticity of catching fish*. This confers the significant advantages of increased realism in the model and flexibility in terms of the different questions that can be asked and analyses conducted with later model versions. As such *HakeSim 2.3*, the version in which the four assumptions were relaxed, is used as the basis for the development of the next model version.

The full model prototype, *HakeSim 3.*0, which incorporates money (South African Rands and Euros), in addition to the fresh and frozen fish model currencies of the earlier model prototypes, was developed and described in Chapter 6. The objective of this chapter was to develop the model to a final version that would allow some of the original questions on the trade-offs between TAC, CPUE, fuel price, exchange rate and market factors such as price and demand, to be examined. Additionally, during the data collection, stakeholder consultation and data analysis phases new ideas to test emerged. A number of scenarios were developed to test these and the original questions.

It was found that the final version of the model behaved realistically and produced some interesting outputs that coincided with real world observations and supported most of the perspectives put forward following industry consultation. The model was found to be sensitive to changes in fleet size, the quota of large and medium companies, catch per unit effort, exchange rate and (most expectedly) situations where the TAC was reduced to zero. This indicated that the model was behaving as a good approximation for the real world, as these were all processes that were indicated as being important drivers of the industry from stakeholder consultation and expert opinion. Companies were found to have different strategies for trading off risk against profit; large and medium companies opted for higher risk, higher profit, while small and super-cluster companies opted for lower risk, but reduced profits. Large and medium companies can likely buffer their riskier strategies because of their economies of scope and scale and take advantage of the greater profits this strategy yields at times. All model companies show an increased risk without increased profits in the face of increased *stochasticity of catching fish*. The result of this increased risk with uncertainty is an interesting area for further exploration, particularly since the stochasticity used is a poor proxy for true environmental stochasticity and likely underestimates the multiplicity of its effects in the real world.

There were clear interactions of fuel price with CPUE, stochasticity of catching fish, exchange rate and with price paid by markets for hake. CPUE had a more important impact on profit than fuel price, since all companies made a loss at low CPUE irrespective of whether fuel price was high or low; unsurprisingly, though, the higher the cost of fuel the bigger the loss. Changes in fuel price were more important than the environmental uncertainty proxy '*stochasticity of catching fish*'. This may be partially the result of insufficiently capturing environmental variability in the model. But may also reflect the absence of large-scale changes in the demersal fish communities, in contrast to those observed in the pelagic sub-system, confirming the findings of Watermeyer (2015). Increasing stochasticity did, however, reduce profits, which if other variables were already unfavourable could be sufficient to tip companies from breaking even or making a small profit into making a loss. It is also important to note that environmental variability and its effects on recruitment (which are not properly understood) were likely underestimated (or poorly approximated) by the stochasticity included in the model. Given the importance of CPUE in affecting profitability and catches of fish and its interaction with environmental stochasticity, this is an important area for future ecological research.

Both exchange rate and the price paid by countries (i.e. market value in Euro terms) can buffer the effects of fuel price on profitability through increasing revenue to companies. In cases where fuel price and exchange rate are linked (even when both increase), profitability for companies is high. Similarly, for a set exchange rate, increases in fuel price (a situation which would be expected to occur when the international US$ oil price increases) were buffered in the model by as little as a 25% increase in market value of hake across the board. Companies might be able to achieve price increases in the market value through shifting to a product type with a higher value or net profit. Such a trend was observed in the real world during the 2005 to 2011 period analysed (Chapter 3), where the proportion of value-added product exports increased. Finally, interactions between TAC and CPUE are important for company profitability. When TAC is high and CPUE is low companies make a loss. In such cases having a slightly larger fleet size can help to reduce losses. It is suggested that the present fleet size of industry may have been chosen by companies to ensure that they continue to catch their quota and reduce losses when TAC is high and CPUE is low. This may be especially true given the incentives for companies to meet contractual obligations and ensure the re-allocation of rights in future. Indeed, this corresponds to suggestions made by industry during the consultation phase.

2. <u>Context within similar international models</u>

Internationally there are a number of other models that deal with the economics of hake, gadoid, or demersal fisheries, which are in some ways similar to the South African offshore demersal hake trawl fishery, e.g. similar target species or fishing method.

One model that has been applied to several hake fisheries is MEFISTO, a bio-economic model, as discussed in the introductory chapter. It has been applied to European hake (*Merluccius merluccius*) fisheries in the Gulf of Lions, western Mediterranean Sea, (Lleonart *et al.*, 2003), and to in the Saronikos Gulf in Greece (Merino *et al.*, 2007).The MEFISTO model was not suitable for application in and adaptation to the South African example, because the hake fisheries in South Africa function quite differently to the European examples. The South African fishery is highly vertically integrated, the fish stocks are much larger, and in the offshore trawl sector specific to the hakes as a target species with limited commercial bycatch. Furthermore, MEFISTO doesn't examine export markets, nor is exchange rate important in a European context where trade is between countries with the same currency.

In a different study, standard mathematical modelling approaches have been applied to European hake (*Merluccius merluccius*) Southern Stocks for the Spanish fisheries to examine the effect of different management scenarios on value obtained from fisheries. Stock value was estimated under a range of different scenarios using a surplus production function for total landings and biomass figures from ICES. That is, prices of hake were calculated as a function of landings. Predicted values under a set of modelled management scenarios were compared with real values (Antelo *et al.*, 2012). This model was not concerned with the effects of industry structure or market changes, or individual variability between fishing companies and was therefore again not suited for direct comparison.

Another European example that considers a hake (*M. merluccius*) fishery but also its technical interactions with other demersal fisheries sectors is a multi-species, multi-fleet discrete-time, stochastic, bio-economic model of the Bay of Biscay demersal mixed fishery by Gourguet *et al.* (2013). The main purpose of this model was to look at trade-offs between sustaining economic profits of the different fleets and retaining the spawning stock biomass size. It examined ecological and economic viability of the fleets and target species under different management strategies, focusing in part on technical interactions, and fuel price scenarios (Gourguet *et al.*, 2013). However, since the industry is quite different to the South African example and the effect of export market and industry structure is not considered in the model, results are not easily compared.

In New Zealand a bio-economic model built on the ISIS-Fish simulation platform that considers the technical interactions of hoki (*Macruronus novaezelandiae*) with Southern hake (*Merluccius australis*) fisheries, examined the effect of TACs and deemed value on a variety of target species. Deemed value is the monetary penalty charged for any landings that exceed the allocated fishing right (annual catch entitlement – ACE), since a certain proportion of landings is allowed over the ACE to prevent discarding. The effect of several management strategies on spawning biomass and catches of the targeted species was explored with the model (Marchal *et al.*, 2009). The same approach was used to determine what the effects of various management strategies, some using deemed values, could be if they were to hypothetically be implemented in a demersal fishery in the Eastern English Channel (Marchal *et al.*, 2011). Although penalty prices and the value of landings were considered in the ISIS-Fish model, other economic factors and interactions such as the effect of changes to export markets or exchange rates, which were of interest in the South African offshore hake trawl fishery and explored in *HakeSim 3.0,* were not captured.

There are a number of economic models in North America that have dealt with demersal fisheries, but they have different foci to the model presented in this thesis. For example, in the United States of America (US), Dorn (2001) modelled and examined the behaviour of a single trawler fishing for hake (*Merluccius productus*) and its decision making process (Dorn, 2001). Toft *et al.* (2011) modelled the consequences of a change in management to individual transferable quotas in the groundfish trawl off the US West Coast through the production of a spatial model of fleet and biological dynamics, although this was for different species, Dover sole - *Microstomus pacificus* – and rockfish – *Sebastes crameri* (Toft *et al.*, 2011). In New England, Canada, an empirical model was developed to predict a vessel's choice of fishing location and target species for each fishing trip based on past time series of spatially differentiated revenue rates that were available in different areas, and thereby predict effort at the fishery level (Holland and Sutinen, 1999). Again, the objectives of these models are different from the questions asked in this thesis.

In the European (and typically Northern Hemisphere) situation, but also in Australia and New Zealand which both have fairly strong currencies, exchange rates are less important for fishing industry profits and behaviour, and are not relevant among European countries that have accepted the Euro. However, Namibia and the South American countries would be expected to show similar dynamics in their hake or demersal fisheries to South Africa, in that they also have developing economies and exports that are strongly affected by (often volatile) exchange rate fluctuations.

In Chile a dynamic simulation bio-economic model was built for a large-scale demersal trawl fishery that targets southern hake (*Merluccius australis*) and hoki (*Macroronus magellanicus)* and a small-scale longline fishery that only targets hake, to examine the bio-economic effects of alternative management strategies on the fisheries. The model included hake and hoki populations and five fleets – trawlers and factory trawlers from the large-scale sector and two fleets from the small-scale sector – in three different areas (Cerda-D'Amico *et al.*, 2010). The model consisted of a biological module that examined fish populations and an economic module that represented fleet size and net benefits based on interactions between income, fishing costs and capital investment (Cerda-D'Amico *et al.*, 2010). The fishery upon which this model was based has many similarities with South Africa's fishery. However, the model is not readily comparable since fleet size determines the level of effort in the fishery, which is not the case in South Africa where effort limitations (horsepower sea-days) have been set in an industry-led initiative. Furthermore, the model again does not consider export markets and exchange rates and is thus built for a different purpose than *HakeSim 3.0*.

In Peru there was a bio-economic model that coupled ecosystem and supply chain modelling. This was, however, for anchovy (*Engraulis ringens*) fisheries rather than a hake demersal trawl. The model focused on coupling an EcoSim with EcoPath ecosystem model to a socio-economic model of the supply chain that captured entire industry sectors rather than individual firms (Avadí *et al.*, 2014). In Argentina, a model associated with the industrial aspects of hake dealt with calculating costs of different quality products associated with international health and safety standards (Zugarramurdi *et al.*, 2007), a different subject to the present study.

The Namibian hake fishery is perhaps the most similar to the South African example, and recent studies, (Paterson et al., 2013; Kirchner and Leiman, 2014), provide for some economic comparisons. Kirchner (2014) conducted an economic study and produced a bio-economic model of the Namibian hake (*Merluccius paradoxus* and *M. capensis*) trawl fishery to assess the impacts of different management strategies on the value of the hake fishery. The model estimated actual and potential profits in the fishery. The study also examined the effect of exchange rate, which it found to be the biggest contributor to revenues, and fuel and other costs (labour costs were the greatest contributor to company costs in the Namibian example). The modelling approach was one of traditional economics, using a residual approach to estimate rents and allowing for fish stock fluctuations. Exchange rates, fuel prices and fish prices were kept constant in the model, unlike the agent-based model considered in this thesis where prices could be time and agent (i.e. model entity) dependent. One important distinction from the South African fishery is that the Namibian fishery allocates its TAC between freezer and wet-fish (fresh) trawl. The model therefore also apportions 30% of the TAC to freezer vessels (Kirchner, 2014). This is different from *HakeSim 3.0* where the number of freezer vessels can be manipulated for different model runs and the fish quota of companies is assigned in a variable way between the vessel types that they own. *HakeSim 3.0* is also a different type of model, an agent-based model, which means that it examines individual-level variability between model entities, such as companies, vessels or international export markets.

Agent-based models (ABMs) have been applied in a variety of fishing applications, but these differ substantially from *HakeSim 3.0*. In Australia ABMs were used, for example, to model information flow between vessels, as well as spatial vessel behaviour in a line-fishery (Little *et al.*, 2004), or multiple, competing coastal zone uses and management choice scenarios (McDonald *et al.*, 2008). ABMs have also been used to represent fishing vessel behaviours and spatial choices. For example, Beecham and Engelhard (2007) developed an economic-ecological ABM to illustrate the effect of the strategy trawlers used to choose fishing location on the profit made on catches for each unit of time spent fishing. Yu *et al.* (2009b) produced an ABM of fishing vessel behaviour to explore the effects of area closures on a line-fishery. Bastardie *et al.* (2010) also modelled fishing vessel movements, but considered the effects of fuel-consumption, efficiency and profitability and compared past vessel movements with model predictions under different scenarios in Danish marine fisheries. None of these models are applicable to the questions addressed in this thesis, or adaptable due to differences in fishery and industry structure. These models also all had purposes quite different to those of *HakeSim 3.0*.

In their review of EU bio-economic models, Prellezo *et al.* (2012) concluded that the diversity of models and modelling approaches that exist in the EU context is representative of the need to adapt models and their development to answer the diverse questions that are posed in real world fisheries. This point could be doubly argued for fisheries from different regions of the world that face different problems and are often structured or function quite differently. Indeed, the novel model in this thesis, *HakeSim 3.0*, was developed to answer a specific question from a real world situation that was quite different to situations and questions dealt with in existing models from other parts of the world. Kettenring *et al.* (2006) recommend the careful application of existing models to answer new questions in new contexts and emphasized that model approaches must be compatible if models were to be adapted from one case to another. Since I could not find an existing model that had compatible assumptions, objectives and a real-world system upon which it was based, I chose not to adapt an existing model. Instead I chose rather to develop a novel model that could capture the particular structure and function of the harvest and post-harvest industry and exports of the South African offshore demersal hake trawl fishery, and address the most pertinent questions therein.

3. <u>Shortcomings</u>

During the data collection and model development phases there were a number of challenges and limitations that could not be overcome.

Quantitative data could not be obtained for the size of the domestic market, including types of products purchased and their value. As such, proportions of the domestic market had to be estimated based on qualitative information and international examples. For model purposes the domestic market, since it took processed fish products, was estimated to be about 25% of total world demand for processed product, since companies estimated that it accounted for around 30% of TAC in whole-mass terms. Estimations of the proportion of TAC that was sea-frozen fish (95%) were also based on qualitative information from companies. In terms of the price paid, the world average value was used for fresh and frozen fish, although a lower value is possible. It was therefore not possible to accurately examine the relative importance of the domestic and export markets for companies.

Another limiting factor concerned the size-based processing and sale of products. Although initially desired, it was impossible to include fish size in addition to quantity in the model, since it turned out impossible to link the broad export codes to exact product types and therefore fish sizes. Furthermore, although the size composition of landings is known, once fish enter a factory (or factory ship) they may exit as a broad variety of products that are not entirely size-dependent, making it even more difficult to make the link between fish sizes, product categories and export codes. Unfortunately this information is confidential and company-specific and could not be obtained. Fish size was therefore ignored in the model and only fresh and frozen fish were distinguished. This, however, does represent a challenge for understanding the effects of changes in size composition of fish populations on company function and profits. It also does not allow for the effects of markets on the desirable fish size to be examined.

Bycatch species are also presently ignored in the model, although the fisheries for some of these species are financially viable, e.g. monk (*Lophius vomerinus*) and kingklip (*Genypterus capensis*). Due to further issues of disentangling catches, processing and sale of products, for the present model version they were ignored. However, it might be interesting to include additional species into the model at a later stage, once better data are available.

A further process, which is not well understood in the real world, is the effect of environment on hake recruitment and subsequently on hake abundance and catchability. This was captured in a broad-brush manner as *stochasticity of catching fish,* a model variable that introduces stochasticity into vessel catches. However, in the real world the effect of environmental variability are likely to be more complex and affect more model input parameters. Given the importance of CPUE and TAC in the model and the ability of environmental stochasticity to increase risk and reduce profits, getting a handle on this component of the biology emerges as an important area of research, in terms of its economic consequences. One potential means of incorporating some ecological effects into the economic model is through linking it to an ecosystem model, as discussed in the next section.

The model produced in this thesis does not incorporate ecosystem dynamics and fish biology explicitly, which of course is a limitation. But the model was produced with this in mind and with the primary aim of undertaking the first, fundamental step in solidly understanding the economic system of hake, producing a model of this and identifying potential links to the natural systems that contextualize hake (*Merluccius capensis* and *M. paradoxus*). The main objective that the thesis then sought to achieve was to produce the starting point for understanding the linkages and interactions of the human and natural dimensions of the hake fishery. Specifically, it aimed to build a model of the economic dimension of the fishery that would identify linkages to the ecological system and allow for future studies to explore these.

4. <u>Future research</u>

As Folke *et al.* (2007) point out, any actions related to sustainability are underpinned through the linkages of ecosystems to social and economic systems. Ecosystem models can also give us insight into the current functioning of ecosystems, as well as possible future trends under different management or environmental scenarios. Interdisciplinary modelling is a means of incorporating the social, ecological and economic dimensions into systems thinking. One way of expanding the present model to incorporate ecological aspects and their effects on the economic system is through examining environmental and ecological effects on CPUE and TAC through the use of outputs from an ecosystem model.

Furthermore, it might be interesting to examine the effects of other fisheries (and sectors) which interact with the hake demersal offshore trawl and the economic consequences of these interactions. Indeed there has been recognition that there is a need to better understand the direct and indirect impacts of other fisheries on the hake fishery (Petersen *et al.*, 2010). This is especially important in light of the fact that lanternfish (*Lampanyctodes hectoris*, and *Maurolicus muelleri*), known food items of Cape hake and forming up to about 30% of *Merluccius paradoxus* diet on the West Coast, have been caught along with the target species in the purse seine fishery since the 1960s (Payne *et al.*, 1987; Prosch *et al.*, 1989; Pillar and Barange, 1997), and that there have recently been suggestions around introducing a directed mesopelagics fishery (DAFF, 2011). Pillar and Barange (1997) found that mesopelagics as a group constituted about half the diet of *M. paradoxus* on the West Coast when sardine and anchovy were not abundant. The ecological consequences for hake of changing fishing mortalities on lanternfish, for example, can be explored with an ecological model. The resulting ecological outputs can then be used to inform environmental input scenarios (e.g. TAC and CPUE) for the *HakeSim* economic model to explore the economic consequences of these ecological processes.

Table 7.1: A comparative table of ecosystem models after a presentation by Smith (2011).

	Atlantis	EwE	OSMOSE
Model currency	nitrogen	biomass	individuals
spatial structure	dedicated (polygons)	none	grid
time step	12 hr	monthly	weekly
oceanography	Yes (e.g. links to ROMS model)	model coupling with version 6	yes, forcing/coupling (e.g. ROMS)
trophic groups	~60: vertebrates, plankton, benthos, primary producers	<100: vertebrates, plankton, benthos, primary producers	~10: typically forage and demersal fish
age structure	vertebrates: 10 age classes	"multistanza" age classes	cohorts
nitrogen cycling	Nitrogen cycling	None	None
functional response	Holling type I, II, III, others	"foraging arena": implicit refugees	size-based predation and max ingestion rate
reproduction	Ricker, Beverton, fixed #/adult, others	biomass growth rate with compensation in juveniles	based on fecundity and SSB=f (predation efficiency)
movement	foraging and seasonal	seasonal	foraging and seasonal
fishing	spatial: fleets' catch, effort, or F	Fleets' catch, effort, or F	non-spatial fishing mortality rates
in summary	flexible	fast, stakeholder game playing	IBM, focused on forage and demersal fish

It becomes apparent that a spatial ecosystem model will be valuable in understanding ecosystem function and hake tropho-dynamics in the Southern Benguela given the above and the fact that hake diet and fishing effort differ spatially between the Agulhas Bank and the West Coast. Mesopelagics and crustaceans are more important to *Merluccius capensis* diet on the West Coast than the South Coast, while anchovy, horse mackerel, round herring, sardine and demersal fish are more important on the Agulhas Bank (Pillar and Wilkinson, 1995). There are also coastal differences in the prevalence of intra-species and inter-species hake cannibalism (Pillar and Wilkinson, 1995). The hake species composition also differs, being estimated to be around 75% *M. paradoxus* and 25% *M. capensis* on the West Coast compared to 9% *M. paradoxus* and 91% *M. capensis* on the Agulhas Bank during the 1980s (Jarre *et al.*, 1998). Furthermore, hake-directed fishing effort varies spatially by sectors, as described in the introduction. An appropriate ecosystem modelling platform will need to allow for these spatial differences to be captured. A review was made of three potential existing models of the Southern Benguela Ecosystem for this purpose: ECOPATH with ECOSIM, OSMOSE and Atlantis (Table 7.1).

OSMOSE seemed a particularly good fit for potential future linkage to or scenario analysis in conjunction with the economic model since it is an individual-based model that assumes size-based opportunistic predation (hake dietary studies are outdated); it is a spatial model and life-cycles are explicitly represented (Travers *et al.*, 2010). OSMOSE has also been coupled to ROMS-N2P2Z2D2, the three-dimensional hydrodynamic model of the Southern Benguela known as Regional Ocean Modelling Systems coupled with N2P2Z2D2, a bio-geochemical model of plankton (Travers *et al.*, 2009). This allows the low trophic level plankton communities, driven by hydrodynamics and bio-geochemical processes, to be coupled to the high trophic level communities of OSMOSE through predation (Travers *et al*., 2009). This end-to-end model can therefore incorporate some degree of environmental variability into the model. It is therefore one viable possibility for future linkages, and some aspects of *HakeSim*, such as the time-step, have been developed with linking to OSMOSE in mind.

If *HakeSim* is to be coupled or linked to an ecosystem model in future it will need further modifications, such as attempting to incorporate size-based aspects of hake catching and processing and size-based fish value, bycatch species and their values, and spatialized fishing and cost equations. These modifications, if possible, will also provide further insights into the functioning of the hake industry. In the simplest terms linkages of the two models could take the form of using outputs of one model to inform the inputs of the other or to inform possible scenarios to explore with the other. If a full-fledged coupling were to be attempted, the *HakeSim* model would need to be re-implemented using a completely different programming language and platform, such as Java (language) and Eclipse (platform) which OSMOSE is implemented with. Although, studies have cautioned *against* the production of increasingly complex models (e.g. Plagányi *et al.*, 2014). As such, it may be prudent to first explore the use of outputs from the ecosystem model to inform the parameterization of, or scenarios to explore in, *HakeSim*, or vice versa. This alone may answer pertinent questions and will determine whether it is relevant or sensible to develop a coupled, more complex model.

In conclusion, the process of successfully developing the full prototype, *HakeSim 3.0*, of the offshore demersal hake trawl in South Africa, including collection of data on the real world, has been fruitful and has achieved the aims of this thesis. *HakeSim 3.0* is capable of specifically examining economic aspects of the industry. A good understanding of the economics, the structure and function of the industry has been developed and has provided novel insights; in particular industry structure was explicitly quantified, major hake export trends and markets were identified and changes in export products were linked to changes in vessel ownership. In addition to assisting in the development of an understanding of the industry the model has allowed the examination of industry dynamics and the assessment of the relative importance of internal and external drivers, such as market demand and value, exchange rate, fuel price and CPUE. It has served to identify future areas for scientific enquiry and further research expansion. Added resolution with regard to fish size is desirable. Identified links between the economic and ecological systems could be taken forward into a coupled model of the economic-ecological system of the Southern Benguela, with special reference to hake.

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APPENDICES

Appendix 1: Additional information pertaining to Chapter 2.

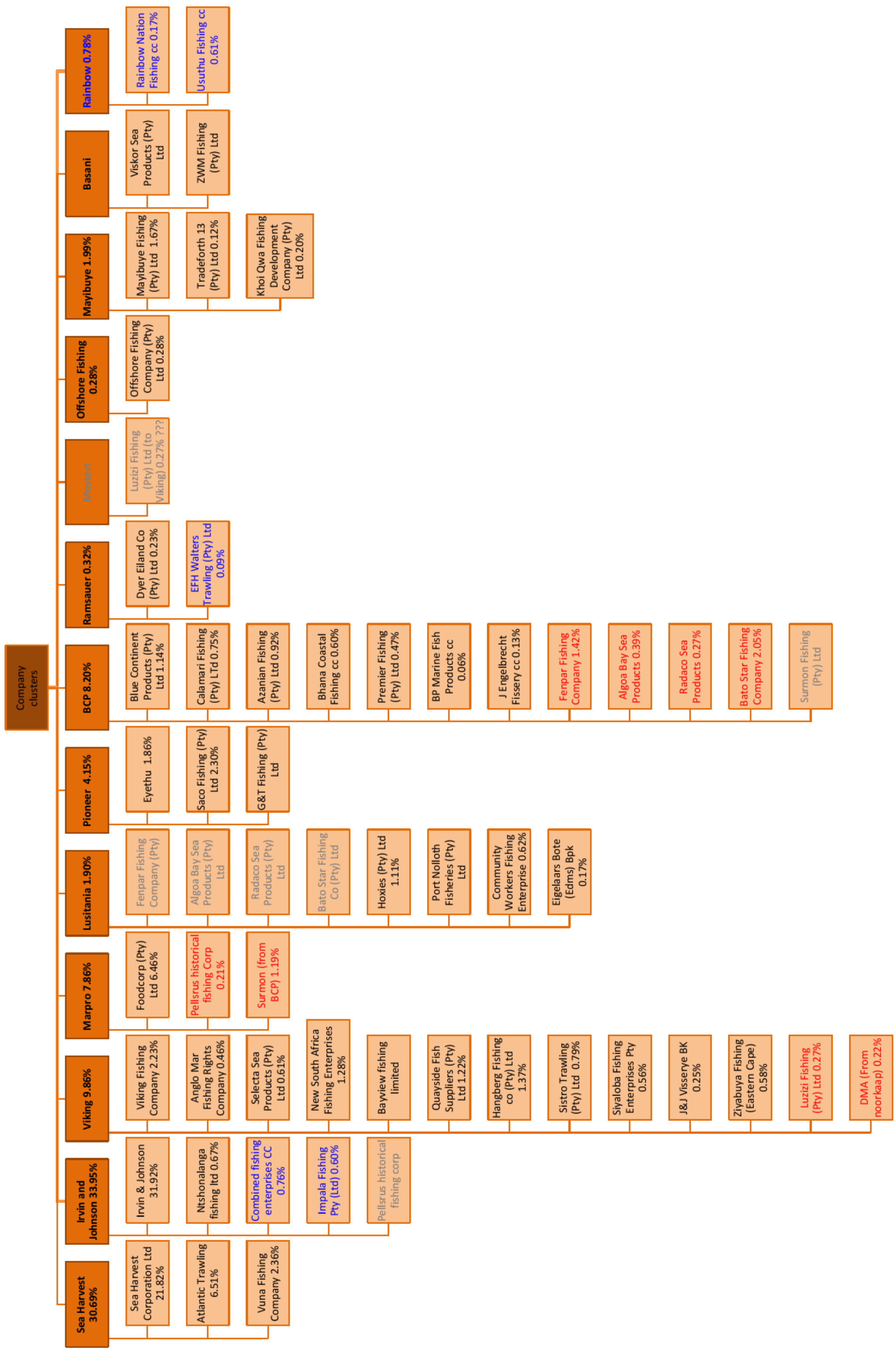

Figure A1.1: A preliminary cluster diagram representing initial ideas of the offshore demersal hake trawl industry structure. This preliminary schematic was based on the long term rightsholder successful applicants from 2006 for offshore trawl that was downloaded from the DAFF (Department of Agriculture, Forestry and Fisheries) repository of public information, and the SADSTIA (South African Deep Sea Trawling Industry Association) website, as described in Chapter 2 Methods.

Appendix 1 continued.

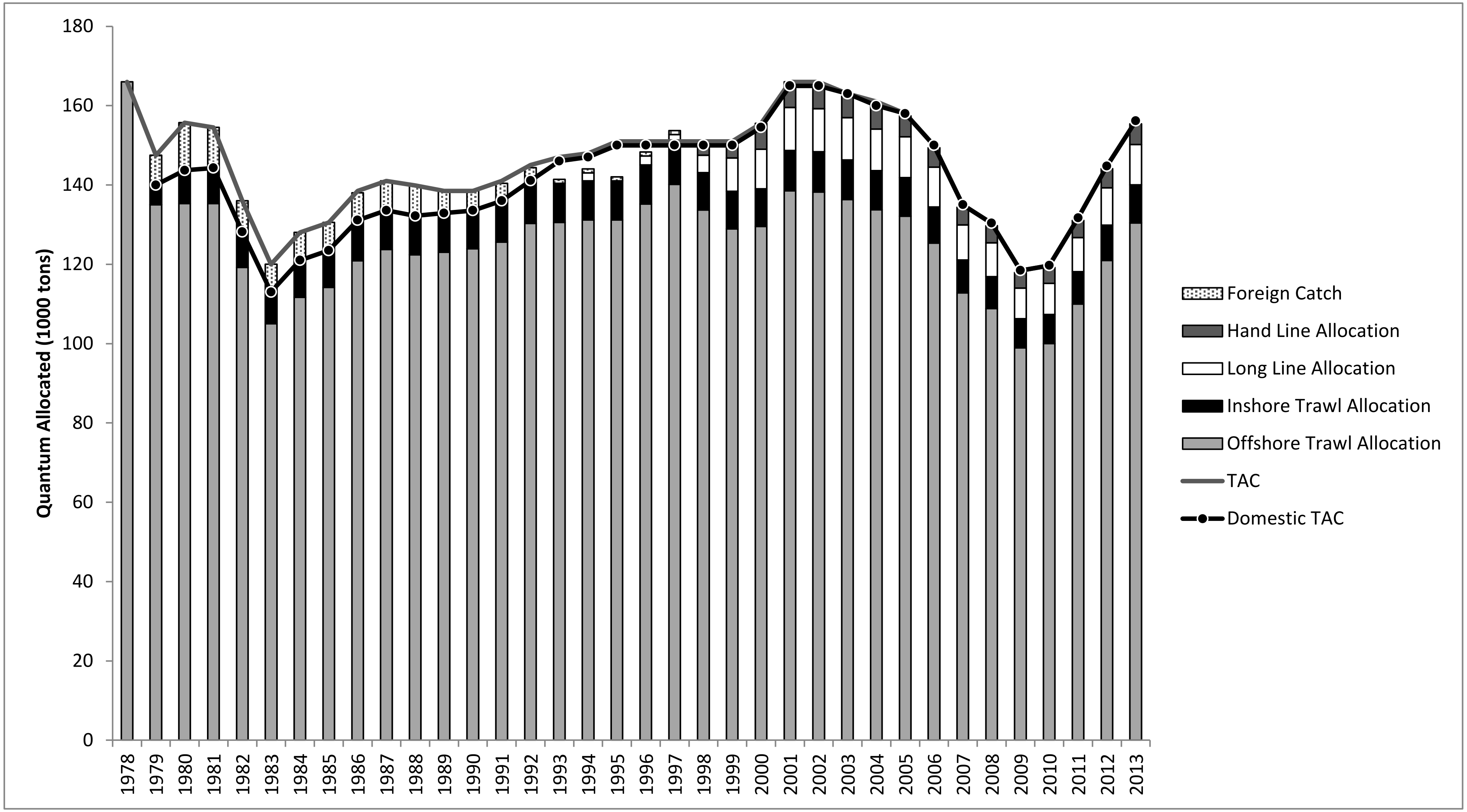

Figure A1.2: Changes in the total allowable catch by sector over time, along with an indication of the foreign catch that happened in the earlier half of the time period.

Appendix 2: Material used in the industry consultation of Chapter 3.

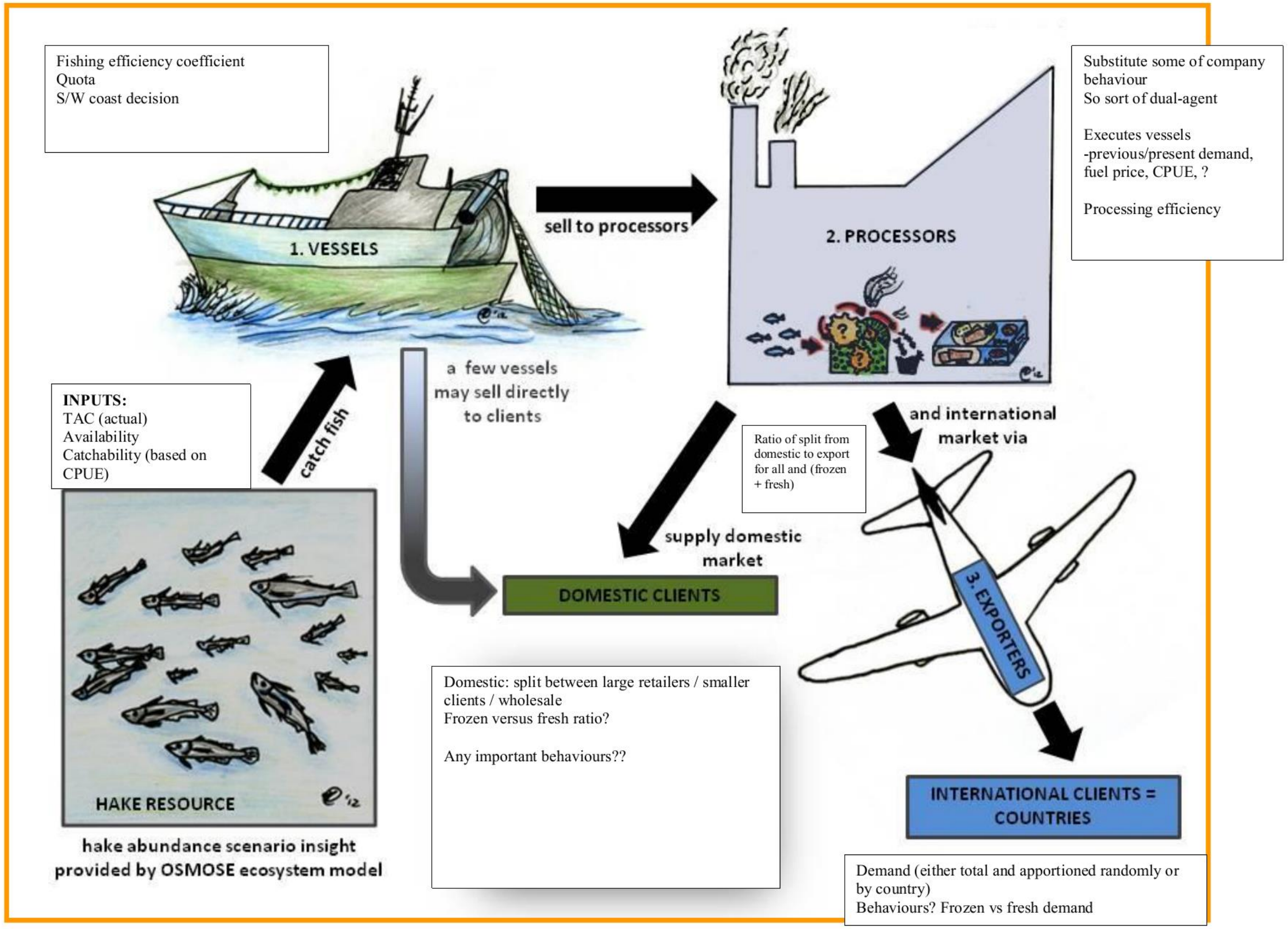

Figure A2. 1: An annotated flow diagram used for illustrative purposes during the industry consultation described in Chapter 3 Methods (Illustrations by Rachel Cooper).

Appendix 2 continued.

The following is a list of potential questions or talking points that were used to guide interviews in a general sense. Not every point was discussed in every interview and some interviews covered topics not listed below. These questions/talking points take the form of quite rough bullet point notes that were used to prepare for and conduct interviews.

Vessels

- e.g. decisions
  - Do I catch all my quota (full vessel) if fuel price high
  - Do I catch all quota (full vessel) if CPUE low
  - Do any vessels sell directly to clients
  - Number of freezer vs wet-fish trawlers/vessels
- What determines the number of sea hours you put out
- Average length of vessel trip? –wet-fish vs frozen
- What is effect of fuel price on vessel location from homeport?
- Main directive of vessel captains – fill vessel or find particular products?
- What is the major factor determining vessel behaviour
- Over what time scales are massive changes to overall vessel activity – e.g. number of vessels deployed?
- Over what time scales does fuel price have an effect?

Processors / rightsholders' companies?

- Do I send more vessels if:
- Do I sell more fish to domestic or international market if:
- Do I change distribution of frozen vs fresh fish if:
- (How do I determine the ratio between ACTIVE frozen and wet-fish trawlers)
- Do I decrease processing time (man hours) if:
  - CPUE low/high
  - Fuel price low/high
  - TAC low/high
  - Exchange rate low/high
  - Size of fish changes
  - Locational distribution of fish changes
  - Overall market demand changes
- Processing coefficient (efficiency to reduce weight of fish) – do I use and aggregate from conversion factors
- Do I model some processors that don't buy from local fishing vessels and have them buying some 'imports' & then processing to meet demand- include import substitution behaviour
- What is the major driver for this import substitution behaviour – changes in domestic or international market
- Does fuel price affect decision of whether or not to send out vessels, how often to fish – or does it just affect where to fish? - industry indicates that they go out of their way to catch their quota – how true is this and for only big players or for all
- Any other important CEO behaviours – drivers?
- What (proportion of frozen vs fresh) goes to local retailers vs local delis etc?
- How important is import substitution if market demand increases?
- What are the major factors affecting company behaviour
- What are the major factors affecting profitability?
- Major cause for downsizing of production (Sea Harvest)?
- What are the time-scales of orders, processing?

Appendix 2 continued.

- Are small fish less valuable / more valuable for companies that value-add
- Processing clusters: Are there specialists in fresh or frozen fish or is there general processing?
- Do clusters all (sell) market together, or do they just deliver to the big guys? Do they have contracts etc? How long are these for?
- Does any fish from longline get processed in trawling company processors – on different processing lines I guess? Do they end in different product types?

Clients

- Fixed client base irrespective of exchange rate – is this true (for smaller guys)?
    - Effect of decreased PQ demand on small guy
    - Small companies: fresh or frozen
- Time scales of changes in consumption /processing – how often do orders change, constant over season, year, month??
- Relative quantities of frozen versus fresh that are purchased? Fresh head-on versus h&g versus processed hake?
- How much do you think is trawled versus longlined (export and domestic)
- Does domestic market source from trawlers directly or via middle men

General

- What has domestic market done over the last few years?
- How relatively important is it?
- Price taker vs price maker idea of domestic vs international market?
- How much fishing on West Coast versus South Coast? is there any kind of instructional stuff in how this gets distributed – vessel decisions or processor decision
- Make sure to check the accuracy of the conversion factors
- Importance of interest rate – traditional economic theory dictates that it is, but this doesn't seem to be the case in SA?
- (How do remuneration packages work for vessel captains)
- What are the major factors affecting decision of split between fresh and frozen, W/S coast, export/domestic market per product?

Fish import/export/local processing and size

- Does size affect processing route for products – what sorts of products (codes) do you think different size classes would end up in?

Appendix 2 continued.

Table A2.1: Potential conversion factors to convert fish product weights back to whole-mass equivalents (i.e. the weight of the unprocessed fish from which the product was made). These were based on the standard conversion factors that DAFF (Department of Agriculture, Forestry and Fisheries) uses for hake. This table was used during industry consultation to discuss which product types were exported under a variety of HS export codes (shown left) and which conversion factors might be appropriate for these product categories. The resulting conversion factors that were determined based on industry-wide consultation can be found in Table 3.2.

Potential DAFF conversion factors

160419*	fishnes prepared or preserved excl….	**?**	sausage/mince?
030269	whole fish nes fresh, chilled excl heading	**1.16** **1.10** **1.46**	Hake gutted and gilled Hake gutted Hake headless and gutted
030378	whole hake frozen, excl heading	**1.46**	hake headless and gutted
030420*	fish fillets frozen (in packs or blocks)	**2.25** **1.94**	hake, trimmed skinless fillets hake, untrimmed fillets
030429*	frozen fish fillets (in packs or blocks)	**2.25** **1.94**	hake, skin off fillets hake, skin on fillets
030499*	frozen fish meat whether or not minced	**2.25** **1.94**	hake, trimmed skinless fillets hake, untrimmed fillets

*is there a possibility that double counting of whole-fish occurs among 160419, 030499, 030420 and 030429 due to offcuts from fillets being reused in other products. How could this issue be dealt with?

Appendix 3: Additional details of the export analyses conducted in Chapter 3.

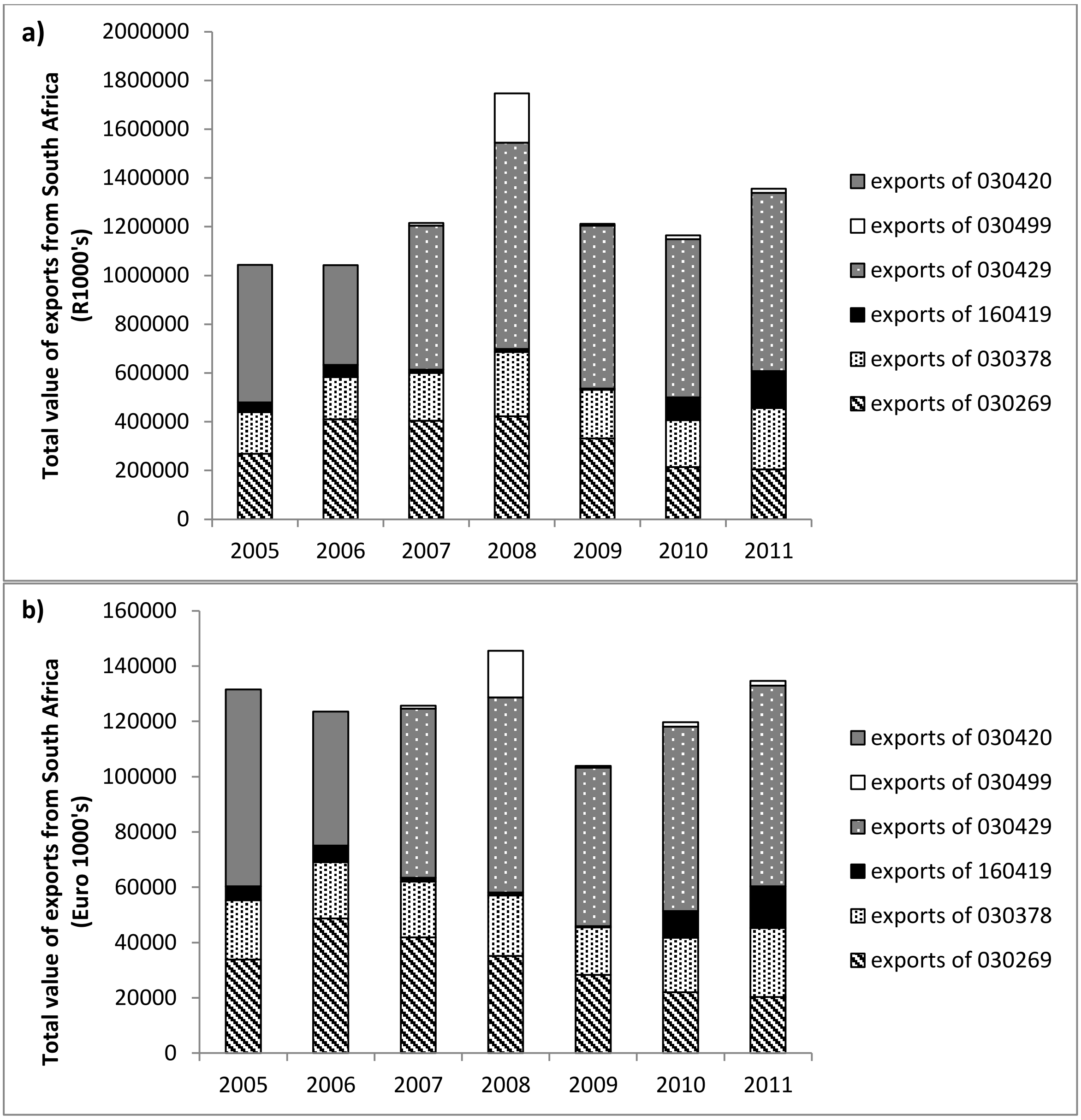

Figure A3.1: Total annual values in a) ZAR and b) Euros, of fish exported from South Africa under the HS codes that could include hake, as extracted from SARS (South African Revenue Service) export data in TradeMap. The HS codes beginning 0304 are all related codes that were used during different time periods to export the same types of hake fillet products. See Table 3.1 for detailed descriptions of codes.

Appendix 3 continued.

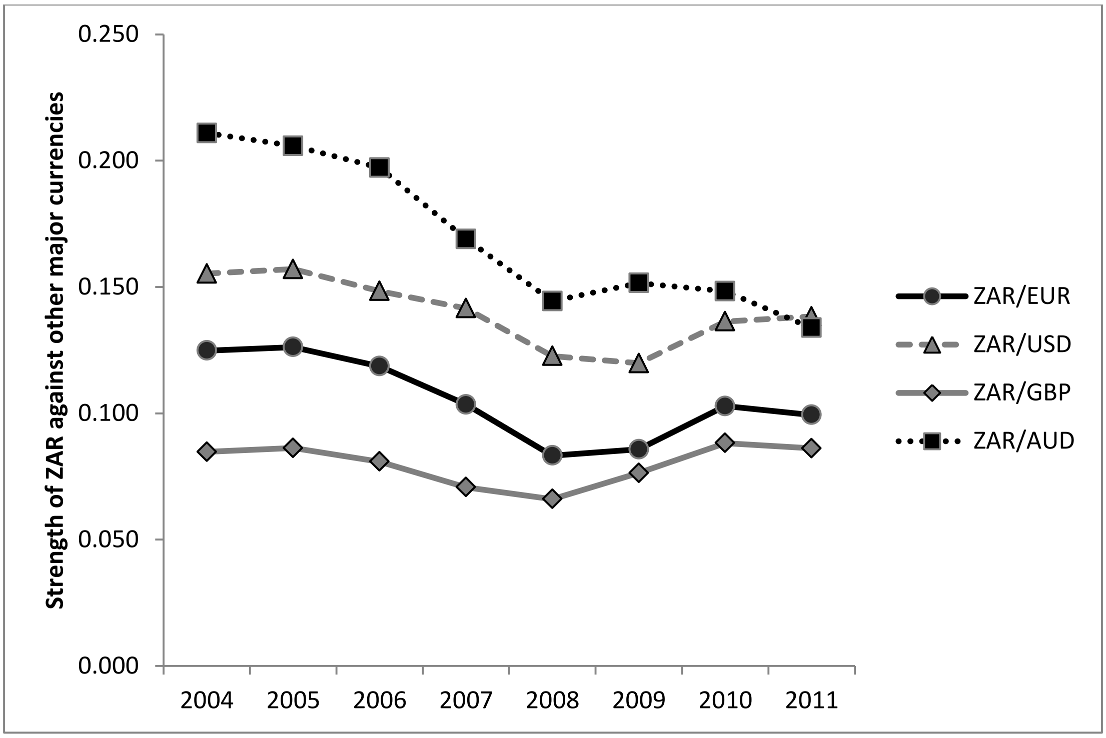

Figure A3.2: The strength of the South African Rand (ZAR) in relation to other major international currencies, the Euro (EUR), the US Dollar (USD), the Great British Pound (GBP) and the Australian Dollar (AUD), for the period 2004 to end 2011, obtained from Oanda.com. Note that these are the reference exchange rates for the export analyses.

Appendix 3 continued.

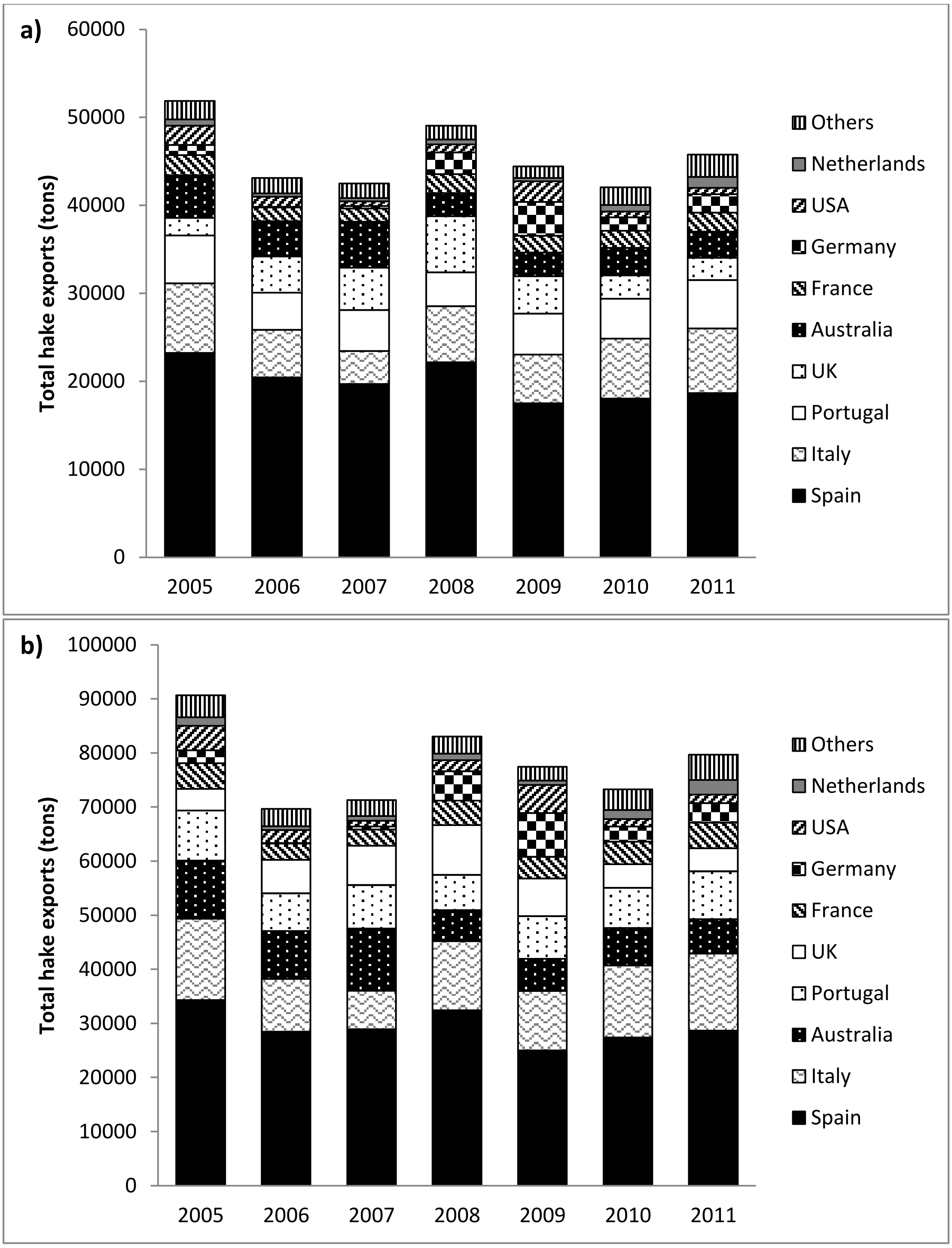

Figure A3.3: Total annual exports of hake from South Africa broken down by major importing country, as extracted from SARS (South African Revenue Service) export data in TradeMap. In a) values represent actual export quantities of fish, but in b) they represent whole-mass equivalents that have been calculated. Only countries purchasing more than an average of 500 tons of actual annual exports from South Africa are represented. Exports to all countries worldwide that individually purchase less than 500 tons are aggregated as "Others". Whole-mass equivalent quantities of hake were estimated using conversions factors for each export code for each of the countries, as described in Chapter 3.

Appendix 3 continued.

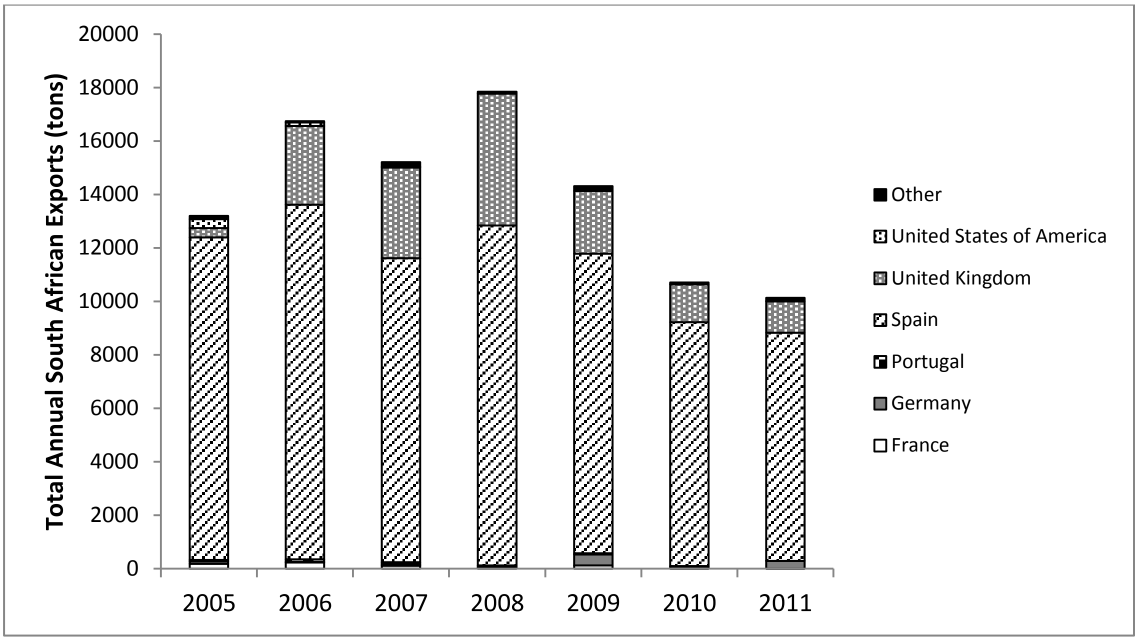

Figure A3.4: Total annual exports of fish, primarily hake, exported under the *030269* (fresh, whole fish) HS export code from South Africa broken down by major importing country, as extracted from SARS (South African Revenue Service) export data in TradeMap (http://www.trademap.org/). Only countries purchasing large quantities of exports of hake from South Africa are represented. Exports to all other countries worldwide are aggregated as "Other". For a detailed description of the HS codes see Table 3.1.

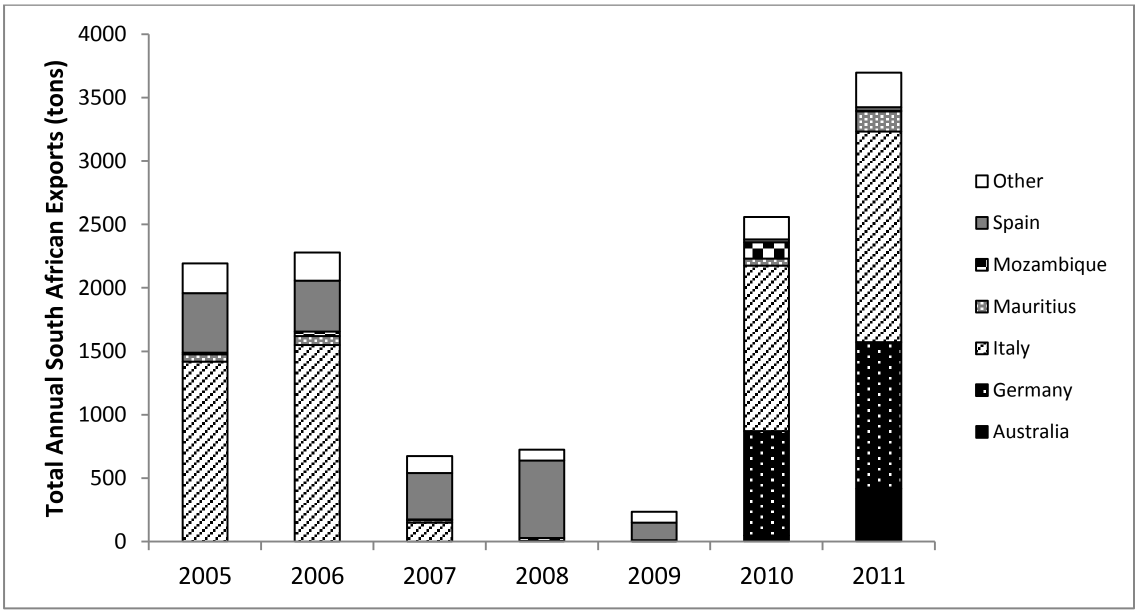

Figure A3.5: Total annual exports of fish, primarily hake, exported under the 160419 (prepared fish) HS export code from South Africa broken down by major importing country, as extracted from SARS (South African Revenue Service) export data in TradeMap (http://www.trademap.org/). Only countries purchasing large quantities of exports of hake from South Africa are represented. Exports to all other countries worldwide are aggregated as "Other". For a detailed description of the HS codes see Table 3.1.

Appendix 3 continued.

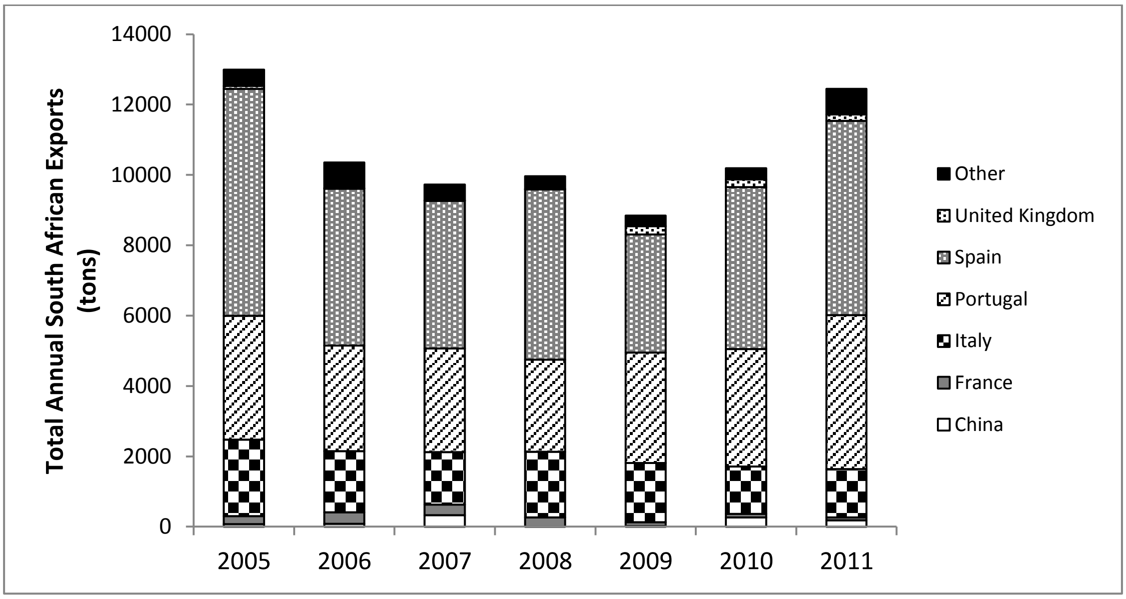

Figure A3.6: Total annual exports of fish, primarily hake, exported under the 030378 (whole, frozen fish) HS export code from South Africa broken down by major importing country, as extracted from SARS (South African Revenue Service) export data in TradeMap (http://www.trademap.org/). Only countries purchasing large quantities of exports of hake from South Africa are represented. Exports to all other countries worldwide are aggregated as "Other". For a detailed description of the HS codes see Table 3.1.

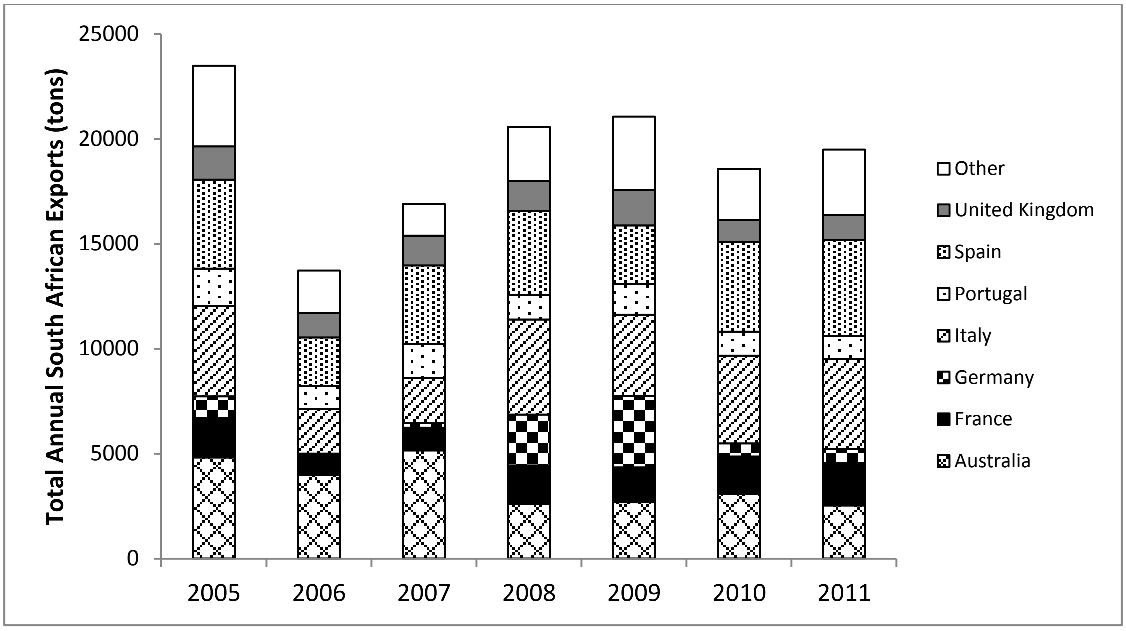

Figure A3.7: Total annual exports of fish, primarily hake, exported under the 030420, 030429 and 030499 (fish fillets) HS export codes (combined) from South Africa broken down by major importing country, as extracted from SARS (South African Revenue Service) export data in TradeMap (http://www.trademap.org/). Only countries purchasing large quantities of exports of hake from South Africa are represented. Exports to all other countries worldwide are aggregated as "Other". For a detailed description of the HS codes see Table 3.1.

Appendix 3 continued.

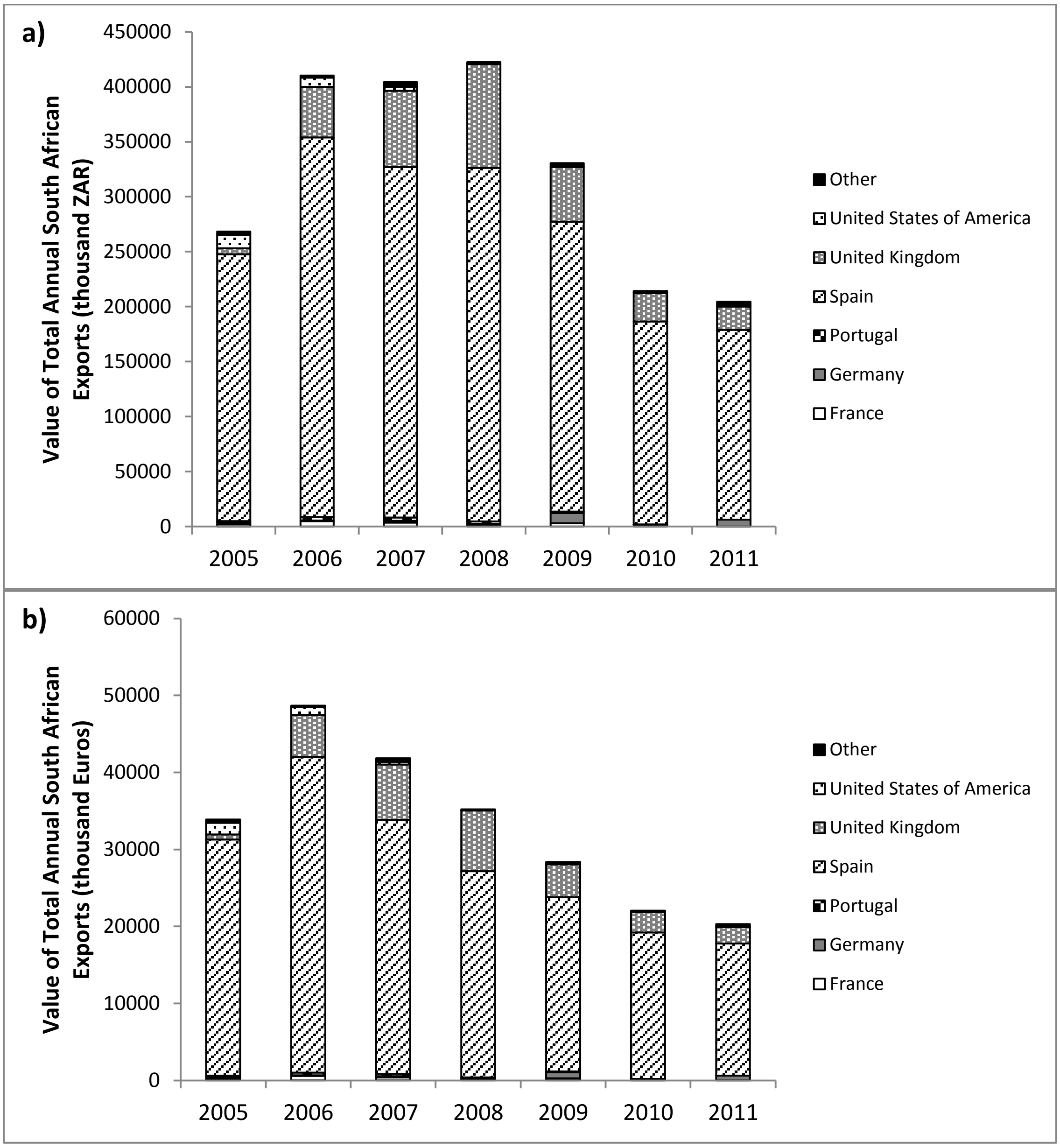

Figure A3.8: Total annual export values of fish, primarily hake, exported under the 030269 (fresh, whole fish) HS export code from South Africa broken down by major importing country, as extracted from SARS (South African Revenue Service) export data in TradeMap (http://www.trademap.org/). Export values are given in a) thousand ZAR and b) thousand Euros. Only countries purchasing large quantities of exports of hake from South Africa are represented. Export values for all other countries worldwide are aggregated as "Other". For a detailed description of the HS codes see Table 3.1.

Appendix 3 continued.

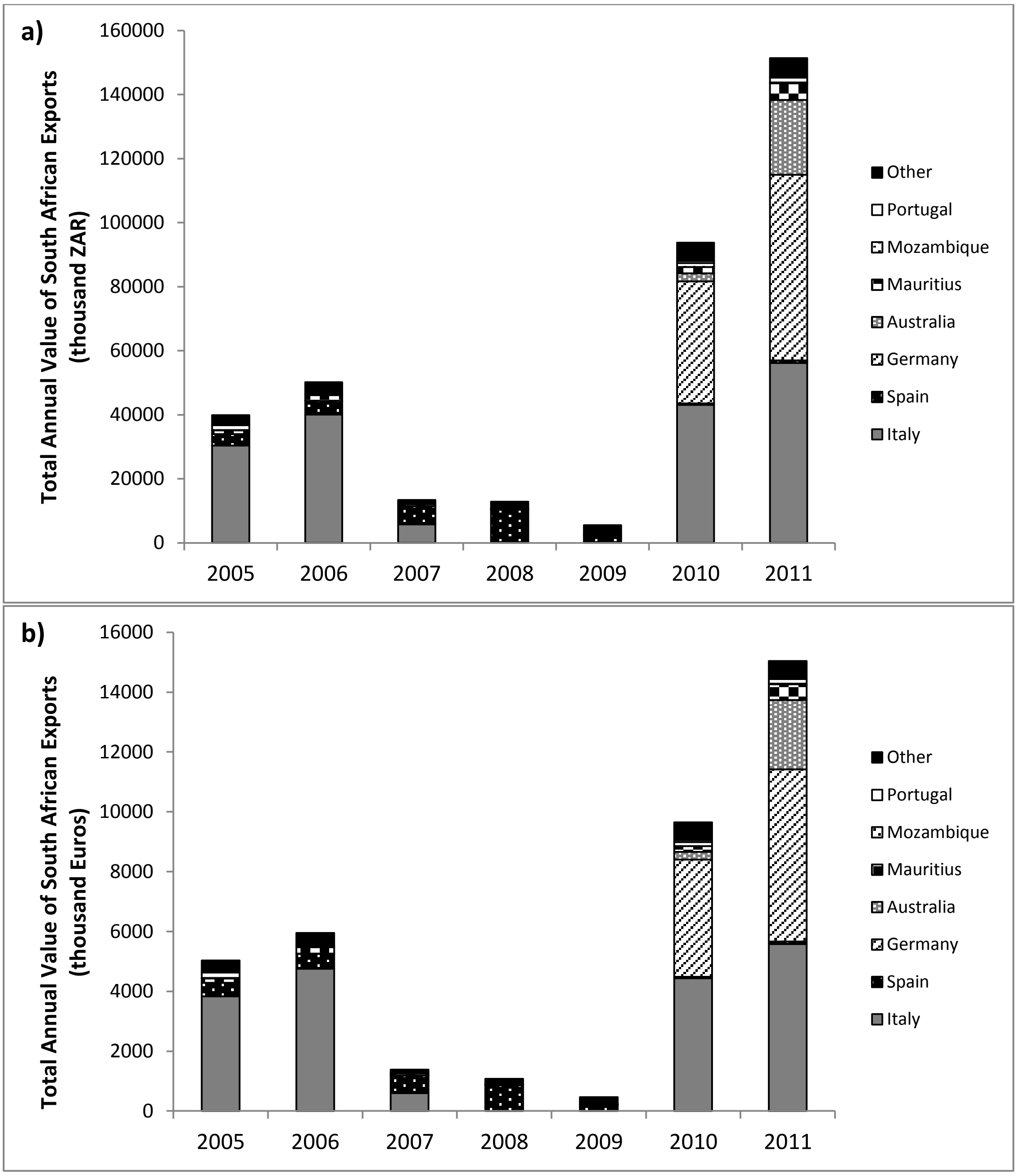

Figure A3.9: Total annual export values of fish, primarily hake, exported under the 160419 (prepared fish) HS export code from South Africa broken down by major importing country, as extracted from SARS (South African Revenue Service) export data in TradeMap (http://www.trademap.org/). Export values are given in a) thousand ZAR and b) thousand Euros. Only countries purchasing large quantities of exports of hake from South Africa are represented. Export values for all other countries worldwide are aggregated as "Other". For a detailed description of the HS codes see Table 3.1.

Appendix 3 continued.

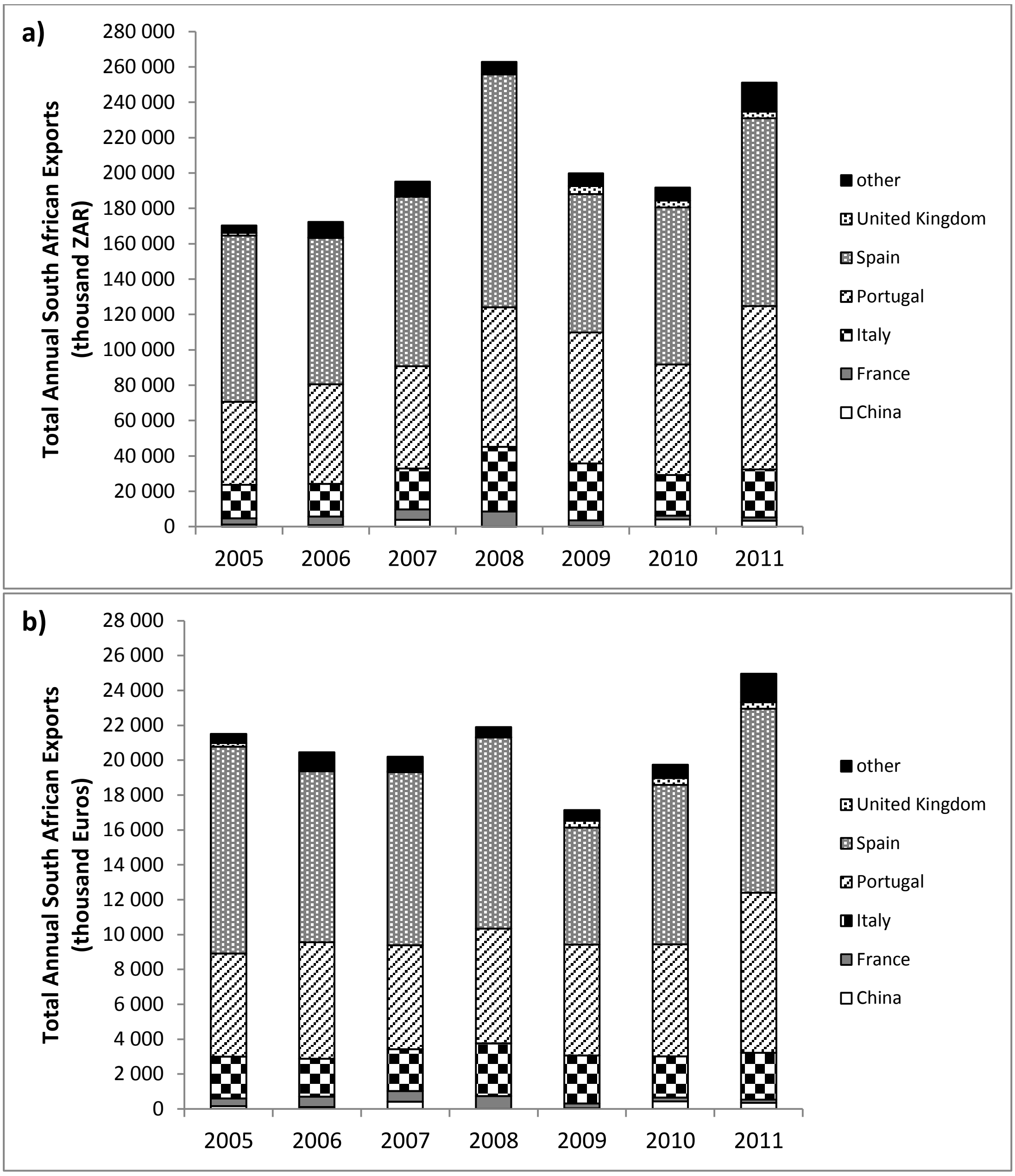

Figure A3.10: Total annual export values of fish, primarily hake, exported under the 030378 (whole, frozen fish) HS export code from South Africa broken down by major importing country, as extracted from SARS (South African Revenue Service) export data in TradeMap (http://www.trademap.org/). Export values are given in a) thousand ZAR and b) thousand Euros. Only countries purchasing large quantities of exports of hake from South Africa are represented. Export values for all other countries worldwide are aggregated as "Other". For a detailed description of the HS codes see Table 3.1.

Appendix 3 continued.

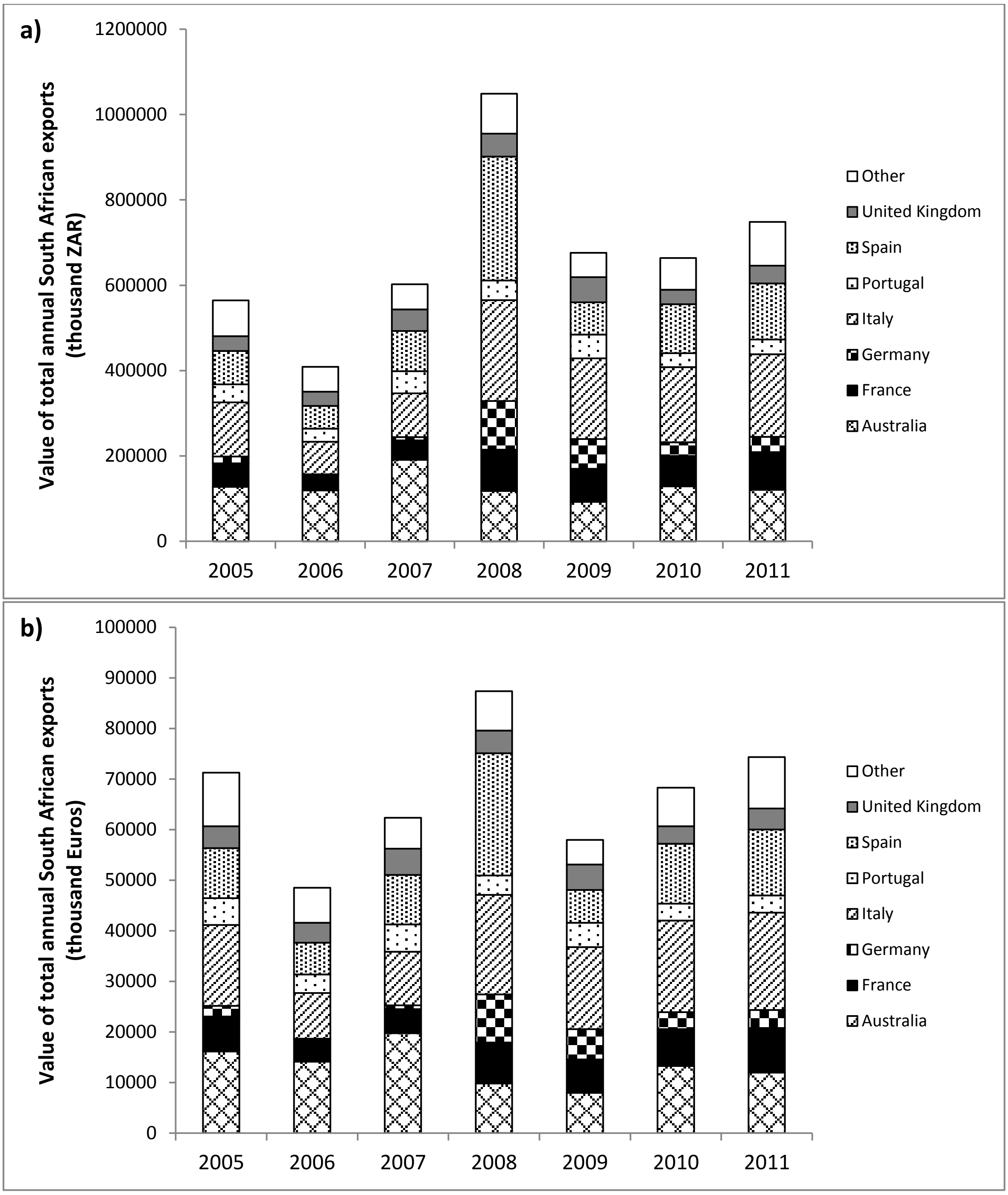

Figure A3.11: Total annual export values of fish, primarily hake, exported under the 030420, 030429 and 030499 (fish fillets) HS export codes (combined) from South Africa broken down by major importing country, as extracted from SARS (South African Revenue Service) export data in TradeMap (http://www.trademap.org/). Export values are given in a) thousand ZAR and b) thousand Euros. Only countries purchasing large quantities of exports of hake from South Africa are represented. Export values for all other countries worldwide are aggregated as "Other". For a detailed description of the HS codes see Table 3.1.

Appendix 3 continued.

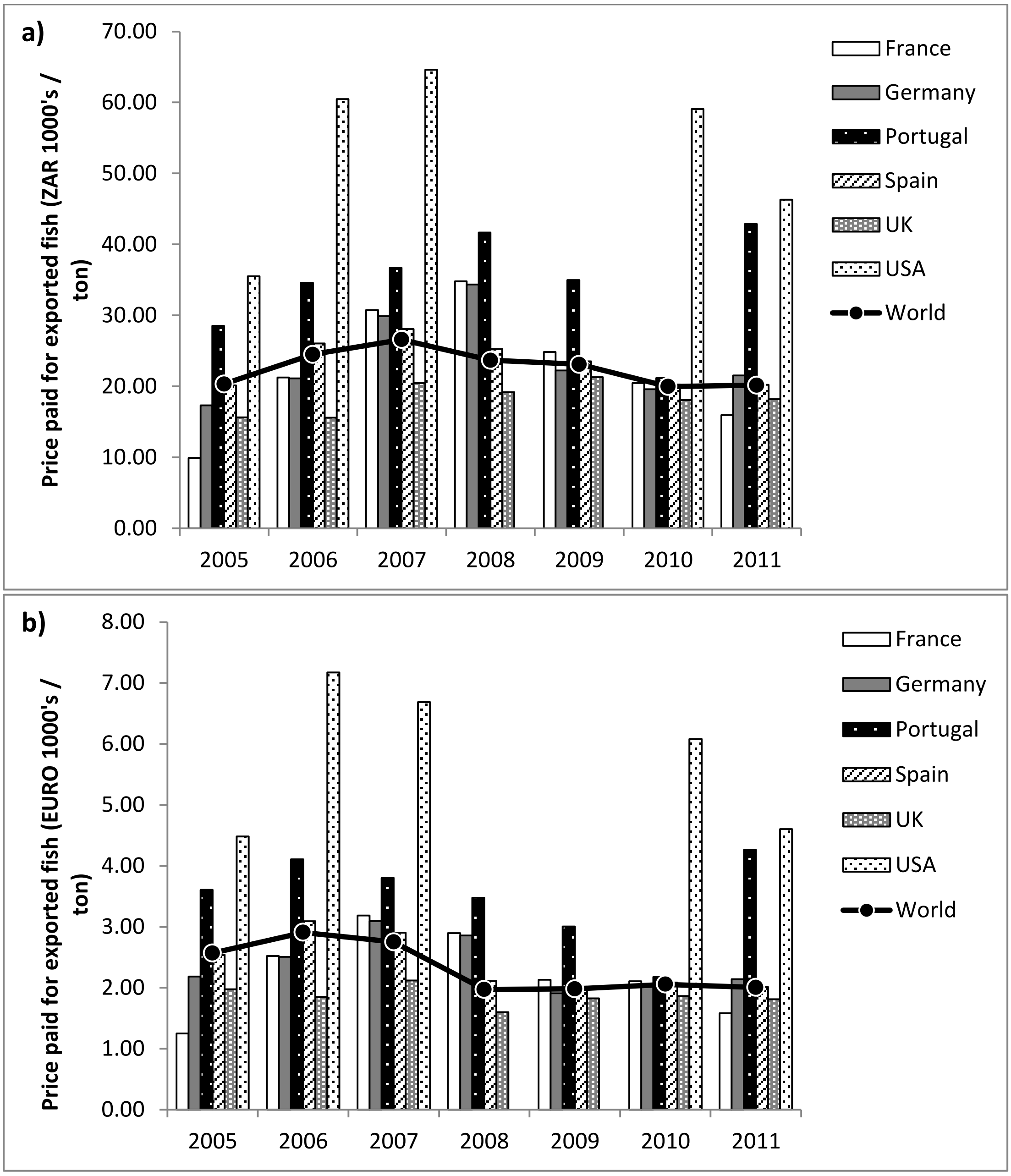

Figure A3.12: Total annual export price paid per ton of fish, primarily hake, exported under the 030269 (fresh, whole fish) HS export code from South Africa for major importing country and the world average, as extracted from SARS (South African Revenue Service) export data in TradeMap (http://www.trademap.org). Export prices paid per ton of fish exported are given in a) thousand ZAR and b) thousand Euros per ton. Only countries purchasing large quantities of exports of hake from South Africa are represented. For a detailed description of the HS codes see Table 3.1.

Appendix 3 continued.

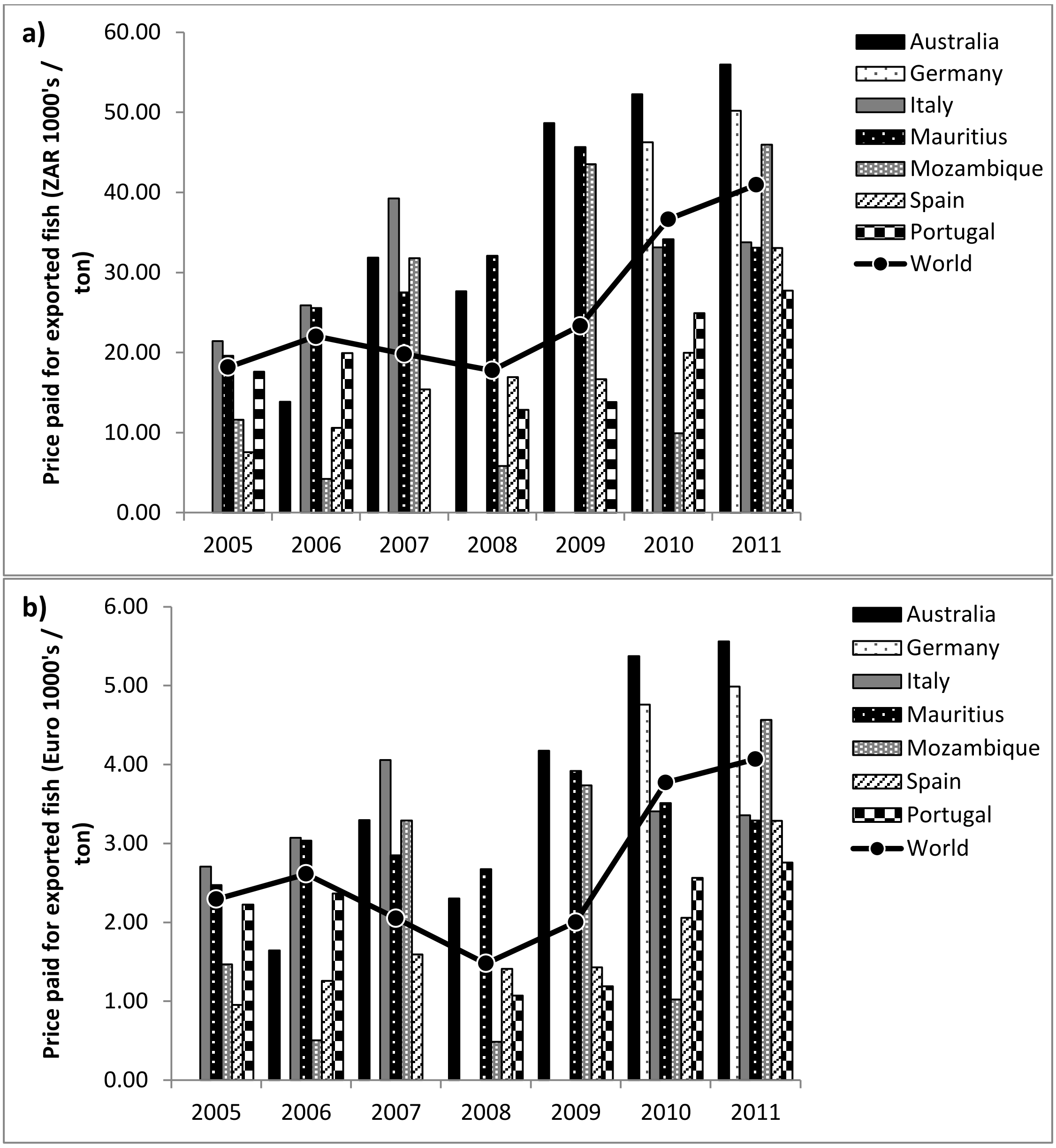

Figure A3.13: Total annual export price paid per ton of fish, primarily hake, exported under the 160419 (prepared fish) HS export code from South Africa for major importing country and the world average, as extracted from SARS (South African Revenue Service) export data in TradeMap (http://www.trademap.org). Export prices paid per ton of fish exported are given in a) thousand ZAR and b) thousand Euros per ton. Only countries purchasing large quantities of exports of hake from South Africa are represented. For a detailed description of the HS codes see Table 3.1.

Appendix 3 continued.

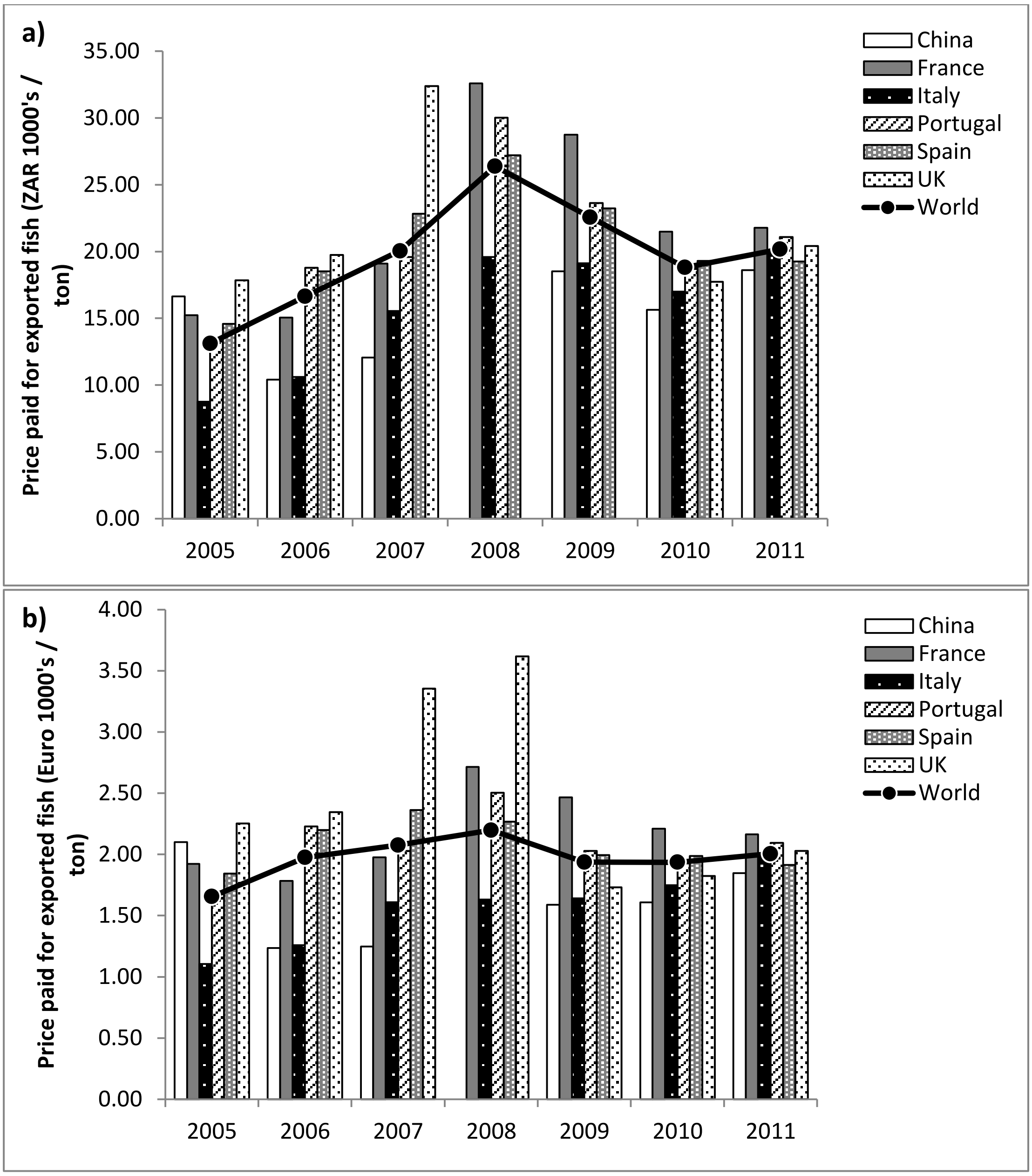

Figure A3.14: Total annual export price paid per ton of fish, primarily hake, exported under the 030378 (whole, frozen fish) HS export code from South Africa for major importing country and the world average, as extracted from SARS (South African Revenue Service) export data in TradeMap (http://www.trademap.org). Export prices paid per ton of fish exported are given in a) thousand ZAR and b) thousand Euros per ton. Only countries purchasing large quantities of exports of hake from South Africa are represented. For a detailed description of the HS codes see Table 3.1.

Appendix 3 continued.

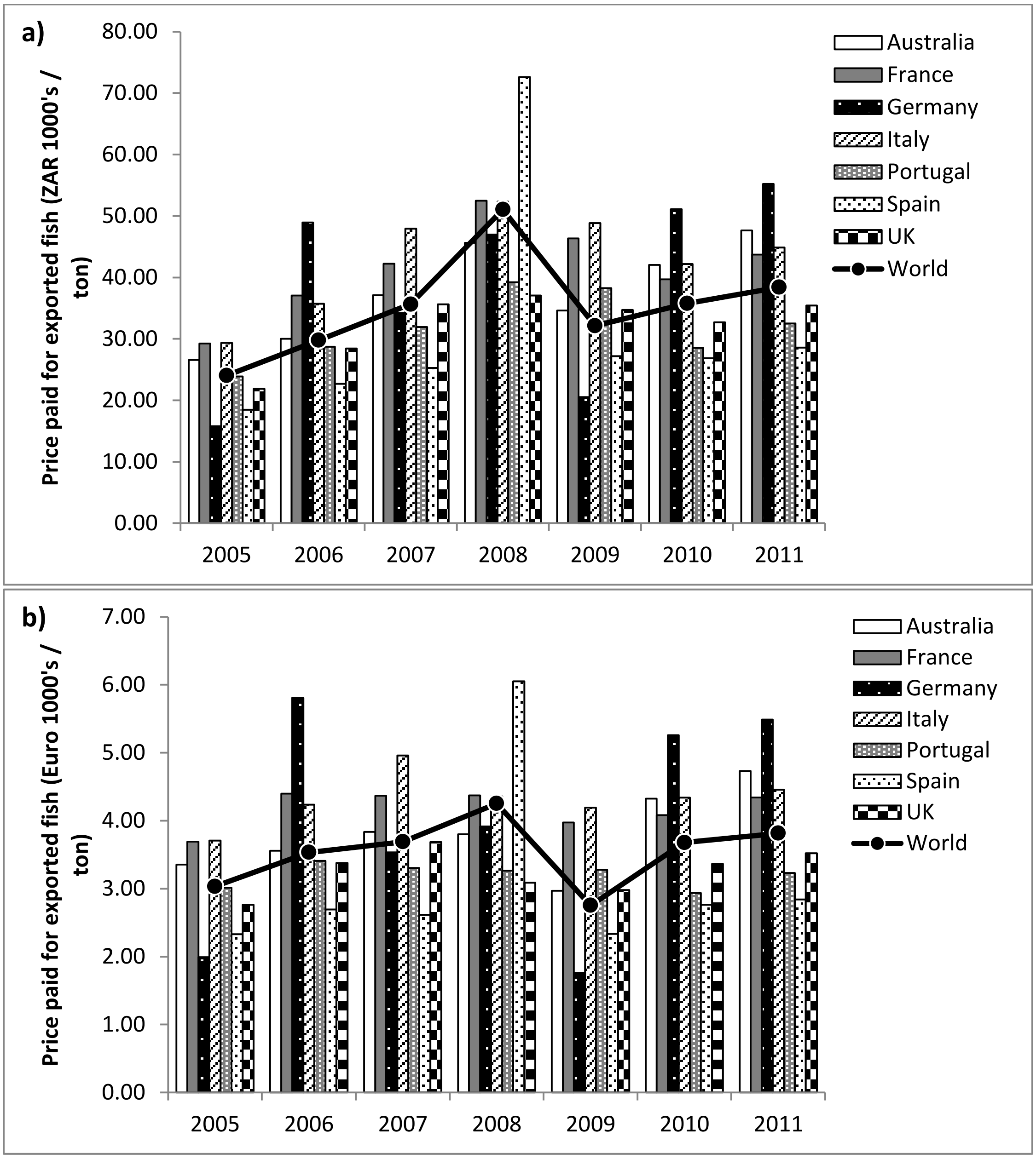

Figure A3.15: Total annual export price paid per ton of fish, primarily hake, exported under the 030420, 030429 and 030499 (fish fillets) HS export codes (combined) from South Africa for major importing country and the world average, as extracted from SARS (South African Revenue Service) export data in TradeMap (http://www.trademap.org). Export prices paid per ton of fish exported are given in a) thousand ZAR and b) thousand Euros per ton. Only countries purchasing large quantities of exports of hake from South Africa are represented. For a detailed description of the HS codes see Table 3.1.

Appendix 3 continued.

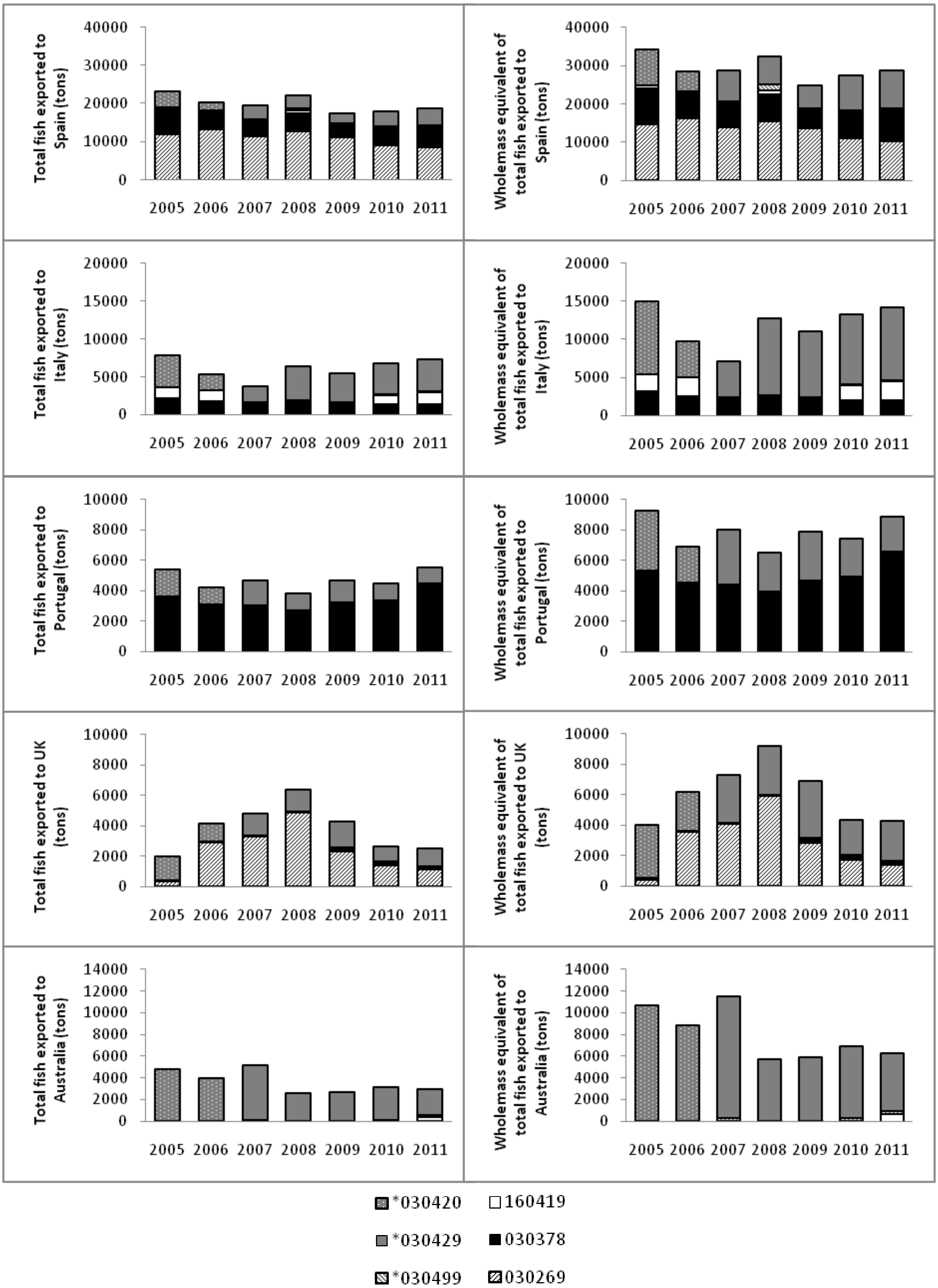

Figure A3.16: Total annual exports of hake from South Africa to the major exporting countries, as identified in respective axis titles. Note that figures to the left are actual export quantities and figures to the right are whole-mass equivalent quantities of hake exports. Scales differ between countries.

Appendix 3 continued.

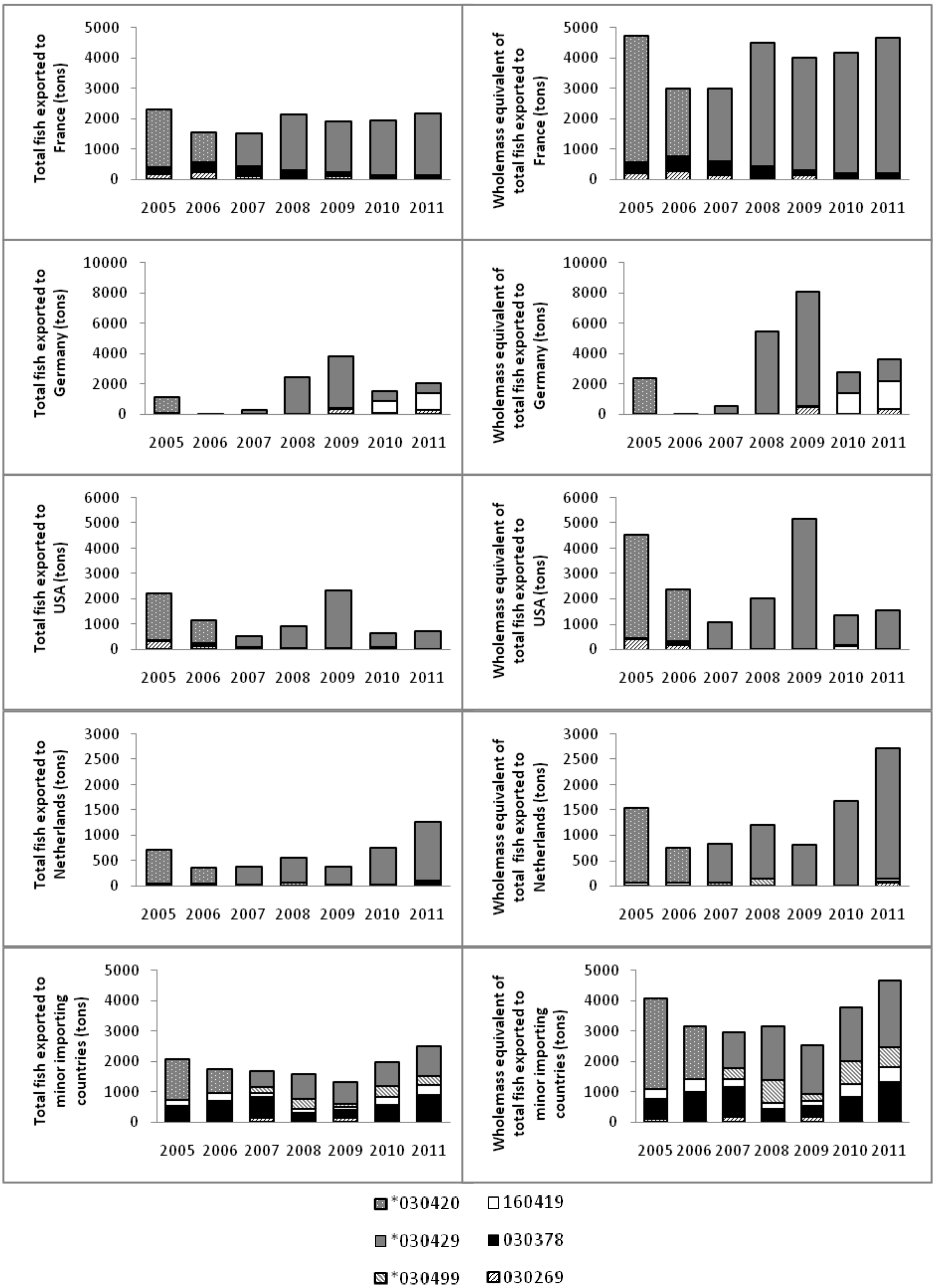

Figure A3.16 continued: Exports to all countries worldwide that individually purchase less than 500 tons are aggregated as "minor importing countries”. Whole-mass equivalent quantities of hake were estimated using conversions factors for each export code, as described in Chapter 3. Export data extracted from TradeMap.

Appendix 4: Model Inputs for Chapter 4

Table A4.1: The annual Total Allowable Catch (tonnes) for hake (*Merluccius capensis* and *M. paradoxus* combined) from 1978 until present, and the maximum, minimum and average for the period. Data kindly provided courtesy of Department of Agriculture, Forestry and Fisheries. The average for the period was rounded to 143 000 tons for use in the model inputs of Chapter 4 and subsequent chapters.

Year	Hake TAC	*Year*	Hake TAC
1978	103 000	***1996***	151 000
1979	147 500	***1997***	151 000
1980	155 700	***1998***	151 000
1981	154 500	***1999***	151 000
1982	136 000	***2000***	155 500
1983	120 000	***2001***	166 000
1984	128 000	***2002***	166 000
1985	130 500	***2003***	163 000
1986	138 500	***2004***	161 000
1987	141 000	***2005***	158 000
1988	139 900	***2006***	150 000
1989	138 500	***2007***	134 998
1990	138 500	***2008***	130 532
1991	141 004	***2009***	118 578
1992	145 000	***2010***	119 860
1993	147 000	***2011***	131 846
1994	148 000	***2012***	144 671
1995	151 000	***2013***	156 075
Max	166 000	***Min***	103 000
Ave	143 435		

Appendix 4 continued.

Table A4.2: The average, standard deviation, minimum and maximum total annual frozen and fresh hake exports and proportion fresh and frozen fish for the 2005 to 2011 period. These values are based on export data extracted from TradeMap (http://www.trademap.org/) and industry consultation as described in Chapter 3. They are used to inform the model inputs used in Chapter 4 and subsequent chapters.

		Total Annual Exports of Hake (tons)			
		Average	**SD**	**min**	**max**
Spain	***total annual export to***	19957.96	1975.67	17494.96	23226.77
	total frozen	8776.14	1680.22	6285.91	11160.46
	total fresh	11181.82	1768.31	8533.42	13262.35
	% fresh	56.04	6.55	45.73	64.86
	% frozen	43.96	6.55	35.14	54.27
Italy	***total annual export to***	6168.62	1287.19	3773.45	7911.53
	total frozen	6167.84	1390.06	3772.29	7911.53
	total fresh	0.77	1.60	0.00	4.26
	% fresh	0.01	0.02	0.00	0.06
	% frozen	99.99	0.02	99.94	100.00
Portugal	***total annual export to***	4685.17	558.82	3850.53	5510.18
	total frozen	4638.56	620.29	3795.84	5506.59
	total fresh	46.62	32.11	3.59	89.30
	% fresh	1.05	0.70	0.07	2.13
	% frozen	98.95	0.70	97.87	99.93
UK	***total annual export to***	3827.80	1418.87	2004.36	6374.47
	total frozen	1466.58	250.34	1192.69	1921.30
	total fresh	2361.22	1546.74	345.51	4928.21
	% fresh	55.73	18.89	17.24	77.31
	% frozen	44.27	18.89	22.69	82.76
Australia	***total annual export to***	3637.82	980.11	2615.29	5205.28
	total frozen	3637.80	1058.61	2615.29	5205.14
	total fresh	0.02	0.06	0.00	0.15
	% fresh	0.00	0.00	0.00	0.00
	% frozen	100.00	0.00	100.00	100.00
France	***total annual export to***	1931.88	276.64	1515.25	2292.83
	total frozen	1828.04	339.22	1339.24	2139.20
	total fresh	103.84	82.20	21.24	227.95
	% fresh	5.76	4.60	0.98	14.54
	% frozen	94.24	4.60	85.46	99.02
Germany	***total annual export to***	1624.29	1217.99	55.17	3837.25
	total frozen	1486.46	1207.09	24.60	3428.01
	total fresh	137.83	145.84	30.57	409.24
	% fresh	16.23	16.94	1.41	55.40
	% frozen	83.77	16.94	44.60	98.59
USA	***total annual export to***	1216.15	696.59	527.80	2345.33
	total frozen	1136.26	699.27	475.42	2345.33
	total fresh	79.89	124.96	0.00	339.95
	% fresh	5.90	5.94	0.00	15.43
	% frozen	94.10	5.94	84.57	100.00
Netherlands	***total annual export to***	632.17	299.98	357.13	1265.87
	total frozen	610.14	308.62	350.14	1198.97
	total fresh	22.04	22.24	0.00	66.90
	% fresh	3.46	2.39	0.00	8.11
	% frozen	96.54	2.39	91.89	100.00
Others	***total annual export to***	1841.03	359.88	1321.23	2508.08
	total frozen	1759.01	414.89	1174.02	2462.95
	total fresh	82.02	44.68	35.87	147.21
	% fresh	4.89	3.24	1.80	11.14
	% frozen	95.11	3.24	88.86	98.20
Domestic*	***total sales to***	15174.30	1224.58	14008.19	17281.01
	% fresh				
	% frozen	95.00			

** domestic figures are estimated on the basis of industry consultation*

Appendix 4 continued.

Table A4.3: Input values of Total Allowable Catch (TAC) that were used in the *sensitivity analysis* of Chapter 4. These inputs are based on the average of the TAC time series in South Africa that is given in Table A4.1

	TAC (tons)
-100%	0
-50%	71500
-30%	100100
-20%	114400
-10%	128700
standard run	**143000**
+10%	157300
+20%	171600
+30%	185900
+50%	214500
+100%	286000

Table A4.4 Input values of country demand for hake that were used in the *sensitivity analysis* of Chapter 4. These are based on average quantities of hake exports from South Africa that were purchased by countries given in Table A4.2. The domestic market size is based on estimates from industry consultation.

	Quantity of hake demanded (tons)										
	Domestic	**Spain**	**Italy**	**Portugal**	**UK**	**Australia**	**France**	**Germany**	**USA**	**ND**	**Other**
-100%	0	0	0	0	0	0	0	0	0	0	0
-50%	7587	9979	3085	2343	1914	1819	966	812	608	316	921
-30%	10622	13971	4318	3280	2680	2547	1352	1137	851	442	1289
-20%	12139	15966	4935	3748	3062	2910	1546	1299	973	506	1473
-10%	13657	17962	5552	4217	3445	3274	1739	1462	1094	569	1657
standard run	**15174**	**19958**	**6169**	**4685**	**3828**	**3638**	**1932**	**1624**	**1216**	**632**	**1841**
+10%	16691	21954	6786	5154	4211	4002	2125	1786	1338	695	2025
+20%	18209	23950	7403	5622	4594	4366	2318	1949	1459	758	2209
+30%	19726	25945	8020	6091	4976	4729	2512	2111	1581	822	2393
+50%	22761	29937	9254	7028	5742	5457	2898	2436	1824	948	2762
+100%	30348	39916	12338	9370	7656	7276	3864	3248	2432	1264	3682

Appendix 4 continued.

Table A4.5 Input values of the proportion of frozen fish that were used in the *sensitivity analysis* of Chapter 4. These were based on average quantities of fresh and frozen exports purchased by countries given in Table A4.2. Estimates for the South African domestic market were based on industry consultation.

	Domestic	Spain	Italy	Portugal	UK	Australia	France	Germany	USA	ND	Other
-100%	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-50%	0.475	0.220	0.500	0.495	0.221	0.500	0.471	0.419	0.471	0.483	0.476
-30%	0.665	0.308	0.700	0.693	0.310	0.700	0.660	0.586	0.659	0.676	0.666
-20%	0.760	0.352	0.800	0.792	0.354	0.800	0.754	0.670	0.753	0.772	0.761
-10%	0.855	0.396	0.900	0.891	0.398	0.900	0.848	0.754	0.847	0.869	0.856
standard run	**0.950**	**0.440**	**1.000**	**0.990**	**0.443**	**1.000**	**0.942**	**0.838**	**0.941**	**0.965**	**0.951**
10%		0.484			0.487		1.037	0.921			
20%		0.528			0.531		1.131				
30%		0.571			0.575		1.225				
50%		0.659			0.664		1.414				
100%		0.879			0.885		1.885				
max**	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

** the index varies from 0 - 1, meaning that not all % transformations of the inputs are possible. Impossible inputs are left blank and 1 is always the maximum

Appendix 4 continued.

Table A4.6 Input values of the processing efficiency of fresh and frozen hake of companies (i.e. the efficiency with which companies convert whole fish to final fish products) that were used in the *sensitivity analysis* of Chapter 4. These were based on average values reported by companies during the industry consultation described in Chapter 3.

	Frozen efficiency				**Fresh efficiency**			
	small	**medium**	**large**	**super-cluster**	**small**	**medium**	**large**	**super-cluster**
-100%	0	0	0	0		0	0	
-50%	0.34	0.41	0.41	0.34		0.26	0.265	
-30%	0.476	0.574	0.574	0.476		0.364	0.371	
-20%	0.544	0.656	0.656	0.544		0.416	0.424	
-10%	0.612	0.738	0.738	0.612		0.468	0.477	
standard run	**0.68**	**0.82**	**0.82**	**0.68**	**0**	**0.52**	**0.53**	**0**
10%	0.748	0.902	0.902	0.748	0.1	0.572	0.583	0.1
20%	0.816	0.984	0.984	0.816	0.2	0.624	0.636	0.2
30%	0.884			0.884	0.3	0.676	0.689	0.3
50%					0.5	0.78	0.795	0.5
100%					1			1
max**	1	1	1	1	1	1	1	1

** the index varies from 0 - 1, meaning that not all % transformations of the inputs are possible. Impossible inputs are left blank and 1 is always the maximum

Table A4.7 Input values of the quota (i.e. the proportion of rights where 1 is 100% of the TAC) for different sized company agents that were used in the *sensitivity analysis* of Chapter 4 and subsequent chapters. These were based on the aggregated values of % rights held by the small, medium (med), large and super-cluster types described in Chapter 2 which are given as the standard run.

	small	**med**	**large**	**super-cluster**
standard run	**0.031**	**0.225**	**0.529**	**0.059**
small variations	0.000	0.235	0.539	0.069
	0.500	0.167	0.167	0.167
	1.000	0.000	0.000	0.000
medium variations	0.106	0.000	0.604	0.134
	0.167	0.500	0.167	0.167
	0.000	1.000	0.000	0.000
large variations	0.207	0.401	0.000	0.235
	0.167	0.167	0.500	0.167
	0.000	0.000	1.000	0.000
SC variations	0.051	0.245	0.549	0.000
	0.167	0.167	0.167	0.500
	0.000	0.000	0.000	1.000

Appendix 4 continued.

Table A4.8: Input values of the proportion of frozen hake exported to Spain that were used in the *scenarios* tested with the model, as described in Chapter 4. These were based on quantities of fresh and frozen hake exported from South Africa to that are summarized in Table A4.2.

		proportion of frozen fish			
inputs from year 0 to 10	year from which real data taken	Real limits*	realistic Spain*	hypothetical all fresh to all frozen	hypothetical all frozen to all fresh*
0		0.351	0.480	0.000	1.000
1		0.351	0.480	0.100	0.900
2	2005	0.375	0.480	0.200	0.800
3	2006	0.400	0.351	0.300	0.700
4	2007	0.425	0.422	0.400	0.600
5	2008	0.450	0.426	0.500	0.500
6	2009	0.475	0.359	0.600	0.400
7	2010	0.500	0.494	0.700	0.300
8	2011	0.543	0.543	0.800	0.200
9		0.543	0.543	0.900	0.100
10		0.543	0.543	1.000	0.000

*these scenarios are played out by simply changing the input files

Table A4.9: Input values of Spain's 'demand' for hake that were used in the *scenarios* tested with the model, as described in Chapter 4. These were based on the export quantities of South African hake to Spain that are summarized in Table A4.2.

inputs from year 0 to 10	year from which real data taken	Spain demand realistic decrease	Spain demand realistic increase	Spain hypothetical demand decrease	Spain hypothetical demand increase	Spain real demand change
0		23227	17495	39916	0	23227
1		22654	18068	35924	3992	23227
2	2005	22080	18641	31933	7983	23227
3	2006	21507	19215	27941	11975	20447
4	2007	20934	19788	23950	15966	19679
5	2008	20361	20361	19958	19958	22164
6	2009	19788	20934	15966	23950	17495
7	2010	19215	21507	11975	27941	18032
8	2011	18641	22080	7983	31933	18662
9		18068	22654	3992	35924	18662
10		17495	23227	0	39916	18662

*these scenarios are played out by simply changing the input files

Appendix 4 continued.

Table A4.10: Input values of Total Allowable Catch (TAC) of hake that were used in the *scenarios* tested with the model, as described in Chapter 4. These were based on the time series of South African hake TAC described in Table A4.1.

inputs from year 0 to 10	year from which real data taken	hypothetical TAC increase	hypothetical TAC decrease	real TAC changes	TAC realistic increase	TAC realistic decrease
0	2003	0	286000	163000	103000	166000
1	2004	28600	257400	161000	109300	159700
2	2005	57200	228800	158000	115600	153400
3	2006	85800	200200	150000	121900	147100
4	2007	114400	171600	134998	128200	140800
5	2008	143000	143000	130532	134500	134500
6	2009	171600	114400	118578	140800	128200
7	2010	200200	85800	119860	147100	121900
8	2011	228800	57200	131846	153400	115600
9	2012	257400	28600	144671	159700	109300
10		286000	0	130000	166000	103000

Appendix 5: Model Inputs for Chapter 5.

Table A5.1: Nominal Catch per Unit Effort (CPUE) time series from 1978 to 2012, courtesy of Department of Agriculture, Forestry and Fisheries, and a transformed unitless scale that was produced for input to the model. Transformed values were computed, by averaging the two hake species CPUE, determining the maximum of the species average nominal CPUE (57.378 tons/month) and using a maximum just above this value (60 tons/month) as the maximum possible CPUE which would be equivalent to 1 on the transformed scale. For Chapter 5 and subsequent chapters the final transformed CPUE time-series is used for model reality testing and the average value is used for standard runs in the sensitivity analysis.

	Nominal CPUE (tons/month)			**transformed CPUE (unitless)**
Year	***M. paradoxus***	***M. capensis***	***M. spp* average**	***M. spp* average**
1978	29.346	36.792	33.069	0.551
1979	28.908	64.824	46.866	0.781
1980	28.908	50.808	39.858	0.664
1981	28.032	52.560	40.296	0.672
1982	27.594	55.626	41.610	0.694
1983	31.098	58.254	44.676	0.745
1984	33.726	66.576	50.151	0.836
1985	37.668	77.088	57.378	0.956
1986	38.982	58.692	48.837	0.814
1987	35.916	47.742	41.829	0.697
1988	38.106	59.568	48.837	0.814
1989	38.106	68.328	53.217	0.887
1990	46.428	53.436	49.932	0.832
1991	49.494	60.882	55.188	0.920
1992	53.436	49.056	51.246	0.854
1993	60.882	34.164	47.523	0.792
1994	65.262	38.982	52.122	0.869
1995	56.064	46.866	51.465	0.858
1996	67.890	30.222	49.056	0.818
1997	57.816	25.404	41.610	0.694
1998	60.444	34.602	47.523	0.792
1999	57.816	44.676	51.246	0.854
2000	41.610	63.510	52.560	0.876
2001	37.668	46.866	42.267	0.704
2002	35.040	23.214	29.127	0.485
2003	39.858	24.528	32.193	0.537
2004	32.412	25.404	28.908	0.482
2005	30.660	14.454	22.557	0.376
2006	32.412	20.148	26.280	0.438
2007	38.106	24.090	31.098	0.518
2008	42.924	20.148	31.536	0.526
2009	49.494	29.784	39.639	0.661
2010	60.882	35.478	48.180	0.803
2011	59.130	43.800	51.465	0.858
2012	51.246	28.908	40.077	0.668
min	***27.594***	***14.454***	***22.557***	***0.376***
max	***67.890***	***77.088***	***57.378***	***0.956***
average	***43.525***	***43.299***	***43.412***	***0.724***

Appendix 5 continued.

Table A5.2: Inputs of Total Allowable Catch (TAC) and country (market) demand used in the *sensitivity analysis* of Chapter 5 are shown in black. TAC and demand are based on the values in Table A4.1 and A4.2, respectively.

	TAC	Domestic	Spain	Other
-100%	0	0	0	0
-50%	71500	7587	9979	920.5
standard run	**143000**	**15174**	**19958**	**1841**
+50%	214500	22761	29937	2762
+100%	286000	30348	39916	3682

Table A5.3: Inputs of the processing efficiency of companies for fresh and frozen hake, and the proportion frozen hake demanded by companies that were used in the *sensitivity analysis* of Chapter 5 are shown in black. These are based on the values of Table A4.2.

	proportion frozen			**frozen efficiency**				**fresh efficiency**			
	Domestic	**Spain**	**Other**	**small**	**medium**	**large**	**super-cluster**	**small**	**medium**	**large**	**super-cluster**
-100%	0	0	0	0	0	0	0		0	0	
-50%	0.475	0.2198	0.476	0.34	0.41	0.41	0.34		0.26	0.265	
standard run	**0.95**	**0.4396**	**0.951**	**0.68**	**0.82**	**0.82**	**0.68**	**0**	**0.52**	**0.53**	**0**
50%		0.6594						0.5	0.78	0.795	0.5
100%		0.8792						1			1
max**	1	1	1	1	1	1	1	1	1	1	1

** the index varies from 0 - 1, meaning that not all % transformations of the inputs are possible. Impossible inputs are left blank and 1 is always the maximum

Appendix 5 continued.

Table A5.4: Input values of the quota (i.e. the proportion of rights where 1 is 100% of the TAC) for different sized company agents that were used in the *sensitivity analysis* of Chapter 5 are shown in black. These were based on the aggregated values of % rights held by the small, medium (med), large and super-cluster types described in Chapter 2 which are given as the standard run.

	small	med	large	super-cluster
standard run	**0.031**	**0.225**	**0.529**	**0.059**
small variations	**0.000**	0.235	0.539	0.069
	0.500	0.167	0.167	0.167
	1.000	0.000	0.000	0.000
medium variations	0.106	**0.000**	0.604	0.134
	0.167	0.500	0.167	0.167
	0.000	**1.000**	0.000	0.000
large variations	0.207	0.401	**0.000**	0.235
	0.167	0.167	0.500	0.167
	0.000	0.000	**1.000**	0.000
SC variations	0.051	0.245	0.549	**0.000**
	0.167	0.167	0.167	0.500
	0.000	0.000	0.000	**1.000**

Table A5.5: Inputs of the numbers of factory freezer, freezer stern trawlers and wet-fish stern trawlers that were used for *sensitivity analysis* of Chapter 5 and subsequent chapters. Values shown in black were those used in Chapter 5. Values used in the standard run are representative of vessel numbers quantified during the industry consultation and data collection phases of Chapters 2 and 3.

	small			**medium**			**large**			**super-cluster**		
	factory freezers	**freezer trawlers**	**wet-fish**	**factory freezers**	**freezer trawlers**	**wet-fish**	**factory freezers**	**freezer trawlers**	**wet-fish**	**factory freezers**	**freezer trawlers**	**wet-fish**
100%**	2	2	2	6	28	10	6	6	32	2	6	2
50%	2	2	2	5	21	8	5	5	24	2	5	2
Standard run	1	1	1	3	14	5	3	3	16	1	3	1
-50%	1	1	1	2	7	3	2	2	8	1	2	1
-100%	0	0	0	0	0	0	0	0	0	0	0	0

** all values rounded to the nearest integer as fractional vessels are not possible

Appendix 5 continued.

Table A5.6: Inputs of Catch per Unit Effort (CPUE) and stochasticity of catching fish that were used for the *sensitivity analysis* in Chapter 5 and subsequent chapters. Those shown in black were used in Chapter 5. CPUE values are based on the average of the transformed time series in table A5.1 and stochasticity values are based on the use of an intermediate value in the standard run.

	CPUE	stochasticity
-100%	0.00	0.00
-50%	0.36	0.25
-30%	0.51	0.35
-20%	0.58	0.40
-10%	0.65	0.45
standard run	**0.724**	**0.500**
+10%	0.80	0.55
+20%	0.87	0.60
+30%	0.94	0.65
+38.21%*	1.00	1.00

*stochasticity is +100%

Appendix 6: Model Inputs for Chapter 6.

Table A6.1: Average monthly fuel price of Diesel (500ppm and 10 000 ppm Sulphur) for the years 2000-2012, based on data courtesy of members of the offshore demersal trawl industry in South Africa. Fuel price has been aggregated, averaged and presented with fewer decimal places here to avoid publicizing confidential data.

	nett fuel cost (South African Rands)			
year	**Average**	**max**	**min**	**Std Dev**
2000	2.00	2.42	1.57	0.35
2001	2.06	2.15	1.98	0.07
2002	2.35	2.68	2.14	0.17
2003	2.13	2.59	1.66	0.29
2004	2.41	3.03	1.93	0.33
2005	3.19	3.71	2.29	0.52
2006	3.99	4.73	3.38	0.45
2007	4.36	5.33	3.61	0.53
2008	7.31	9.39	5.34	1.39
2009	4.27	4.56	3.99	0.21
2010	4.78	5.16	4.42	0.21
2011	6.42	7.61	5.18	0.65
2012	7.58	8.24	6.91	0.40
entire period	4.11	9.39	1.57	1.97

Table A6.2: Average annual EUR/ZAR exchange rates based on monthly mid-point foreign exchange rate data from oanda.com for the 2003 to 2014 period.

		EUR/ZAR Exchange rate		
Year	**Average**	**Minumum**	**Maximum**	**Std Dev**
2003	8.53	7.87	9.21	0.45
2004	8.00	7.51	8.73	0.35
2005	7.91	7.55	8.20	0.16
2006	8.51	7.30	9.64	0.91
2007	9.65	9.34	9.97	0.20
2008	12.05	10.24	13.43	0.86
2009	11.69	10.94	13.15	0.82
2010	9.72	9.04	10.65	0.48
2011	10.08	9.22	11.05	0.57
2012	10.55	10.03	11.32	0.47
2013	12.81	11.64	14.19	0.88
2014	14.43	13.83	15.02	0.36
entire period	10.30	7.30	15.02	2.04

Appendix 6 continued.

Table A6.3: Value in Euros paid for every ton of *fresh* hake exported from South Africa to major importing countries. Values presented for fresh hake for the time series 2005-2011 are based on the analysis of export data extracted from TradeMap (www.trademap.org) that is described in Chapter 3.

	Value by weight of fresh hake exports (Euros/ton)							
Importers	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**Average**
World	2572.20	2880.04	2754.44	1965.00	1977.33	2056.60	2001.41	2315.29
Australia	0.00	0.00	5073.08	0.00	0.00	0.00	0.00	5073.08
France	1254.36	2499.67	3187.73	2887.36	2124.62	2106.56	1582.21	2234.64
Germany	2189.97	2481.36	3097.58	2849.13	1904.24	2015.61	2136.96	2382.12
Italy	0.00	0.00	3161.63	0.00	0.00	0.00	7968.04	5564.84
Netherlands	2968.37	1985.12	3273.39	2513.62	2184.04	0.00	1591.49	2419.34
Portugal	3609.63	4066.99	3804.15	3458.78	2993.94	2177.37	4252.74	3480.52
Spain	2544.96	3060.30	2905.73	2097.48	2011.27	2082.99	2006.21	2386.99
United Kingdom	1977.71	1832.77	2121.42	1590.95	1821.52	1860.60	1805.15	1858.59
USA	4488.84	7104.98	6692.71	0.00	0.00	6077.02	4593.75	5791.46
Other countries	3872.41	5823.17	3164.36	2261.04	1590.23	2126.51	4277.90	3302.23

Table A6.4: Value in Euros paid for every ton of *frozen* hake exported from South Africa to major importing countries. Values presented for frozen hake for the time series 2005-2011 are based on the analysis of export data extracted from TradeMap (www.trademap.org) that is described in Chapter 3. Frozen hake quantities are calculated as the sum of all fish exported under HS export codes that represented frozen hake (i.e. 0304--, 030378 and 160419), weighted according to the proportional contribution of each code to total world frozen exports. Details on product types and hake exports can be found in Table 3.1, Chapter 3 and Appendix 3.

	Value by weight of frozen hake exports (Euros/ton)							
Importers	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**Average**
World	1784.3	2134.9	2224.1	2265.4	1989.3	2379.8	2526.4	**2186.3**
Australia	2474.2	3220.7	2579.4	3179.8	3004.8	4930.6	5039.6	**3489.9**
France	2108.9	2109.4	2082.0	2629.9	2504.0	2461.8	2543.8	**2348.5**
Germany	52.3	261.7	324.0	231.9	2301.7	1192.7	1313.9	**811.2**
Italy	1401.0	1689.6	2062.0	1682.5	1769.9	2206.0	2369.8	**1883.0**
Netherlands	2787.5	1981.4	430.3	203.0	201.9	2757.5	2676.4	**1576.9**
Portugal	1790.4	2283.2	2027.9	2446.2	2087.8	2101.5	2281.6	**2145.5**
Spain	1733.0	2039.1	2342.9	2427.8	1998.0	2042.1	2248.3	**2118.8**
United Kingdom	1952.4	1968.4	3189.3	3553.0	1769.6	1563.9	1639.2	**2233.7**
USA	1100.7	1528.2	1714.6	6255.9	3443.6	4184.8	1471.7	**2814.2**
Other countries	1366.7	1508.5	1723.1	1727.7	1691.2	1981.6	2249.0	**1749.7**

Appendix 6 continued.

Table A6.5: Total Allowable Catch (TAC) and market demand model inputs used in the *sensitivity analysis* of Chapter 6 are highlighted in black. These inputs are based on the average of the TAC time series in South Africa that is presented in Table A4.1 and the demand (i.e. quantity of hake purchased by countries) presented in Table A4.2. Abbreviations are as follows: UK – United Kingdom, Aus – Australia, Ger – Germany, USA – United States of America and Nd – Netherlands.

	TAC	Domestic	Spain	Italy	Portugal	UK	Aus	France	Ger	USA	Nd	Other
-100%	0	0	0	0	0	0	0	0	0	0	0	0
-50%	71500	7587	9979	3084.5	2342.5	1914	1819	966	812	608	316	920.5
-30%	100100	10621.8	13971	4318.3	3279.5	2679.6	2546.6	1352.4	1136.8	851.2	442.4	1288.7
-20%	114400	12139.2	15966	4935.2	3748	3062.4	2910.4	1545.6	1299.2	972.8	505.6	1472.8
-10%	128700	13656.6	17962	5552.1	4216.5	3445.2	3274.2	1738.8	1461.6	1094.4	568.8	1656.9
standard run	**143000**	**15174**	**19958**	**6169**	**4685**	**3828**	**3638**	**1932**	**1624**	**1216**	**632**	**1841**
+10%	157300	16691.4	21953	6785.9	5153.5	4210.8	4001.8	2125.2	1786.4	1337.6	695.2	2025.1
+20%	171600	18208.8	23950	7402.8	5622	4593.6	4365.6	2318.4	1948.8	1459.2	758.4	2209.2
+30%	185900	19726.2	25945	8019.7	6090.5	4976.4	4729.4	2511.6	2111.2	1580.8	821.6	2393.3
+50%	214500	22761	29937	9253.5	7027.5	5742	5457	2898	2436	1824	948	2761.5
+100%	286000	30348	39916	12338	9370	7656	7276	3864	3248	2432	1264	3682

Table A6.6: Input values of the proportion of frozen fish that were used in the *sensitivity analysis* of Chapter 6 are shown in black. Values were based on average quantities of fresh and frozen exports purchased by countries given in Table A4.2. Estimates for the South African domestic market were based on industry consultation. Abbreviations are as follows: UK – United Kingdom, USA – United States of America and Nd – Netherlands.

**	Domestic	Spain	Italy	Portugal	UK	Australia	France	Germany	USA	ND	Other
-100%	0	0	0	0	0	0	0	0	0	0	0
-50%	0.475	0.2198	0.49995	0.49475	0.22125	0.5	0.4712	0.4188	0.4705	0.4827	0.47555
-30%	0.665	0.30772	0.69993	0.69265	0.30975	0.7	0.65968	0.58632	0.6587	0.67578	0.66577
-20%	0.76	0.35168	0.79992	0.7916	0.354	0.8	0.75392	0.67008	0.7528	0.77232	0.76088
-10%	0.855	0.39564	0.89991	0.89055	0.39825	0.9	0.84816	0.75384	0.8469	0.86886	0.85599
standard run	**0.95**	**0.4396**	**0.9999**	**0.9895**	**0.4425**	**1**	**0.9424**	**0.8376**	**0.941**	**0.9654**	**0.9511**
10%		0.48356			0.48675			0.92136			
20%		0.52752			0.531						
30%		0.57148			0.57525						
50%		0.6594			0.66375						
100%		0.8792			0.885						
MAX	1	1	1	1	1	1	1	1	1	1	1

** the index varies from 0 - 1, meaning that not all % transformations of the inputs are possible. Impossible inputs are left blank and 1 is always the maximum

Appendix 6 continued.

Table A6.7: Input values of the processing efficiency of fresh and frozen hake of companies (i.e. the efficiency with which companies convert whole fish to final fish products) that were used in the *sensitivity analysis* of Chapter 6 are highlighted in black. These were based on average values reported by companies during the industry consultation described in Chapter 3.

	frozen processing efficiency				fresh processing efficiency			
	small	**medium**	**large**	**super-cluster**	**small***	**medium**	**large**	**super-cluster***
-100%	0	0	0	0	0	0	0	0
-50%	0.34	0.41	0.41	0.34	0.26	0.26	0.265	0.26
-30%	0.476	0.574	0.574	0.476	0.364	0.364	0.371	0.364
-20%	0.544	0.656	0.656	0.544	0.416	0.416	0.424	0.416
-10%	0.612	0.738	0.738	0.612	0.468	0.468	0.477	0.468
standard run	**0.68**	**0.82**	**0.82**	**0.68**	**0.52**	**0.52**	**0.53**	**0.52**
10%	0.748	0.902	0.902	0.748	0.572	0.572	0.583	0.572
20%	0.816	0.984	0.984	0.816	0.624	0.624	0.636	0.624
30%	0.884			0.884	0.676	0.676	0.689	0.676
50%					0.78	0.78	0.795	0.78
80%					0.936	0.936	0.954	0.936
max**	1	1	1	1		1	1	1

** the index varies from 0 - 1, meaning that not all % transformations of the inputs are possible. Impossible inputs are left blank and 1 is always the maximum

* note that fresh processing efficiency for small and super-cluster companies was assumed to be similar to that of medium companies.

Table A6.8: Input values of the quota (i.e. the proportion of rights where 1 is 100% of the TAC) for different sized company agents that were used in the *sensitivity analysis* of Chapter 6 are indicated in black. These were based on the aggregated values of % rights held by the small, medium (med), large and super-cluster types described in Chapter 2 which are given as the standard run.

	small	**med**	**large**	**super-cluster**
standard run	***0.031***	***0.225***	***0.529***	***0.059***
small variations	**0.000**	0.235	0.539	0.069
	0.500	0.167	0.167	0.167
	1.000	**0.000**	0.000	0.000
medium variations	0.106	0.000	0.604	0.134
	0.167	0.500	0.167	0.167
	0.000	**1.000**	0.000	0.000
large variations	0.207	0.401	**0.000**	0.235
	0.167	0.167	0.500	0.167
	0.000	0.000	**1.000**	0.000
SC variations	0.051	0.245	0.549	**0.000**
	0.167	0.167	0.167	0.500
	0.000	0.000	0.000	**1.000**

Appendix 6 continued.

Table A6.9: Exchange rate and fuel price model inputs used in the *sensitivity analysis* of Chapter 6 are indicated in black. These are based on the 2003-2014 average of exchange rates presented in Table A6.2 and the average fuel price for 2000-2012 presented in Table A6.1. Note that a zero value for both inputs is unrealistic in the real world.

	Exchange rate (Euro/Rand)	Fuel price (ZAR)
-100%	0.000	0.000
-50%	5.150	2.055
-30%	7.210	2.877
-20%	8.240	3.288
-10%	9.270	3.699
standard run	**10.299**	***4.110***
+10%	11.329	4.521
+20%	12.359	4.932
+30%	13.389	5.343
+50%	15.449	6.165
+100%	20.599	8.220

Appendix 6 continued.

Table A6.10: Vessel fuel usage and vessel and company costs that were used as model inputs for the *sensitivity analysis* of Chapter 6 are shown in black. Vessel fuel usage is based on estimated use per horsepower provided by industry (see Table 6.2). Company and vessel costs are based on values from Table 6.3. Fuel price is based on data provided by industry for the 2000 - 2012 period (Table A6.1).

	Fuel usage per month (L)			cost of active vessels per month (ZAR)*			monthly cost to company per vessel (ZAR)**			
	wet-fish vessel	freezer vessel	factory freezer vessel	wet-fish vessel	freezer vessel	factory freezer vessel	large company	medium company	small company	super-cluster company
-100%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-50%	63614.13	39778.27	101972.00	191680.27	191680.27	191680.27	83333.07	83333.07	83333.07	83333.07
-30%	89059.79	55689.57	142760.80	268352.38	268352.38	268352.38	116666.30	116666.30	116666.30	116666.30
-20%	101782.61	63645.23	163155.20	306688.44	306688.44	306688.44	133332.91	133332.91	133332.91	133332.91
-10%	114505.44	71600.88	183549.60	345024.49	345024.49	345024.49	149999.52	149999.52	149999.52	149999.52
standard run	**127228.27**	**79556.53**	**203944.00**	**383360.55**	**383360.55**	**383360.55**	**166666.14**	**166666.14**	**166666.14**	**166666.14**
+10%	139951.09	87512.19	224338.40	421696.60	421696.60	421696.60	183332.75	183332.75	183332.75	183332.75
+20%	152673.92	95467.84	244732.80	460032.66	460032.66	460032.66	199999.37	199999.37	199999.37	199999.37
+30%	165396.75	103423.49	265127.20	498368.71	498368.71	498368.71	216665.98	216665.98	216665.98	216665.98
+50%	190842.40	119334.80	305916.00	575040.82	575040.82	575040.82	249999.21	249999.21	249999.21	249999.21
+100%	254456.53	159113.07	407888.00	766721.09	766721.09	766721.09	333332.28	333332.28	333332.28	333332.28

*cost is at vessel-level only by vessel per month. This cost excludes fuel-related costs.

** cost is at vessel-level. Represents L/M/S/SC_other_company_costs, which in model are multiplied by total number of vessels that companies own to get a per-company cost.

Appendix 6 continued.

Table A6.11: The price paid by markets per ton of *fresh* hake (Euros/ton) that were used as model inputs for the *sensitivity analysis* of Chapter 6 are indicated in black. Values of 'price paid' are based on actual prices per ton of fresh hake exported from South Africa that were paid by major importing countries, as presented in Table A6.3. The abbreviations UK stand for United Kingdom and USA for the United States of America.

	Domestic*	Australia	France	Germany	Italy	Netherlands	Portugal	Spain	UK	USA	Other countries
-100%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-50%	1157.64	2536.54	1117.32	1191.06	2782.42	1209.67	1740.26	1193.49	929.29	2895.73	1651.11
-30%	1620.70	3551.15	1564.25	1667.48	3895.39	1693.54	2436.36	1670.89	1301.01	4054.02	2311.56
-20%	1852.23	4058.46	1787.72	1905.70	4451.87	1935.47	2784.41	1909.59	1486.87	4633.17	2641.78
-10%	2083.76	4565.77	2011.18	2143.91	5008.35	2177.40	3132.46	2148.29	1672.73	5212.32	2972.01
standard run	**2315.29**	**5073.08**	**2234.64**	**2382.12**	**5564.84**	**2419.34**	**3480.52**	**2386.99**	**1858.59**	**5791.46**	**3302.23**
+10%	2546.82	5580.39	2458.11	2620.33	6121.32	2661.27	3828.57	2625.69	2044.45	6370.61	3632.45
+20%	2778.34	6087.69	2681.57	2858.55	6677.80	2903.20	4176.62	2864.39	2230.31	6949.75	3962.68
+30%	3009.87	6595.00	2905.04	3096.76	7234.29	3145.14	4524.67	3103.09	2416.17	7528.90	4292.90
+50%	3472.93	7609.62	3351.97	3573.18	8347.25	3629.01	5220.77	3580.48	2787.88	8687.19	4953.34
+100%	4630.57	10146.16	4469.29	4764.24	11129.67	4838.67	6961.03	4773.98	3717.18	11582.92	6604.46

*** the world average value of price paid (per ton) was used as a substitute for the domestic market, where real values were unobtainable**

Appendix 6 continued.

Table A6.12: The price paid by markets per ton of *frozen* hake (Euros/ton) that were used as model inputs for the *sensitivity analysis* of Chapter 6 are indicated in black. Values of 'price paid' are based on actual prices per ton of frozen hake exported from South Africa that were paid by major importing countries, as presented in Table A6.3. The abbreviation USA stands for the United States of America.

	Domestic*	Australia	France	Germany	Italy	Netherlands	Portugal	Spain	United Kingdom	USA	Other countries
-100%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-50%	1093.15	1744.94	1174.27	405.58	941.49	788.43	1072.75	1059.38	1116.85	1407.10	874.85
-30%	1530.41	2442.91	1643.98	567.82	1318.09	1103.80	1501.85	1483.13	1563.58	1969.94	1224.79
-20%	1749.04	2791.90	1878.84	648.93	1506.39	1261.49	1716.40	1695.01	1786.95	2251.36	1399.76
-10%	1967.67	3140.89	2113.69	730.05	1694.69	1419.18	1930.95	1906.88	2010.32	2532.78	1574.73
standard run	**2186.30**	**3489.87**	**2348.55**	**811.16**	**1882.98**	**1576.86**	**2145.50**	**2118.76**	**2233.69**	**2814.20**	**1749.70**
+10%	2404.93	3838.86	2583.40	892.28	2071.28	1734.55	2360.05	2330.64	2457.06	3095.62	1924.67
+20%	2623.56	4187.85	2818.26	973.40	2259.58	1892.23	2574.60	2542.51	2680.43	3377.04	2099.64
+30%	2842.19	4536.84	3053.11	1054.51	2447.88	2049.92	2789.15	2754.39	2903.80	3658.45	2274.61
+50%	3279.45	5234.81	3522.82	1216.75	2824.48	2365.29	3218.25	3178.14	3350.54	4221.29	2624.55
+100%	4372.60	6979.75	4697.09	1622.33	3765.97	3153.72	4291.00	4237.52	4467.39	5628.39	3499.40

*** the world average value of price paid (per ton) was used as a substitute for the domestic market, where real values were unobtainable**

Appendix 6 continued.

Table A6.13: Inputs of Catch per Unit Effort (CPUE) and stochasticity of catching fish that were used for the *sensitivity analysis* in Chapter 6 are shown in black. CPUE values are based on the average of the transformed time series in table A5.1 and stochasticity values are based on the use of an intermediate value in the standard run.

	CPUE	stochasticity
-100%	0.00	0.00
-50%	0.36	0.25
-30%	0.51	0.35
-20%	0.58	0.40
-10%	0.65	0.45
standard run	**0.724**	**0.500**
+10%	0.80	0.55
+20%	0.87	0.60
+30%	0.94	0.65
+38.21%*	1.00	1.00

*stochasticity is +100%

Appendix 6 continued.

Table A6.14: Inputs of the numbers of factory freezer, freezer stern trawlers and wet-fish stern trawlers belonging to small, medium, large and super-cluster companies that were used for the *sensitivity analysis* of Chapter 6 are shown in black. Values used in the standard run are representative of vessel numbers quantified during the industry consultation and data collection phases of Chapters 2 and 3. Inputs can only be whole numbers, so fractional vessel numbers were rounded to the nearest integer. Runs included either all vessels for all companies at maximum and minimum, and all freezers/wet-fish vessels at maximum and minimum, and all vessels for each company at maximum and minimum, while other companies were held at the standard run value.

	small			medium			large			super-cluster		
	factory freezers	freezer trawlers	wet-fish	factory freezers	freezer trawlers	wet-fish	factory freezers	freezer trawlers	wet-fish	factory freezers	freezer trawlers	wet-fish
100%**	2	2	2	6	28	10	6	6	32	2	6	2
50%	2	2	2	5	21	8	5	5	24	2	5	2
Standard run	1	1	1	3	14	5	3	3	16	1	3	1
-50%	1	1	1	2	7	3	2	2	8	1	2	1
-100%	0	0	0	0	0	0	0	0	0	0	0	0

** all values rounded to the nearest integer as fractional vessels are not possible