Chapter 1

The Appeal and Power of Strategic Modelling

Introduction[1]

I have always been fascinated by models and games and particularly by model conceptualisation, the process by which people represent and simplify situations from the real world to make sense of them. Consider for example, the popular board game of Monopoly. Players find themselves as property developers in an imaginary city. It could be London or New York, except of course (and this is the curious thing) the board doesn't look remotely like a real city or even like a geographical map of either city. The game board is just a large square of card on which are printed neatly labelled and coloured boxes displaying familiar place names like cheap and cheerful Old Kent Road in brown, bustling Trafalgar Square in red and elegant Mayfair in dark blue. There are houses and hotels, but no streets. There are stations, but no railway lines. There is a community chest, but no community of people. There is a jail, but no police department. Players move around the city with a throw of the dice in a curious assortment of vehicles: a boot, a ship, a horse, an iron, a cannon and even a top hat. It is a fantasy world, a much simplified view of

[1]The introduction contains edited extracts from my 2000 paper, 'Creativity and Convergence in Scenario Modelling'.

real estate in a city, and yet it captures something real – the essence of commercial property ownership and development in a growing competitive market. The more property you own and control, the more you earn. Bigger is better, winner takes all.

The challenge of any kind of modelling lies precisely in deciding, among myriad factors, what to include and what to leave out. The same principle applies whether you are devising a board game like Monopoly or building a simulator for a management team in BMW, Dow Chemical, Goldman Sachs, Harley-Davidson, Mars Inc., Microsoft, Royal Dutch/Shell or Transport for London. The starting point is essentially, 'what's important here?' What do you and others have in mind when you think about the strategy and future success of a business, a city or an entire industry? What is the issue under investigation and which factors need most attention to address the issue? These practical questions in turn raise a more basic philosophical question about how we conceptualise the enterprises in which we live and work. How do people, whether they are leaders, advisers or commentators, make sense of firms, industries or societies, explain them to others, and anticipate outcomes well enough to shape and communicate intelligent strategy and policy?

I can recall this fascination with conceptualisation from a time when business dynamics, or more generally system dynamics (and its specialist visual language of stocks, flows and information feedback), was entirely new and unfamiliar to me. It was back in the early 1970s. The *Limits to Growth* study, a research project exploring how to create an economically and ecologically sustainable society, was attracting attention worldwide. The project was conducted at the Massachusetts Institute of Technology (MIT) and two influential books based on this work, *World Dynamics* (Forrester, 1971) and *Limits to Growth* (Meadows *et al.*, 1972), had already been published. Further work on the paradox of global growth and sustainability was in full flow. Thousands of miles away I was a graduate student at London University's Imperial College, completing a masters degree in operational research. I had only just encountered *Industrial Dynamics*, the seminal book that marked the beginning of system dynamics (Forrester, 1961).

Nevertheless, I experienced a sense of excitement about the possibility of using computer models to visualise and simulate issues that were foremost in the minds of business and political leaders and important for our everyday lives. Certainly I was no novice to computer modelling, but up until then I had used computational power for optimisation and decision support. What I found appealing in this new area of system dynamics was the promise of a subject aimed at broad policy making backed up by the discipline of model building and the power of simulation.

Imagine you are contemplating the dilemma of fast-growing global population in a world of finite resources. Today, there are 7 billion of us on the planet. Back in 1850 there were just over one billion. By 2050 there could be as many as nine billion people. Is it really possible that mankind could outgrow the planet and overexploit its abundant natural resources to usher in a dark age of pollution, poverty and suffering? Why might this happen and when? How do you begin to answer such questions and how do you conceive a 'global system' in your mind? I was captivated by a representation in *World Dynamics* that limited itself to only two pages of symbols whose clearly defined purpose was to explore alternative future time paths for global industrial society. It was a bold sketch on a compact canvas.

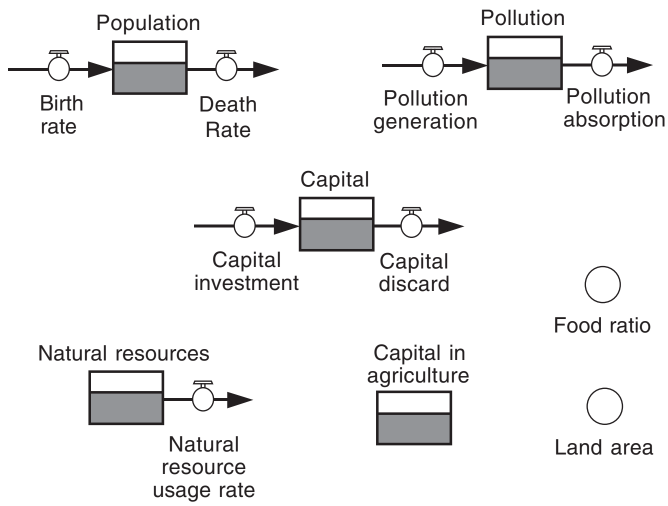

Figure 1.1 Stock accumulations for global growth
Source: Adapted from Forrester (1971, pp. 20–21).

For those who have read *World Dynamics*, Figure 1.1 will evoke memories of the model. However, for most readers who are new to system dynamics you will glimpse what I saw as a graduate student: strange symbols and familiar phrases which claim to set some sort of boundary on the set of factors that will shape the environmental and economic destiny of mankind. I have deliberately chosen to show a much-simplified diagram that leaves out many intermediate variables and the complex network of connections, because that is how I first perceived the model. There are only four stock accumulations (shown as rectangles with inflows and outflows), representing aspects of our world, that have grown steadily and relentlessly over many centuries: population, capital, pollution and natural resources (which have declined). This fact alone I found remarkable for its brevity yet common-sense appeal. To understand global limits to growth one surely has to think hard about the drivers of population (birth rate and death rate, shown as small circles with tiny taps superimposed on arrows); the engines of human economic activity (capital investment, capital discard and the usage rate of natural resources); and the consequences of human activity on the global environment (the processes of pollution generation and absorption).

These factors must co-evolve over time. But what forces or influences make sure they evolve in a balanced way that can satisfy the aspirations and sustain the living standards of a healthy global population? My picture does not show the full web of coordinating forces. That is something you will learn to model and interpret later in the book. For now you just have to imagine there is such a web operating behind the scenes that determines how, for example, the birth rate depends on population, capital and pollution, or how capital investment depends on population and natural resources. But can a sustainable balance be achieved? Is there a coordinating web that will steer global growth within the constraints of finite natural resources, limited land area, and biological/physical laws (that govern the world's ecology), while at the same time meeting the needs of billions of global stakeholders (parents and families, investors in productive capital, exploiters of natural resources)?

It came as a shock all those years ago to realise there is no nation, no government and no responsible business community that has the power or the information to mastermind a global growth engine.[2] A coordinating web is certainly there (reproduced in the Appendix as Figure 1.13), but it is a weak and imperfect invisible hand. In the long run, this invisible hand will achieve a ruthless balance of population, resources and human activity. But the time path to this ultimate balance may involve a catastrophic decline of living standards and population or spiralling pollution.

Figure 1.2 compares two (among many) alternative time paths that summarise the message as I recall it from my early encounter with system dynamics (Randers, 1980). Bear in mind these are rough hand-drawn sketches, not formal simulations. Nevertheless, the century-long timescale on these charts is representative of the time horizon in the original study and left a deep impression about the ambition of the field to understand the long term by simulating the interaction of human decisions-and-actions with enduring natural forces. On the left is a likely scenario. Global carrying capacity (defined as how much human activity the globe can sustain) starts high in the uncrowded world of the 1950s. Human activity starts low. As population and capital grow, human activity rises steadily and exponentially, approaching the

[2]The same idea of limited ability to control situations applies to firms in competitive industries and, to some extent, to business units and functional areas inside corporations and firms. Management teams can devise strategy (the intended strategy), but a whole organisation stands between their ideas and resulting action, so the implemented strategy is often different than intended. The levers of power are only loosely connected to operations.

finite (but unknown) global capacity around the turn of the millennium. There is no particularly strong signal to announce that this hidden capacity limit has been reached, nor any coalition of stakeholders with the power to restrict human activity once the limit is exceeded. So 'the band plays on' for another 20 years. Collectively, we live beyond the generous but limited means of our planet. This overexploitation of resources and the environment leads to a steady erosion of global carrying capacity and a consequent rapid decline in human activity. In human terms, this multi-decade period of decline is a dark age of low living standards, high pollution, food shortage, premature death and economic depression. It is a dramatic story arising from simple yet plausible assumptions about human behaviour and planetary limits.

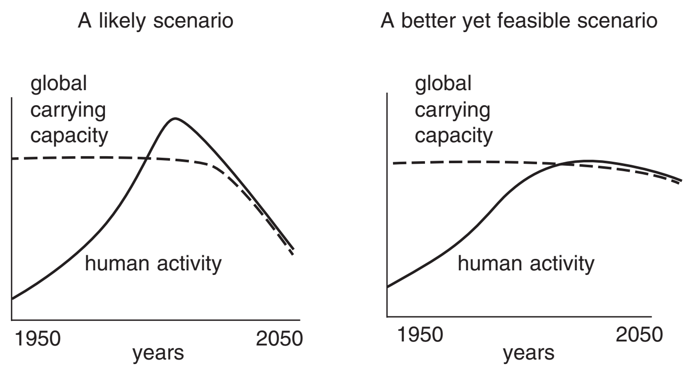

Figure 1.2 Limits to global growth – rough sketches of alternative futures

The story has not really changed in the four decades since it was first simulated. But there was always another, much more optimistic story. This alternative and sustainable future is sketched on the right of Figure 1.2. I won't say here what differences in the coordinating web can lead to this new outcome. Instead, I invite you to think about the task of balancing the stock accumulations in Figure 1.1 in light of what you learn from the book. I also refer you to the comprehensive simulations of the *Limits to Growth* team (Meadows *et al.*, 1972; 2002 and Cerasuolo, 2013) and to two of the original simulations from *World Dynamics* reproduced in the Appendix as Figure 1.14.

A New Approach to Modelling

World Dynamics and *Limits to Growth* anticipated a new and participative approach to modelling and simulation. People's ability to manage their complex world can be improved by visualising and simulating it. Plans and alternative futures become clearer by rehearsing them (O'Brien and Dyson, 2007). Only now is this approach coming to be widely appreciated in business, political and academic circles. During the 1970s, models were still viewed as instruments for accurate prediction whose validity rested primarily on short-term predictive power, conformance with established economic theory and goodness-of-fit to historical data. Modelling for learning, of the kind presented in this book and intended to complement people's mental models, was in its infancy.

The idea of rehearsing alternative futures is fundamental to contemporary strategic modelling and scenario development. The purpose of models and simulations is to prepare organisations and individuals for alternative futures by bringing these futures to life so they are imagined more vividly than would otherwise be possible. Moreover, as you will see throughout the book, strategic models not only help people to generate alternative futures for their firms and industries, but also to challenge, shape, change and enrich their interpretation of a complex world.

An important objective for modellers (and arguably for anyone in a leadership position who has to make sense of complex business or social situations, devise strategies and communicate them) is to find a compact 'shareable' description of how a firm, industry or social system operates. Sooner or later, the creative and divergent thoughts that are present at a very early stage of enquiry (captured in the phrase 'there's a lot going on out there') must be turned to convergent thoughts that focus group attention on the essence of the situation at hand (by agreeing, through ruthless pruning, what's really important and what can be safely ignored). In business dynamics, this creative process of simplification (known as 'conceptualisation') takes shape as a picture of a firm or industry that the modeller agrees with the project team. There are of course guidelines to follow. You begin by identifying so called stock accumulations and feedback loops, the visual building blocks of system dynamics models and simulators. Striking the right balance of creativity and convergence is an essential art of modelling. The parsimonious structure of the *World Dynamics* model is evidence of creativity and disciplined convergence in model conceptualisation. The model's enduring appeal and power to communicate lies partly in its concise yet compelling representation of a massively complex reality.[3]

[3]Modelling can be controversial. *World Dynamics* was and still is a thought-provoking model, a potent catalyst for political debate and an instrument for serious policy making. It was also a focus of learned criticism about the nature and use of modelling and simulation in the social sciences. Quotations from the press and academic literature at the time convey the impact, both positive and negative, of the model on opinion leaders: 'This is likely to be one of the most important documents of our age ...', *New York Times*; 'There are too many assumptions that are not founded, and there is too high a level of aggregation in the model', *Science*; 'This year will not see the publication of a more important book than Forrester's *World Dynamics*, or a book more certain to arouse dislike', *Fortune*; 'This is a piece of irresponsible nonsense, a publicity stunt ... extremely simplistic, given the

The Puzzling Dynamics of International Fisheries

By now I hope your curiosity about modelling is stirred, but before probing the basic concepts and tools used by system dynamics modellers, I want to show you a model, a small model, designed to address an important contemporary issue facing society. I will explain its main assumptions, demonstrate some simulations and then give you the opportunity to run the simulator for yourself.

The topic is fisheries. The problems of overexploitation facing international fisheries are well known, widely reported in the press and a subject of government policy in many nations. The performance of international fisheries is indeed puzzling. Fish naturally regenerate. They are a renewable resource, in apparently endless supply, providing valuable and healthy food for billions of consumers and a livelihood for hundreds of thousands of fishing communities worldwide. The fishing industry has been in existence since the dawn of civilisation and should last forever. Yet fish stocks around the world are volatile and some are even collapsing. Once rich fishing grounds such as Canada's Grand Banks now yield no catch at all. Stocks in other areas, such as the English Channel, the North Sea and the Baltic, are in terminal decline.

The issue is powerfully expressed by environmental journalist Charles Clover (2004) in his acclaimed book *The End of the Line*. Here is an excerpt from Chapter 1:

> Fish were once seen as renewable resources, creatures that would replenish their stocks forever for our benefit. But around the world there is evidence that numerous types of fish, such as the northern cod, North Sea mackerel, the marbled rock cod of Antarctica and, to a great extent, the west Atlantic bluefin tuna, have been fished out, like the great whales before them, and are not recovering … The perception-changing moment for the oceans has arrived. It comes from the realisation that in a single human lifetime we have inflicted a crisis on the oceans greater than any yet caused by pollution. That crisis compares with the destruction of the mammoths, bison and whales, the rape of rainforests and the pursuit of bushmeat. It is caused by overfishing.
>
> (from *The End of the Line* by Charles Clover, published by Ebury. Reprinted by permission of The Random House Group Ltd and Charles Clover.)

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current state of knowledge in the social sciences', economists from Yale. Notice the sharp division of opinion on the scope, size, adequacy and usefulness of the model. The serious press thinks the work is important for its readers and worthy of policymakers' attention. Academics question the model's apparent simplicity. Not surprisingly judgements vary about the complexity and accuracy required of models (or even ideas and theories) for them to offer useful guidance to business and society. Modellers need to strike a careful balance.

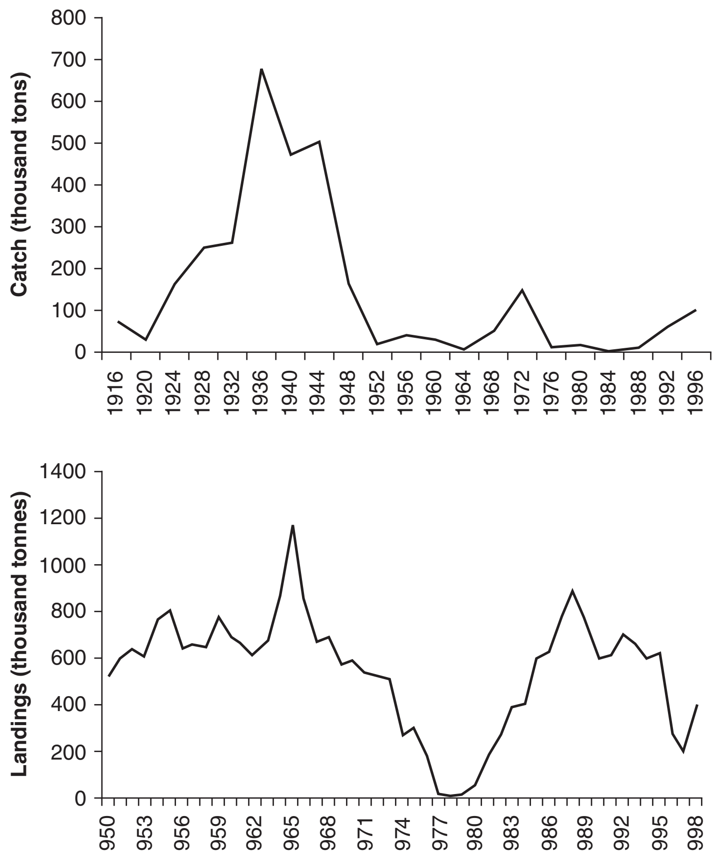

Figure 1.3 Pacific sardine catch (top) and North Sea herring catch (bottom) from Fish Banks debriefing materials (Meadows *et al.*, 2001)
Source: Nichols (1999).

Figure 1.3 shows evidence of overfishing from two real fisheries. This kind of time series data is a useful focus for model building because it contains the dynamics of interest. The top chart shows the Pacific sardine catch in thousands of tonnes per year over the period 1916–1996. The annual catch grew remarkably between 1920 and 1940, starting at around 50 thousand tonnes per year and peaking at 700 thousand tonnes per year – a 14-fold increase. Over the next four years to 1944, the catch fell to 500 thousand tonnes per year, stabilised for a few years and then collapsed dramatically to almost zero in 1952. Since then it has never properly recovered. The bottom chart shows a similar story for the North Sea herring catch in the period 1950 to 1998. However, in this case, following a collapse between 1974 and 1979, the fishery did recover in the 1980s and early 1990s with an average annual catch around 600 thousand tonnes per year – similar to the catch in the 1950s and 1960s.

Why does overfishing happen? We can be sure that no fishermen set out with the deliberate intention of depleting fisheries and wrecking their own livelihoods. Yet this outcome has been repeated in fishing communities around the world.[4] A good explanation is to be found in a fisheries gaming simulator called Fish Banks, Ltd (Meadows *et al.*, 2001; Meadows and Sterman, 2011). Since I am not an expert on fisheries, I will base my model on this popular simulator. Fish Banks has been used to teach principles of sustainable development to audiences that include politicians, business leaders and government policy advisers as well as fishing communities and high school students. Incidentally, it is no coincidence that the lead designer and author of Fish Banks, Dennis Meadows, was also a principal investigator in the *Limits to Growth* study. Fish Banks has proven to be a potent metaphor for sustainable development in many industries and enterprises, including the world itself viewed as a huge socio-economic enterprise.

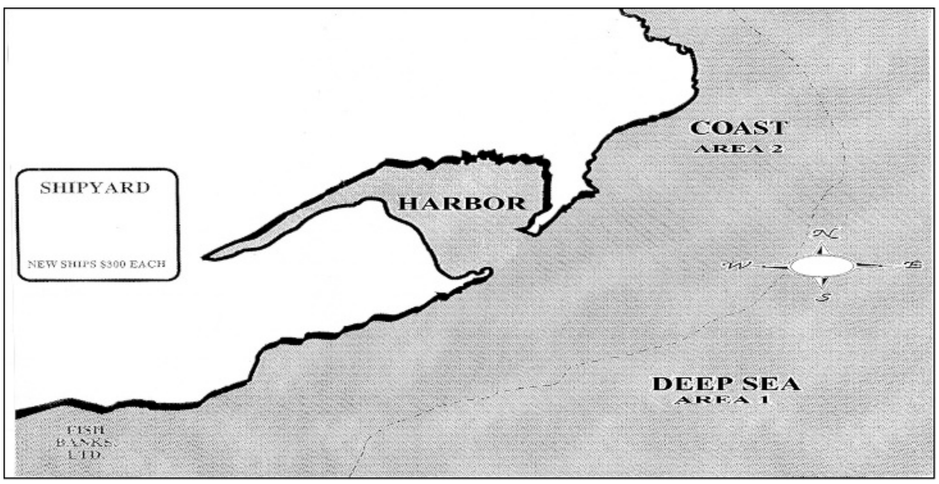

Figure 1.4 An imaginary fishery – the game board of the original FishBanks, Ltd
Source: Meadows, *et al.*, 2001

Figure 1.4 shows the Fish Banks game board and its imaginary fishery. There is a region of ocean, close to land, containing a single species of fish. Fish regenerate as a function of the existing population. The local fishing community buys ships from the shipyard and takes them to sea to harvest fish. The total catch depends on the number of ships, the fish population and other factors, such as the weather. In the game, as in real life, the fish population is not known accurately, although it can be estimated. Also, in the game, as in

[4]Clover describes the poignant scene at Lowestoft in recent years: the unrepaired doorways and shabby 1930s office buildings on the seafront, symbols of economic collapse. This town was once among England's greatest fishing ports, famous the world over, with a history spanning 600 years.

real life, the process of fish regeneration is not fully understood by those in the system (players or fishermen). Regeneration is related to the (unknown) fish population, but the relationship is complex and may involve other external factors.

Model of a Natural Fishery

I have taken the situation and factors outlined above and used them to create a simple fisheries model (though the scaling I use is different from Fish Banks and there are no competing fishing companies). Figure 1.5 shows the fish population and regeneration. For now there are no ships or fishermen – they appear later. So what you see is a natural fishery, free from human intervention.[5] The fish population or fish stock, shown as a rectangle, accumulates the inflow of new fish per year (here the inflow is defined as births minus deaths). Initially, there are 200 fish in the sea and the maximum fishery size is assumed to be 4000 fish. Incidentally, the initial value and maximum size can be re-scaled to be more realistic without changing the resulting dynamics. For example, a fishery starting with a biomass of 20 thousand tonnes of a given species and an assumed maximum fishery size of 400 thousand tonnes would generate equivalent results.

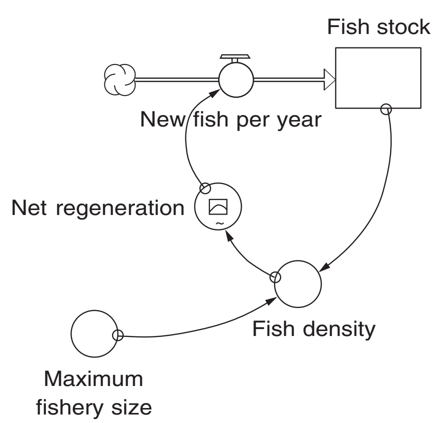

Figure 1.5 Diagram of a natural fishery

[5]The diagram was created in the popular iThink language (isee systems, 2014). The symbols are pretty much standard for all system dynamics models, though there are differences of detail between the main alternative modelling software packages. Here, in Chapter 1, I briefly explain each symbol when I first refer to it in the text. Later, in Chapter 3, there is a more formal introduction to modelling symbols and equations, with a fully documented example.

The flow of new fish per year is shown by an arrow. The size of the inflow varies according to conditions within the fishery, as explained below. This idea of a modulated flow is depicted by a tap or 'flow regulator' placed in the middle of the arrow. At the left end of the arrow is another special symbol, a pool or cloud, depicting the source from which the flow arises – in this case fish eggs.

A very important relationship is the effect of fish density on net regeneration, a causal link shown by a curved arrow. Since fish density itself depends on the number of fish in the fishery region, the result is a circular feedback process in which the size of the fish stock determines, through various intermediate steps, its own rate of inflow.[6] The relationship is non-linear as shown in Figure 1.6.

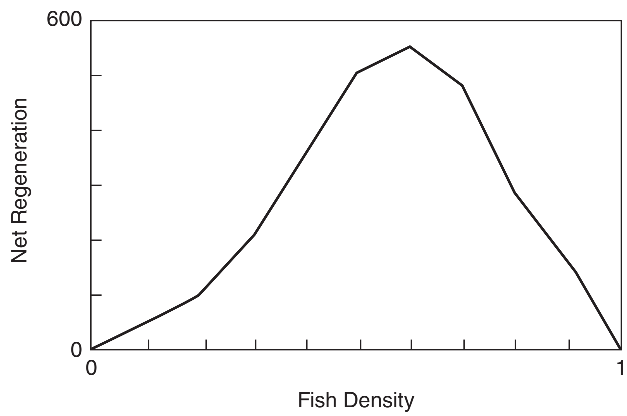

Figure 1.6 Net regeneration as a non-linear function of fish density

When the fish density is low there are few fish in the sea relative to the maximum fishery size and net regeneration is low, at a value of less than 50 fish per year. In the extreme case where there are no fish in the sea, the net regeneration is zero. As fish density rises the net regeneration rises too, on the grounds that a bigger fish population will reproduce more successfully, provided the population is far below the presumed theoretical carrying capacity of the ocean region.

As the fish density continues to rise, there comes a point at which net regeneration reaches a peak (in this case almost 600 fish per year) and then begins to fall because food becomes scarcer. Ecologists say there is increasing

[6]Interestingly, some people dispute the existence of this circularity. They argue that the number of juveniles reaching fishable size each year has nothing to do with the number of parents in the sea because fish such as cod can produce upwards of seven million eggs in a season – most of which perish due to predation and environmental factors. However, the number of fish eggs is certainly related to the population of fish.

intraspecific competition among the burgeoning number of fish for the limited available nutrient. So when, in this example, the fish population reaches 4000 the fish density is equal to one and net regeneration falls to zero. The population is then at its maximum natural sustainable value.

Simulated Dynamics of a Natural Fishery

If you accept the relationships described above then the destiny of a natural fishery is largely pre-determined once you populate it with a few fish. To some people this inevitability comes as a surprise, but in system dynamics it is an illustration of an important general principle: the structure of a system (how the parts connect) determines its dynamic behaviour (performance through time). A simulator shows how. The simulation in Figure 1.7 shows the dynamics of a 'natural' fishery over a period of 40 years, starting with a small initial population of 200 fish. Remember there are no ships and no investment. Fishermen are not yet part of the system.

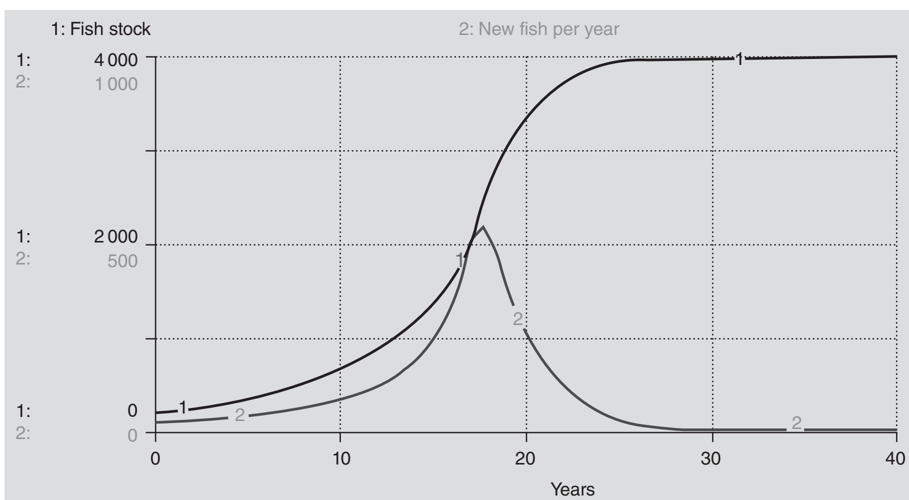

Figure 1.7 Simulation of a natural fishery with an initial population of 200 fish and maximum fishery size of 4000

The result is smooth S-shaped growth. For 18 years, the fish stock (line 1) grows exponentially. The population grows from 200 to 2500 fish and regeneration (new fish per year, line 2) also increases until year 18 as rising fish density enables fish to reproduce more successfully. Thereafter, crowding becomes a significant factor according to the non-linear net regeneration curve shown in Figure 1.6. The number of new fish per year falls as the population density rises, eventually bringing population growth to a halt as the fish stock approaches its maximum sustainable value of 4000 fish.

Operating a Simple Harvested Fishery

Imagine you are living in a small fishing community where everyone's livelihood depends on the local fishery. It could be a town like Bonavista in Newfoundland, remote and self-sufficient, located on a windswept cape 200 miles from the tiny provincial capital of St Johns, along deserted roads where moose are as common as cars. 'In the early 1990s there were 705 jobs in Bonavista directly provided by the fishery, in catching and processing' (Clover, 2004). Let's suppose there is a committee of the town council responsible for growth and development that regulates the purchase of new ships by local fishermen. This committee may not exist in the real Bonavista but for now it's a convenient assumption. You are a member of the committee and proud of your thriving community. The town is growing, the fishing fleet is expanding and the fishery is teeming with cod.

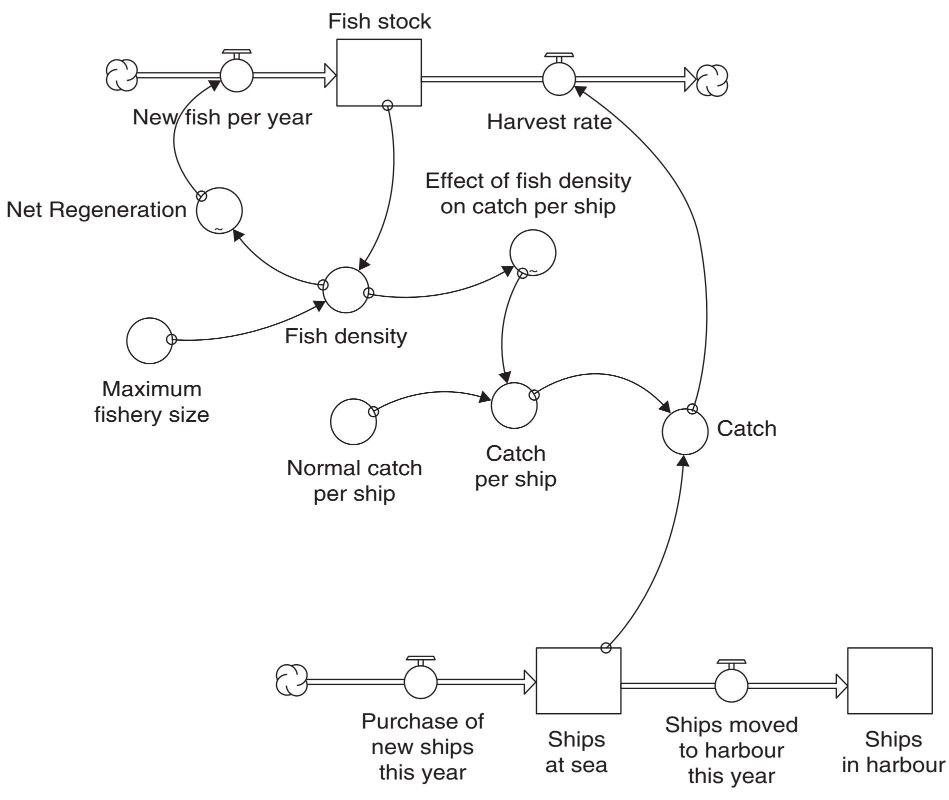

Figure 1.8 Diagram of a simple harvested fishery

Figure 1.8 shows the situation. The fish stock in the top left of the diagram regenerates just the same as before, but now there is an outflow, the harvest rate, that represents fishermen casting their nets and removing fish from the sea. The harvest rate is equal to the catch, which itself depends on the number of ships at sea and the catch per ship. Typically the more ships at sea the bigger the catch, unless the fish density falls very low, thereby reducing the catch per ship because it is difficult for the crew to reliably locate fish. Ships at sea are increased by the purchase of new ships and reduced by ships moved to harbour, as shown in the bottom half of the diagram.

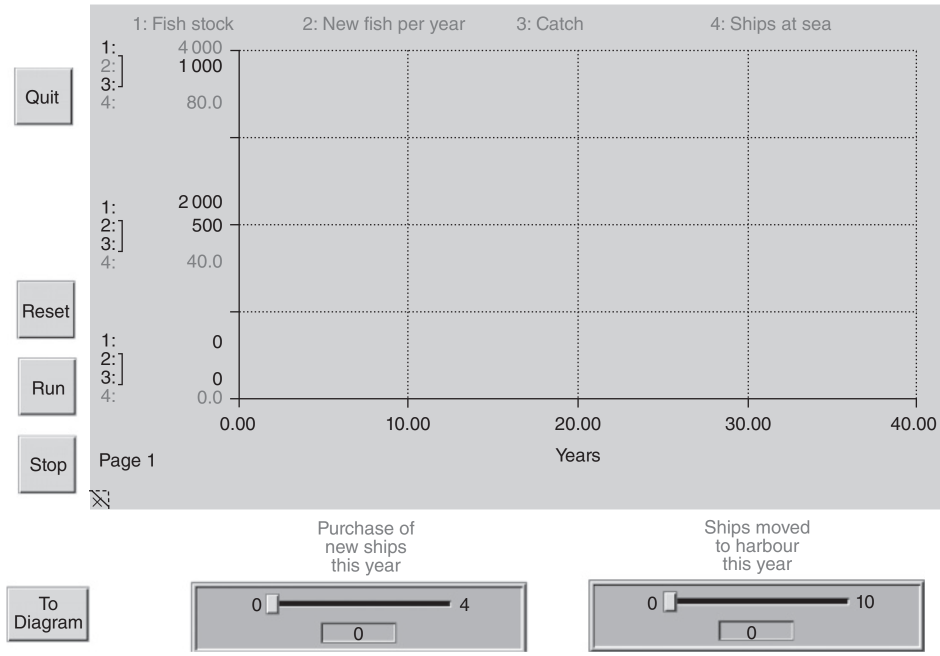

Figure 1.9 Interface for fisheries gaming simulator

The interface to the gaming simulator is shown in Figure 1.9. There is a time chart that reports the fish stock, new fish per year, catch and ships at sea over a time horizon of 40 simulated years. Until you make a simulation, the chart is blank. The interface also contains various buttons and sliders to operate the simulator and to make decisions year by year. There are two decisions. Use the slider on the left for the purchase of new ships and the slider on the right for ships moved to harbour. You are ready to simulate! Open the file called 'Fisheries Gaming Simulator' in the learning support folder for Chapter 1. The interface in Figure 1.9 will appear in colour. First of all, simulate natural regeneration over a period of 40 years, a scenario similar, but not identical, to the simulation in Figure 1.7. The only difference is that the initial fish population is 500 fish rather than 200. What do you think will be the trajectories of the fish stock and new fish per year? How will they differ from the trajectories in Figure 1.7? Would you expect any similarities? To find out, press the button on the left labelled 'Run' (but don't alter either of the two sliders, which are deliberately set at zero to replicate a natural fishery). You will see a five-year simulation. The fish stock (line 1) and new fish per year (line 2) both grow steadily. You can observe the exact numerical values of the variables by placing the cursor on the time chart, then selecting and holding. Numbers will appear under the variable names at the top of the chart. At time zero, the fish stock is 500 and new fish are regenerating at a rate of 63 per year. If you look carefully you will see that the catch (line 3) and ships at sea (line 4) are, as expected, running along at a value of zero, alongside the horizontal axis of the time chart. Press the ‘Run’ button again. Another five simulated years unfold showing further growth in the fish stock and in new fish per year. Continue until the simulation reaches 40 years and then investigate the trajectories carefully and compare them with the time chart in Figure 1.7. Why does the peak value of new fish per year occur so much earlier (year 10 instead of year 16)? Why is the final size of the fish stock identical in both cases?

Harvesting in Bonavista, Newfoundland – A Thought Experiment

Back to Bonavista, or at least a similar imaginary fishery, scaled to the numbers in the simulator. The fishing fleet has been growing and along with it the catch and the entire community supported by the fishery. As a member of the town’s growth and development committee you want to explore alternative futures for the fishery and the simulator is one way to do so. You conjure up a thought experiment. Starting as before with an initial stock of 500 fish, you first simulate growth, through natural regeneration of fish, for a period of 10 years. The result is a well-stocked fishery similar to the one existing some 20 years ago when the hamlet of Bonavista, as it was then, began to expand commercial fishing. You know from the previous experiment that this scenario will lead to plenty of fish in the sea, but in reality you and the fishermen themselves don’t know how many.

To replicate this fundamental uncertainty of fisheries you should ‘hide’ the trajectories for fish stock and new fish per year by colouring them grey so they blend into the background of the time chart. Some playing around with the software is necessary to bring about this change, but the result is important and worthwhile. First, press the ‘Reset’ button on the left of the time chart. The trajectories will disappear to leave a blank chart. Next move the cursor to the tiny paintbrush icon at the right of the tools bar at the top of the interface. Select and hold. A palette of colours will appear. Move the cursor to the bottom line containing greys and blacks. Select the light grey colour on the extreme left. Release the mouse button and move the cursor back onto the time chart where it will now appear as a paint brush. Select and the background of the chart will turn grey. Return to the colour palette and select the light grey colour *second from the left*. Now move the paintbrush cursor so that it lies exactly on top of the phrase ‘Fish stock’ at the top left of the time chart. Select and the phrase will turn from blue to grey and will, as intended,

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be virtually indistinguishable from the background grey. Repeat the same painting procedure for the phrase 'New fish per year'. Your time chart is now ready.

Press the 'Run' button twice to recreate 10 years of natural fishery growth. At first glance the simulated chart will appear quite blank and uninteresting. That's how it should be! Now move the slider for 'Purchase of new ships this year' to a value of 2 by selecting, holding and dragging the slider icon until the number 2 appears in the centre box. This setting means that each simulated year two new ships will be purchased and used by Bonavista fishermen. Press the 'Run' button three times in succession to simulate fleet expansion for years 10–25, a period of historical growth for the imagined Bonavista fishery. Ships at sea (line 4) increase linearly from zero to 30 as you would expect from an investment policy that adds two new ships a year over 15 years. The catch (line 3) increases proportionally in a similar linear pattern. Press the 'Run' button once more to simulate continued fleet expansion for years 25–30. Ships at sea continue the same relentless linear expansion, but notice a dramatic change in the trajectory of the catch (line 3). In year 26, after 16 years of steady growth, the catch levels out and peaks at 786 fish per year even though new ships are being added to the fleet. (To check the numerical values move the cursor onto the time chart, then select, hold and drag.) In year 27 the catch declines for the very first time in the fishery's simulated history. At the start of year 29, the catch is down to 690 fish per year, a decline of 12 per cent from the peak. Imagine the situation in Bonavista. The town's main business is in a downturn. A community, which has become used to growth and success, begins to worry and to ask why. Perhaps the past two years have been unlucky – poor weather or adverse breeding conditions. However, year 29 sees continued decline. The catch falls below 450 fish per year while the fleet grows to 40 ships. A downturn has become a slump.

At this point you can imagine pressure building in the community to do something about the problem. But what? The fishery is in decline. Perhaps the answer is to halt the purchase of new ships and to require some ships to remain in harbour. Such measures may seem logical if you believe that overfishing is to blame. But others will argue the decline is due to a run of exceptionally bad luck and that, sooner or later, the catch will return to normal. And remember nobody knows for certain the size of the remaining fish stock or the regeneration rate. That's all happening underwater. So, as in all practical strategy development, there is scope for argument and conflict about the true state of affairs and how best to react. Moreover, it is politically and economically painful for any community or business to cause itself to shrink deliberately. There are bound to be more losers than winners.

Nevertheless, imagine Bonavista agrees a conservation policy involving a total ban on the purchase of new ships for the next five years and an effective

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reduction in the fleet size to be achieved by moving five ships per year into the harbour. A little mental arithmetic reveals that in its first year of operation this policy idles 12.5% of the active fleet (5 ships out of 40), then 14.3% in the second year (5 ships out of 35), then 16.7% in the third year (5 ships out of 30). After five years, a total of 25 ships have been idled, which is fully 62.5% of the original fleet – a huge reduction in a short time. Adjust the sliders to represent the implementation of this stringent conservation policy. First set the slider for the 'Purchase of new ships this year' to zero, either by dragging the slider icon to the extreme left or by selecting the slider's 'Reset' button (denoted by 'U') in the bottom left of the slide bar. Then, set the slider for 'Ships moved to harbour this year' by dragging the slider icon to the right until the number 5 appears in the centre box. Press the 'Run' button to see the results of the policy. You will notice that ships at sea (line 4) decline steeply as enforced idling takes place. By year 35 of the simulation, the active fleet size is 15 ships at sea, back to where it had been in the early growth heyday of the fishery almost 20 years ago in year 17. Despite the cuts and huge economic sacrifices, however, the catch has declined to less than 10 fish per year, scarcely more than 1 per cent of the peak catch in year 26. In a single decade our imagined Bonavista fishery has gone from productive prosperity to extreme hardship. Each day the community awakes to see the majority of the fishing fleet idle in its once busy harbour, and the remaining active ships returning with a dismally tiny catch. You can imagine that by now many will have lost heart and lost faith in the conservation policy.

To finish the simulation reset to zero the slider for 'Ships moved to harbour this year' and then press 'Run'. In these final years it is no longer possible to enforce further reductions in the active fleet. The number of ships at sea remains constant and the catch falls practically to zero. It's a depressing story, but entirely consistent with the facts of real fisheries. Harvested fisheries are prone to catastrophic decline that nobody involved – fishermen, community leader or consumer – would wish on themselves. Yet this situation in particular, and others like it, arise from nothing more than a desire to purchase ships, catch fish and grow a prosperous community. Why? Fisheries provide but one example of puzzling dynamics that are the focus of this book. As we will see, modelling and simulation can shed useful light on why such puzzling dynamics occur and how to bring about improvement.

A Start on Analysing Dynamics and Performance Through Time

Much of the problem with managing fisheries lies in properly coordinating the number of ships at sea in relation to the number of fish. A sustainable fishery, one that provides a reliable and abundant harvest year after year, regenerates fish at about the same rate as they are being caught. Successful replenishment requires an appropriate balance of ships and fish. Balancing is easier said than done when in practice it is impossible to observe and count the number of fish in the sea, when fishing technology is advancing and when there is a natural human propensity to prefer growth and the prosperity it brings. Imagine we could reliably count the fish stock and observe the regeneration of fish through time. What new light would this new data shed on the rise and fall of Bonavista and the policy options to avoid catastrophic decline in the fish population? In our simulator we can choose to observe and report variables that, in real life, would be unobservable. Use the colour palette and paintbrush to reinstate the original coloured trajectories for the Fish stock (blue) and New fish per year (red). You will find the appropriate colours on the top row of the palette. (If you accidentally set the background colour of the chart to blue or red, which can happen if you don't align the paintbrush with the variable name, don't panic. Simply return to the colour palette, select light grey, and repaint the background. Then try again to re-colour the trajectories.) The resulting chart will look like Figure 1.10, with all the trajectories clearly visible, except that yours will be in colour.

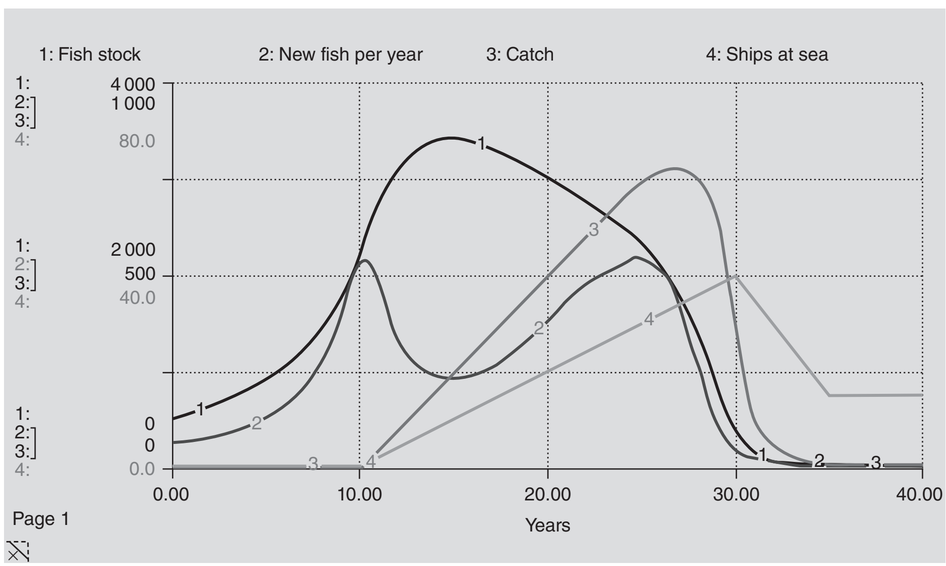

Figure 1.10 Simulation of harvested fishery showing all trajectories

Consider the behaviour over time of the fish stock (line 1). For the first 10 years of the simulation the number of fish grows swiftly because effectively there is a natural fishery (no ships) that is underpopulated relative to its carrying capacity. In years 10–15 commercial fishing begins and each year more ships are sent to sea (line 4). Nevertheless, the fish population continues to increase. These are the early growth years of the Bonavista community. During this entire period the catch is rising (line 3), but is always below the rate of regeneration (new fish per year, line 2). The fishery is sustainable with growing population. In years 15–20 the catch continues to rise steadily in line with fleet expansion, but the fish stock begins to decline gently as the catch exceeds the number of new fish per year (line 3 rises above line 2). This excess of catch over regeneration is not necessarily a problem for long-term sustainability because harvesting is actually stimulating the regeneration of fish, as shown by the steady increase in new fish per year. A harvested fishery, even a well-run one, will always have a fish population considerably lower than the maximum fishery size.

Herein lies a fundamental dilemma for fisheries management. Who is to say whether a decline in fish population is a problem or not? It could just be a sign of effective harvesting in a period of growth. Moreover, and this is vitally important to remember, nobody knows for certain how many fish of a given species are in the fishery. At best there are estimates subject to measurement error, bias and even manipulation. So it is very difficult in practice to make fish stock itself (how many fish are believed to be in the sea) the basis for investment policy (how many ships to purchase). Much more persuasive evidence comes from the catch. The simulation shows catch rising all the way through to year 25 and beyond. The temptation, even in years 20–25, is to believe that further fleet expansion is both desirable and justified. The conflicting signals from fish stock (a weak signal at best) and the catch (a strong and tangible signal of immediate economic and personal importance to fishermen and fleet operators) form the basis of the coordination problem in fisheries. Throughout year 25 and even into year 26 it is not unreasonable to continue fleet expansion even though the invisible fish population is in steady decline.

However, in year 25 something of vital significance happens under water, hidden from all but the fish themselves. The number of new fish per year (line 2) peaks and then starts to decline. This is the first evidence, a kind of early warning signal, that the fishery is being overfished. Fish density is now so low that regeneration is suppressed. The fishery teeters on the brink of catastrophe. The rate of population decline (the steepness of line 1) increases. But the catch keeps on rising throughout year 26 so no action is taken to curtail fleet expansion. In year 27 the catch itself peaks and then declines, gradually at first. This is the first tangible evidence of stock depletion underwater, but even so the signal is likely to be ignored until the trend proves conclusive and until the fishing community persuades itself to limit fishing. In the simulator, we assume that new ship purchasing continues apace until year 30. By then the fish stock has fallen to around 400, only 10% of the maximum fishery size. The regeneration rate (new fish per year) is still in decline and far below the much reduced catch. Measures to halt investment and to idle ships in years 30 to 40, drastic though they are, are too little too late. Bonavista's fish have all but gone and with them the industry on which the community depends. By year 35 there are so few fish left (only 16!) that, even with a total

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ban on fishing, it would take two decades to rebuild the stock to its value in year 10 when our imagined Bonavista first began commercial fishing.

Saving Bonavista – Using Simulation to Devise a Sustainable Fishery

Now you are familiar with the gaming simulator, you can use it to test alternative approaches to growing and developing the Bonavista fishery. First press the 'Reset' button to obtain a new blank time chart and to re-initialise the simulator. Next, without altering either slider, press the 'Run' button twice in order to simulate 10 years of natural growth in the fish population so that Bonavista inherits a well-stocked fishery. Then re-simulate the same fleet expansion as before – two ships per year for years 10–25. You will find yourself back in Bonavista's heyday with a fleet of 30 ships and a history of 15 years of steady growth in the catch. Now it is your responsibility to steer the community toward a sustainable future that avoids the errors of the past. For realism you may, as before, want to 'grey-out' the trajectories for fish stock and new fish per year. What is happening to the fish stock underwater is difficult to know, vague and often subject to controversial interpretation. Also bear in mind the practical political difficulties of curtailing growth and of idling ships in a community that depends on fishing. Think about *plausible* adjustments to the two sliders at your disposal. It is a good discipline to note your intentions, and the reasoning behind them, *before simulating*. Imagine you first have to convince the Bonavista community and fishermen to adopt your plan. Then, when you are ready, simulate, analyse the trajectories and try to make sense of the outcome. Was the result what you expected? If not then why? If you don't like the result then try again.

Dynamic Complexity and Performance Through Time

Although in principle it is possible to create a sustainable Bonavista it is very difficult to do so in practice or even in a simulator, particularly when you inherit a fleet of 30 ships following 15 years of successful economic growth. The fisheries simulator is one example of a dynamically complex system, of which there are others in this book and many more in life. Often such systems give rise to puzzling performance through time – performance far below the achievable and, *despite the best of intentions*, not what people (stakeholders in the system) want. In this case, the fishery is prone to catastrophic decline when perhaps all that fishermen desire, and the fishing community wants, is growth, more and better ships, and a higher standard of living. Dynamic complexity stems from the connections and interdependencies that bind together social and business systems. When a change happens in one part of the system (e.g. more ships are purchased) sooner or later it has implications elsewhere, and vice versa. Moreover, these implications are not always obvious and are often counterintuitive (e.g. more ships can lead to a *greater* rate of fish regeneration, but not always).

Dynamic complexity does not necessarily mean big, detailed and complex, involving hundreds or thousands of interacting components. Indeed, as the fisheries simulator shows, dynamic complexity and puzzling performance can arise from only a few interacting components. What matters is not so much the raw number of components but the intricacy with which they are bound together.

Such intricacy involves time delays, processes of stock accumulation (such as the accumulations of ships and of fish), non-linearities (such as the hump-shaped relationship between fish density and fish regeneration), and closed feedback loops (such as the reinforcing relationship between fish stock, fish density, fish regeneration and fish stock). These special terms, the language of feedback systems thinking, will become clearer later. For now it is sufficient to appreciate that dynamic complexity stems from intricate interdependencies of which there are many, many examples in our increasingly interconnected world. Sometimes it is possible to reduce dynamic complexity by making interdependencies less entwined and more understandable. Indeed, this goal of simplification is really the ultimate aim of policy design in system dynamics – redesigning social and business systems so that, despite their complexity, normally-competent people can run them successfully.

Why are fisheries so dynamically complex? What changes would make them less prone to sudden and catastrophic decline? Herein lies the whole area of fisheries policy involving fishermen, fishing communities, governments, marine scientists, consumers and fish themselves. There is a lot that could be modelled about the interactions among these stakeholders and arguably a serious fisheries policy simulator would be much bigger and would involve many more variables and relationships than those in our small Bonavista model. Nevertheless, at the heart of any such model will be a representation of the factors – biological, economic, political and social – that determine the balance of ships at sea and fish in a commercial fishery.

A vital part of dynamic complexity in fisheries lies in the relationship between the catch and fish density. Not surprisingly, if the fish density is very low then it is difficult for fishermen to locate fish and the catch is lower than normal. But the relationship is non-linear as shown in Figure 1.11. Here, fish density is measured on a scale from zero to one, where one is the highest possible density (the number of fish is equal to the carrying capacity) and zero is the lowest (there are no fish). The vertical axis shows the effect of fish density on catch per ship, also on a scale from zero to one. In our imagined Bonavista, the normal catch per ship is 25 fish per ship per year – remember this is a scale model. The actual catch per ship is obtained from the product of normal catch (25) and the effect of fish density.

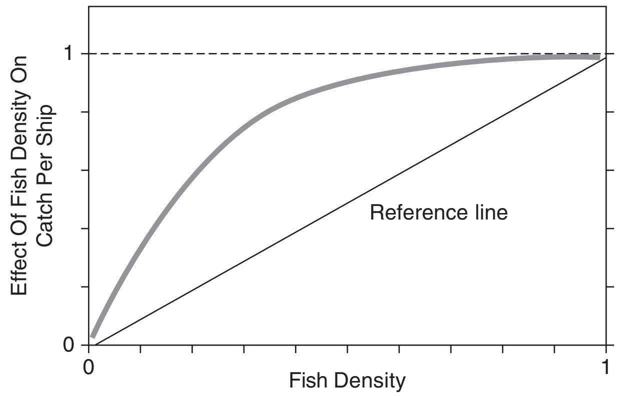

Figure 1.11 Relationship between catch per ship and fish density

When the fish density is high, in the range between 0.7 and one, the catch per ship is stable at 25 because there is little or no depressing effect from fish density. The sea is full of fish and they are easy to find and catch. When the fish density is lower, in the range 0.4 to 0.7, the catch is still very close to normal (25). The assumption, borne out empirically in real fisheries, is that fish are still quite easy to find even when there are fewer, because they tend to cluster. Only when the fish density falls very low, in the range between zero and 0.4, does scarcity make fishing more difficult. In this narrow range the effect of density falls swiftly from 0.9 (almost normal) to zero.

The non-linearity, the sudden depressing effect of density on the catch, makes fisheries management difficult. You can appreciate why if you imagine the argument between a marine biologist and a fisherman about the need to conserve stocks. When the fish population falls to half the maximum (fish density equal to 0.5) the marine biologist argues that stocks are too low. But the fisherman reports (accurately) there is no difficulty catching fish, so what's the problem? In all likelihood, the fisherman thinks the fish stock is actually higher than the marine biologist's estimate. The biologist is exaggerating the problem, or so it seems to someone whose livelihood depends directly on the catch. When the fish population falls to one-quarter of the maximum (fish density equal to 0.25) the marine biologist is frantic and even the fisherman is beginning to notice a reduction in the catch, down by about one-third relative to normal. That outcome, though worrying, is not obviously fatal. Perhaps with a bit more effort and luck the poor catch can be rectified, and why believe the marine biologist now, when he/she was seemingly so wrong and

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alarmist before? The non-linearity creates confusion in the attribution of causality – what causes what in the system – and such confusion is a typical symptom of dynamic complexity.

Cunning Fish – A Scenario with Reduced Dynamic Complexity

If we lived in a world where fish were cunning and took steps to avoid capture when they noticed a decline in their numbers (as though responding to a census) then the dynamic complexity of fisheries would be reduced and, ironically, fish stocks would be easier to manage for sustainability. To represent this thought experiment the effect of fish density on catch per ship is modified. Instead of being non-linear it becomes linear, as shown by the reference line in Figure 1.11. As fish density falls the fish take action to protect themselves. Suppose they disperse instead of clustering. So now, even with a slight decline in density, it is more difficult for fishermen to fill their nets. The effect of density falls below one and the catch per ship is reduced. The lower the density, the lower the catch per ship – a simple linear relationship. Now let's simulate the same Bonavista growth 'strategy' as before: purchase two new ships per year from years 10–30; and then, in years 30–40, stop new purchases and idle some ships by keeping them in harbour.

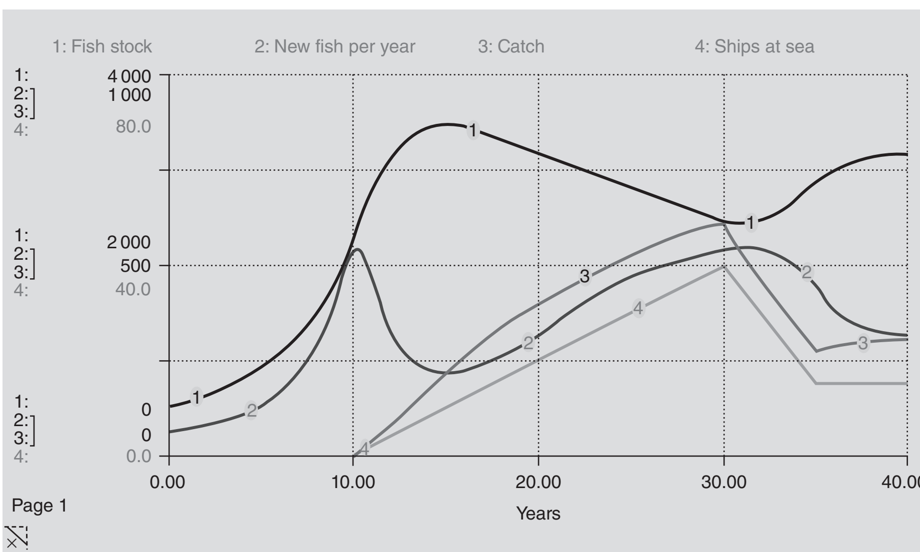

Figure 1.12 Simulation of harvested fishery with cunning fish – a thought experiment

The result is shown in Figure 1.12. This is a scenario of reduced dynamic complexity and is created by running the model called 'Fisheries Gaming Simulator – Cunning Fish' in the learning support folder for Chapter 1. Admittedly it is imaginary and fanciful but nevertheless interesting. The most obvious difference by comparison with Figure 1.10 is that the fish stock (line 1) no longer collapses in the period between years 25 and 30.

Instead, there is a steady and gradual decline in the number of fish from about 2800 in year 25 to 2400 in year 30. Crucially, the trajectory of the catch (line 3) is also different even though Bonavista's fleet profile (line 4) is identical to the profile in Figure 1.10. Here we see the practical effect of cunning fish. Trace the precise shape of the catch in the period between years 10 and 25 and compare it year-by-year with the catch in Bonavista's original years of growth and prosperity in Figure 1.10. Between years 10 and 15, the two trajectories are almost visually identical, a result that is not too surprising because fish are plentiful and growing in number and the fleets are of equal size. However, between years 15 and 20, quite early in Bonavista's growth surge, there is a noticeable difference in the two catches. The rate of increase in Figure 1.12 begins to slow as fish, whose numbers are just beginning to decline, evade capture – at least some of them do. By year 20, the catch is 400 fish per year whereas in Figure 1.10 it is 500 fish per year, 25% higher. The divergence continues through to year 25, with a catch of 530 cunning fish per year in Figure 1.12 versus 750 normal fish per year in Figure 1.10, which is 40% higher. Moreover, it is already becoming apparent to fishermen that cunning fish are fewer in number because the catch per ship is less than it used to be (roughly 18 fish per ship per year in year 25 – obtained by dividing a catch of 532 fish per year by a fleet of 30 ships versus 22 fish per ship per year in year 15 – obtained by dividing a catch of 220 fish per year by 10 ships). By year 30, the fortunes of the two Bonavistas are dramatically reversed. In Figure 1.12, the catch is 615 cunning fish per year and rising by comparison with 380 normal fish per year in Figure 1.10 and plummeting.

In the cunning fish scenario it is much easier to take effective corrective action to save the fishery. By year 30 there is still a reasonably large fish population of almost 2500 fish. However, marine biologists can argue that the stock is significantly depleted (to just over 60 per cent of the fishery's maximum size of 4000 fish) and fishermen will be inclined to agree because the catch per ship they are experiencing is now only about 15 fish per ship per year (615 fish per year by 40 ships) – a productivity decline of 17% in five years and 25% in 10 years. The exact same fleet reduction measures as before now work successfully to revitalise the fishery. Starting in year 30, a combination of enforced idling of five ships per year plus a ban on new purchases causes the active fleet to fall (line 4). Note that by the end of year 30 the catch (line 3) has fallen to equal the regeneration rate of new fish per year (line 2), so the fish population stabilises. By the third quarter of year 32, less than two years after the first cuts in fleet size, the fish stock is growing and fishermen are noticing an increase in catch per ship, up by 7% to 16 fish per ship per year from 15 in year 30. The enforced idling of 10 ships over two years is still very painful for the community, but at least there are positive results to show for the sacrifice. By year 35, the end of enforced idling, the active fleet or ships at sea (line 4) is down to 15, the catch (line 3) is down to 270 fish per year and the catch per ship is up to 18 fish per ship per year – an improvement of 20% over five years. In the final interval to year 40, the active fleet size remains constant at 15 ships. New fish per year (line 2) gradually converge to equal the catch (line 3) so that by year 40 the fishery is in long-term equilibrium with almost 3200 fish. The Bonavista community with its fishermen and its nearby colony of cunning fish has achieved a sustainable future.

Preview of the Book and Topics Covered

The fisheries simulator demonstrates a general point that dynamic complexity within business and social systems makes management and strategy development difficult. The performance of firms and industries over time rarely unfolds in the way we expect or intend. The purpose of strategic modelling and business dynamics is to investigate dynamic complexity by better understanding how the parts of an enterprise operate, fit together and interact. By modelling and simulating the relationships among the parts we can anticipate potential problems, avoid strategic pitfalls and take steps to improve performance.

The rest of the book demonstrates the art and science of system dynamics modelling. Chapter 2 introduces causal loop diagrams as a powerful conceptual tool to visualise interdependencies and take a strategic overview of operations. Chapter 3 introduces the additional concepts and tools required to translate causal loops into algebraic models and simulators. Chapter 4 provides an opportunity to experiment with a simulator and gain insight into cyclical dynamics by 'managing' the water temperature in an imaginary hot water shower. At first glance, World of Showers is far removed from the worlds of business or public policy, but the gaming simulator vividly illustrates the coordination problem at the heart of balancing loop dynamics found in many practical management situations. Players can also redesign the shower model to improve personal comfort, just as business simulators are used to redesign operating policies to improve corporate performance.

Chapters 5, 6 and 7 present a variety of business applications, covering topics such as cyclicality in manufacturing, market growth and capital investment. The models in these chapters are deliberately small and concise so their structure and formulations can be presented in full and used to illustrate principles of model conceptualisation, equation formulation and simulation analysis. Chapters 8 and 9 present larger models that arose from real-world applications. Chapter 8 investigates the upstream oil industry and the dynamics of global oil producers that affect us all through the volatile price of oil and gasoline. The chapter includes a description of the model's conceptualisation,

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a thorough review of the resulting feedback structure of global oil markets, a sample of equation formulations and a comprehensive set of simulations. Chapter 9 presents public sector applications of strategic modelling. We briefly review a classic model about the growth and economic stagnation of cities. Next there is a model that investigates the dynamics of hospital doctors' workload and patient care. Then we return to fisheries and further develop the gaming simulator from this chapter into a fully endogenous model of fisheries that includes investment and regulatory policy. Finally, Chapter 10 addresses the important topic of model validity and confidence building, using a model of product innovation in fast-moving consumer goods to illustrate a variety of tests of model integrity and quality. The chapter ends with a review of all the models covered in the book and some philosophical yet practical comments on realism, model fidelity and learning.

Throughout the book there are exercises with simulators that illustrate the dynamics of interest and allow readers to conduct their own tests and policy experiments. The simulators can be downloaded from the book support website (www.wiley.com/go/strategicmodelling2e). Each is designed with an interface that makes it easy to run simulations, interpret the time charts, change selected parameters and explore the underlying model structure and equation formulations. They offer a useful way to experience dynamic complexity and to develop an intuition for the causes and cures of puzzling dynamics in businesses and society.[7,8]

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[7]Here, at the end of Chapter 1, is a good place to issue a challenge for readers who, on completing the book, wish to further develop their modelling skills on a really important dynamic problem. The task is to rebuild the *World Dynamics* model to address the effects of global warming, with the intention of creating a small-scale simulator that can be used to raise public awareness of the need for us all to cut carbon emissions. By public awareness I mean awareness in your community, company, department, university or school. Background material for this personal project can be found in *2052: A Global Forecast for the Next Forty Years* (Randers 2012), *The Vanishing Face of Gaia* (Lovelock, 2009) and in *Last Call*, a documentary film about the *Limits to Growth* project (Cerasuolo, 2013)). More ideas can be found in the 30-year update of *Limits to Growth* (Meadows, *et al*., 2002), in Thomas Fiddaman's prize-winning work on a climate–economy model (Fiddaman, 2002) and in *A Rough Ride to the Future* (Lovelock, 2014). But remember, the main objective in this challenge is to create a compact and vivid model to raise local public awareness of the effects of climate change rather than to develop a calibrated climate–economy model for climate scientists and policy advisers. Incidentally I decided to set myself the task of rebuilding the *World Dynamics* model. An overview of my approach can be found in 'Metaphorical Models for Limits to Growth and Industrialization' (Morecroft, 2012). Sample models and supporting materials are available online from the System Dynamics Society www.systemdynamics.org. See Morecroft ISDC Workshops 2011–2013 for more details.

[8]See also John Sterman's online interactive simulator on climate change. The simulator, available at http://web.mit.edu/jsterman/www/GHG.html (accessed 20 February 2015), is based on the 'bathtub dynamics' experiments carried out at the MIT System Dynamics Group (Sterman & Booth Sweeney, 2007). The results show that even highly educated people with strong backgrounds in mathematics and the sciences have great difficulty relating the flow of greenhouse gas (GHG) emissions to the stock of greenhouse gases in the atmosphere. Further material on the 'bathtub dynamics' of greenhouse gases can be found in *World Climate*, a vivid interactive role play negotiation of a global climate agreement using a simulator called C-ROADS (Sterman, *et al*., 2011).

There are also two electronic topics that can be found in the folders for ‘v-Lectures 1 and 2’ on the Learners’ website. The topics are ‘dynamics of diversification’ and ‘managing metamorphosis’. Diversification is an important part of corporate (multi-business) strategy and complements material in Chapters 6, 7, 8 and 10 on the dynamics of single-business firms and of entire industries. Metamorphosis is a process of managed adaptation to change in the business environment.

Appendix – Archive Materials from *World Dynamics*

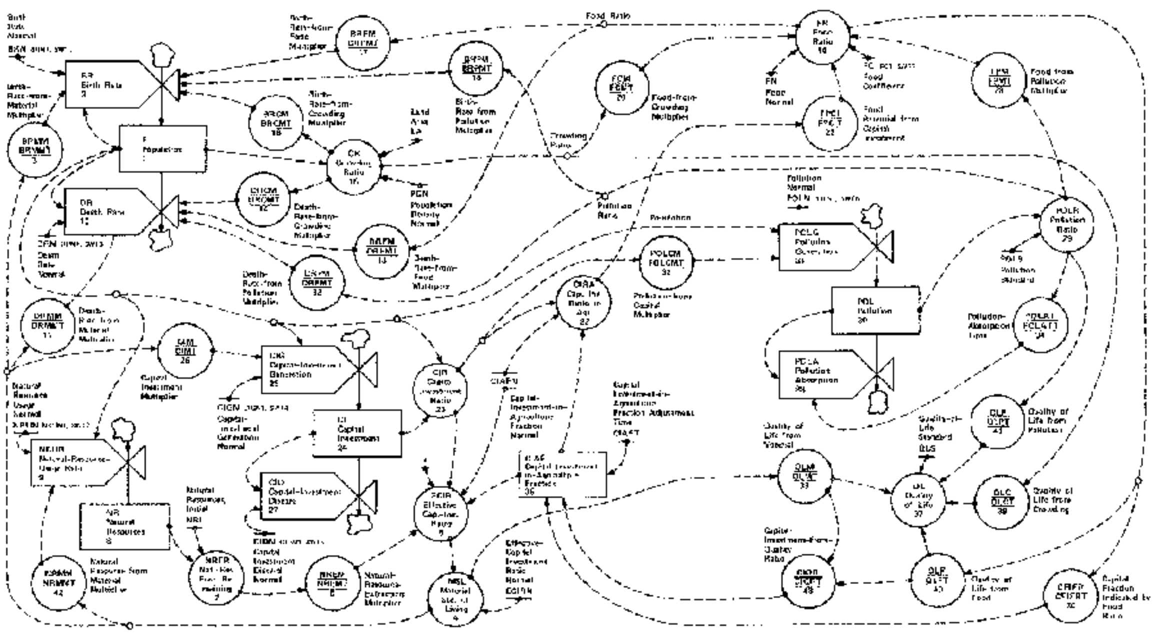
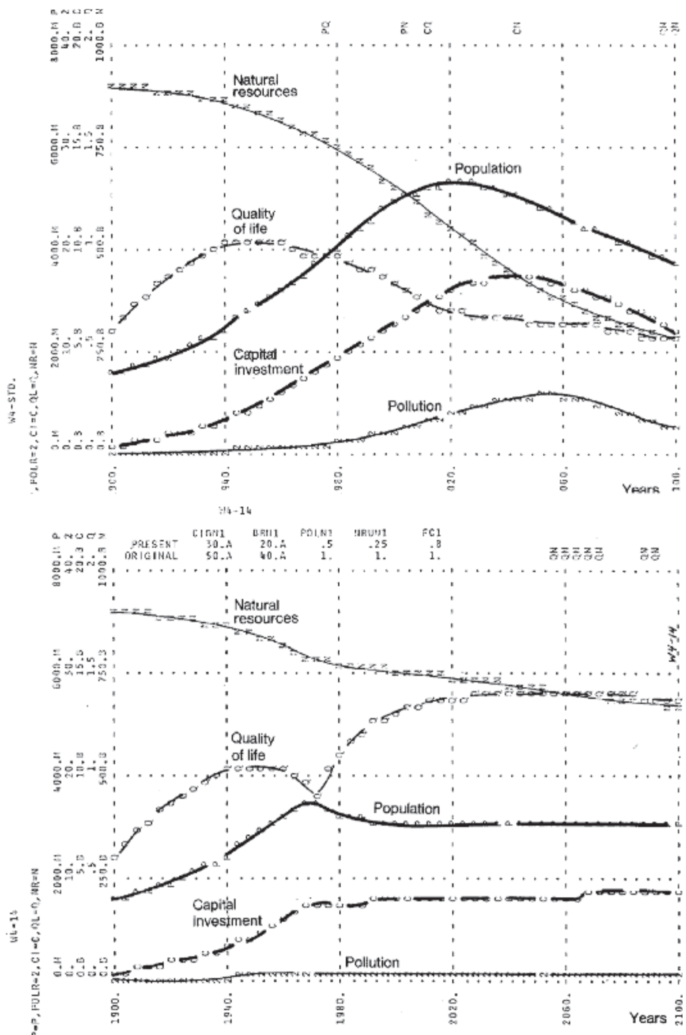


Figure 1.13 Diagram of the original *World Dynamics* model

This world model is a beginning basis for analysing the effect of changing population and economic growth over the next 50 years. The model includes interrelationships of population, capital investment, natural resources, pollution and agriculture. *Source:* Forrester, Jay W., *World Dynamics*. 1973, pp. 20–21, Reproduced by permission of Jay W. Forrester.



Basic world model behaviour showing the mode in which industrialisation and population are suppressed by falling natural resources

One set of conditions that establishes a world equilibrium at a high quality of life. In 1970 normal capital investment rate is reduced by 40 per cent, normal birth rate is reduced by 50 per cent, normal pollution generation is reduced by 50 per cent, normal natural resource usage rate is reduced by 75 per cent, and normal food production is reduced by 20 per cent

Figure 1.14 Simulations of the original world dynamics model

Source: pages 225 and 232 of 'Counterintuitive Behavior of Social Systems', Chapter 14 in the *Collected Papers of Jay W. Forrester*, originally published by Wright-Allen Press, 1975, available from the System Dynamics Society www.systemdynamics.org, Reproduced by permission of Jay W. Forrester.

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