Metaphorical Models for Limits to Growth and Industrialisation

Forthcoming in *Systems Research and Behavioral Science* 2012

John DW Morecroft

London Business School

Regent's Park

London NW1 4SA

UK

jmorecroft@london.edu

Abstract

In this paper I present two system dynamics models and simulators to explore sustainability and limits to growth in industrial society. I first describe a small model of the fishing industry. I then use the same model as a metaphor to think about global growth and industrialisation and to interpret the closed-loop feedback structure and dynamics of Jay Forrester's *World Dynamics* model. This famously concise (yet dynamically intricate) model represents an industrial society whose growth is eventually curtailed. My approach with both models is to investigate the feedback structure surrounding investment policy. Building on this material I examine the value of metaphorical models for interpreting puzzling phenomena in business and society. Finally I discuss generic coordination problems in managing the growth of firms, industries and society.

Keywords: growth and industrialisation; sustainability; investment policy; bounded rationality; coordination; cognitive limits to growth; models for inductive reasoning and learning

Modelling and Realism – A Spectrum of Model Fidelity

It is a paradox of complexity that puzzling performance through time in business and society is often observed in tiny models containing only a handful of dynamical concepts. Even the most basic dynamic process of stock accumulation is poorly understood (Booth Sweeney and Sterman 2000). That such dynamic complexity can appear in simple guise is especially relevant to debate and public understanding of growth, industrialisation and climate change (Sterman 2008).

Figure 1 illustrates a spectrum of model fidelity and realism. Models range in size from large and detailed to small and metaphorical. On the left-hand side are analogue, high-fidelity models epitomised by aircraft flight simulators used to train pilots and to rehearse crisis scenarios. They are constructed with realistic detail and accurate scaling to provide a vivid and lifelike experience of flying the aircraft they represent. People typically expect business and social models to be similarly realistic; the more realistic the better. But very often smaller models are extremely useful, particularly when their purpose is to aid communication and to build shared understanding of contentious problem situations in business and society.

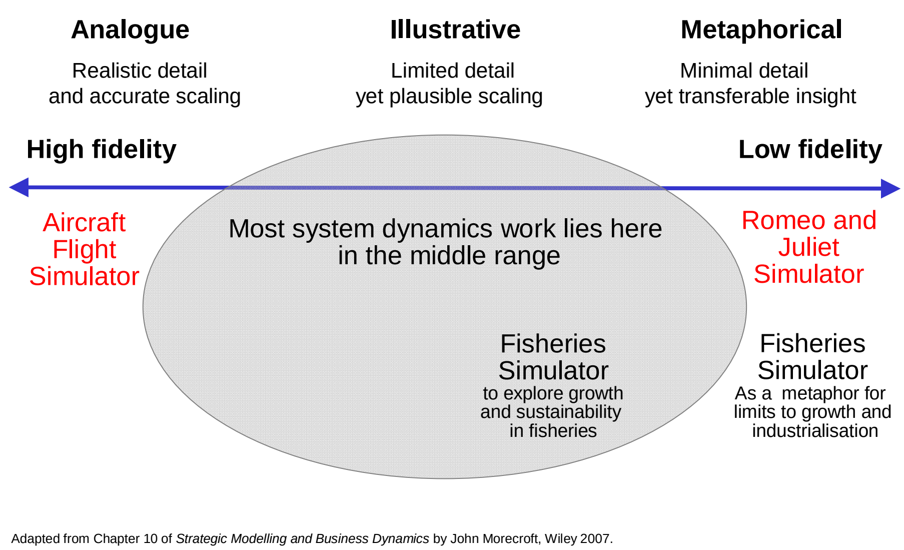


Figure 1: Modelling and Realism: A Spectrum of Model Fidelity

As Figure 1 suggests, the spectrum of useful models can include illustrative models (of limited detail yet plausible scaling) or even tiny metaphorical models (of minimal detail yet transferable insight). At the far right of the spectrum is a low fidelity Romeo and Juliet simulator. The particular simulation model I have in mind contains just four main concepts: Romeo's love for Juliet, Juliet's love for Romeo and the corresponding rates of change of their love. It is used as a metaphorical model or transitional object[i] to help undergraduates and high school students to better understand something complex and abstract – differential equations or even Shakespeare's play. Clearly, a simulator cannot possibly replicate Shakespeare's play, but it can encourage students to study the play more closely than they otherwise would. By simulating the waxing and waning of love between Romeo and Juliet, students engage their natural curiosity about romantic relationships, both in the model and in the play[ii]. It is this metaphorical property of small models - to attract people's attention, to encourage them to reflect and debate - that I wish to illustrate for the interlocking issues of growth, sustainability and industrialisation.

I first describe a small system dynamics model of the fishing industry to explore growth and collapse of commercial fisheries, inspired by the widely-used Fish Banks gaming simulator (Meadows et al 2001). I then use the same model as a metaphor to think about limits to global growth and industrialisation and to interpret the closed-loop feedback structure and dynamics of Jay Forrester's *World Dynamics* model (Forrester 1973). This famously concise (yet dynamically intricate) model represents an industrial society whose growth is eventually curtailed.

All models of business and society are stylised simplifications. It is therefore important to consider the credibility and value of model-based insights and to recognise why and when small and metaphorical models are appropriate and helpful. In the conclusion of the paper I consider these issues in the light of two classic models from the economics literature. I identify properties of these small models that make them useful for inductive reasoning and learning. Similar properties are to be found in the fisheries and *World Dynamics* models. I also discuss sources of evidence for key assumptions in stylised models. Building on this material I discuss generic coordination problems in managing the growth of firms, industries and society.

An Ilustrative Model of a Harvested Fishery

Harvested fisheries are prone to catastrophic decline that nobody involved – fishermen, politicians or consumers - would wish on themselves. Generation-long periods of growth and prosperity are often followed by a surprise collapse in the fish stock. But why? Intuitively one senses it is difficult to coordinate ships at sea with an 'invisible' fish stock, as illustrated in Figure 2. Here the easily-observable aspects of the fishery are depicted in black: purchase of new ships, ships at sea, harvest rate, ships moved to harbour, and ships in harbour. The invisible aspects of the fishery are greyed-out: fish stock and new fish per year.

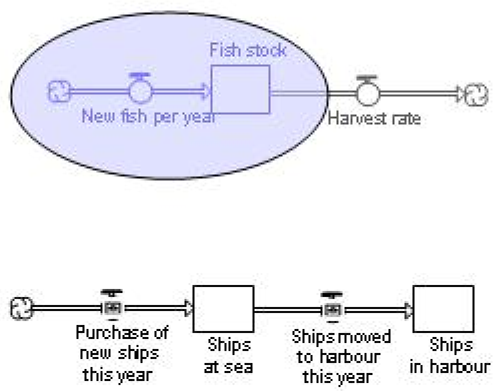


Figure 2: Visible and Invisible Asset Stocks in Fisheries

System dynamics can provide insight into the fisheries coordination problem and a theory of resulting unintended dynamics. To understand the coordination of fish and ships we need to endogenise the purchase of new ships (investment). In other words we need to ‘close the loops’ surrounding investment policy. To do so we make two plausible behavioural assumptions to formulate an endogenous investment policy. The first assumption is that people (fishermen, ship owners, fishing communities) have a propensity for growth and therefore like to acquire more and better ships. The second assumption is that economic forces will eventually curtail investment if the ‘return’ (in this case the catch per ship) is deemed to be too low. The full formulations are described in the Appendix. Later in the paper I consider the evidence that justifies the assumptions, but for now I hope the reader will find them self-evident and reasonable.

Let’s see what happens in a fishery when these assumptions are used to determine the purchase of new ships (in other words investment) and when the function governing fish regeneration is based on standard formulations from marine science (a combination of Ricker’s density dependent stock-recruitment relationship and a density dependent S-shaped natural mortality rate; Stouten 2010, Nikolskii 1969).

Simulated Dynamics of a Harvested Fishery with Endogenous Investment

The model is initialised with 10 ships and 3370 fish, resulting in a catch of 250 fish per year and equivalent net regeneration of 250 fish per year[iii]. This harvest rate is below the maximum sustainable yield to allow room for growth and to investigate the dynamics of investment and the resulting stocks of fish and ships. The propensity for growth in the investment policy is set at a normal value of 0.1, or 10 percent of the current fleet size. The results of following this investment policy are shown in Figure 3.

Starting in year 0 the number of ships at sea (line 4) increases steadily. For fourteen years the catch rises. Meanwhile the catch per ship (line 5) remains constant at a high enough value that continued investment is both feasible and desirable. Below the waves conditions are changing, but remember these conditions cannot be directly observed by fishermen. The regeneration rate of fish (new fish per year, line 2) rises, just as one would expect in a well-harvested fishery. The fish population falls, but that too is expected in a harvested fishery.

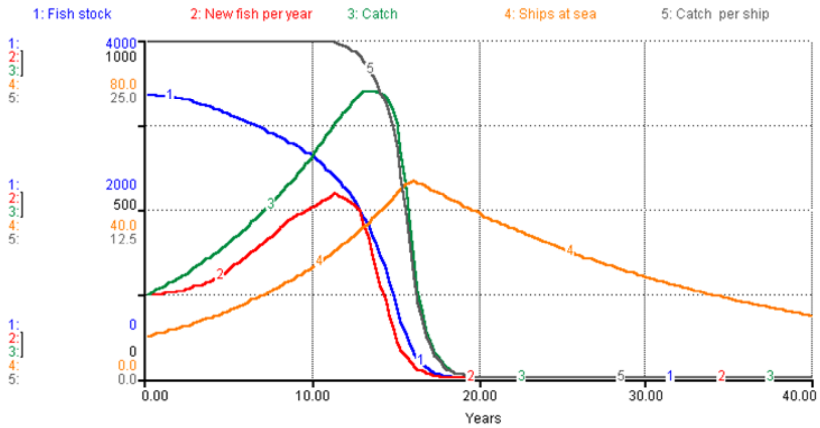


Figure 3: Growth and Unintended Collapse in a Closed-Loop Harvested Fishery with Endogenous Investment

Signs of trouble appear underwater in year 11 when, for the first time, regeneration (new fish per year, line 2) falls. This reversal of replenishment is a signal that the fishery has passed the tipping point of the non-linear regeneration curve. The decline in the fish stock begins to accelerate. But interestingly the catch (line 3) continues to rise for fully three more years, until year 14, and the catch per ship (line 5) remains close to normal. From the viewpoint of growth-oriented fishermen floating on the waves it is business as usual. The fleet continues to grow until year 16 when it reaches a size of 47 ships. By then the catch per ship (line 5) has fallen to less than one third of normal (only 8 fish per ship per year instead of 25), which is sufficiently low to curb further investment.

By now the hidden fish stock (line 1) has fallen to only 300, less than one tenth of its initial value. With so few fish in the sea the regeneration rate is precariously low at only 30 new fish per year, well below the catch of around 300 fish per year. Fishermen are now well aware of the underwater crisis and respond accordingly by selling ships. The fleet size (ships at sea, line 4) falls from a peak of 47 ships in year 16 to 39 ships in year 20. But it is too little action too late. The investment policy fails to reduce the fleet quickly enough to halt the decline of the fish stock. By year 20 there are only four fish left in the sea and regeneration has fallen practically to zero. The fishery has collapsed and is left with a huge excess of relatively new ships owned by fishermen reluctant to sell and still dependent on the fishery for their livelihood. The feedback structure of an unregulated fishery leads to boom and bust in the catch.

The conclusion from simulating a closed-loop harvested fishery is that a natural human desire for growth and prosperity (the spur for enterprise and investment) subsequently leads to overinvestment. However it is very difficult in practice to discern when the dividing line between healthy buoyant investment and overinvestment has been crossed Although in both the model and reality there is eventually downward economic pressure on investment, based on persuasive evidence (declining catch per ship), it is unable to curtail growth soon enough. The fishery collapses.

To avoid collapse, investment policy needs to take proper account of the fish stock and fishing effort needs to be restrained early, when scientific evidence of depletion is first evident. In other words there needs to be much better coordination of fish and ships than is normally achievable from purely operational and market-based pressures. Successful coordination, though rarely achieved in commercial fisheries, comes from rigorous regulation and enforcement based on credible scientific information about the number of fish remaining. Fisheries regulatory policy is a large topic beyond the scope of this paper[iv]. Here I just wish to demonstrate the phenomenon of overfishing in a simple yet plausible model.

Developing the Metaphor

Like a fishery, a sustainable industrial society must coordinate key stock accumulations. Consider for now just two tangible stocks: industrial capital and natural resources. What can we say about the stock and flow network, the coordinating network and interlocking feedback structure? Here are some plausible and enduring assumptions that characterise economic development, and have done so since the industrial revolution in the 1800s: 1. An industrial society has a strong propensity for growth and capital investment; 2. More capital leads to higher output and a higher material standard of living which boosts investment; 3. There is a limited but very large supply of natural resources; 4. Resource usage is proportional to industrial capital.

Industrial capital is rather like ships at sea and investment is shaped by a similar deep-rooted propensity for growth. The more capital the more prosperous is society. Natural resources are, at first glance, rather like the fish stock – they are 'used-up' by industrial capital. However, there is one crucial difference. Unlike fish, many of the natural resources consumed by an industrial society are non-renewable, they do not regenerate themselves. So there is an outflow from the stock of natural resources (proportional to industrial capital) but no inflow.

These assumptions suggest an industrial society will grow until restrained by the available and finite supply of natural resources – an intuitive outcome more obvious than the growth and collapse of fisheries. But what if the pool of natural resources is vast, or can be replenished? Will growth continue and thereby prevent the demise of industrial society? Or could a more subtle and fragile limit be lurking in our midst, rather like the renewable-yet-hidden fish stock?

Pollution is a possible limit which, when included in our thinking, gives the three-stock model shown in Figure 4. But how does the amount of pollution develop through time? Here are some plausible and enduring assumptions about pollution: 1. Pollution generation depends on commercial activity. 2. Pollution accumulates yet is almost invisible (e.g. toxic chemicals in freshwater, CO_2 in the atmosphere); 3. The earth can disperse pollution, but at a decreasing rate as pollution rises.

Conceived in this way, pollution is rather like a mirror image of the fish stock. It is similarly hidden, difficult to measure and therefore contentious in its impact on society. It is a mirror image because its rate of increase is determined by commercial activity (whereas the fish stock is depleted by commercial fishing) and its *outflow* is determined by nature (whereas nature determines the *inflow* of new fish). Importantly the regenerative properties of nature in both cases (pollution absorption and fish births) are non-linear, making coordination of key stock accumulations very difficult. It would not be surprising to find dynamics of growth and unintended collapse in industrial society - just as in fisheries.

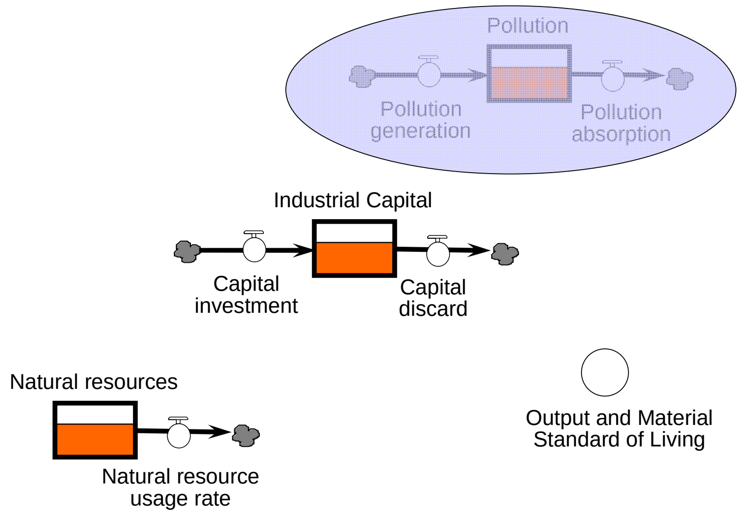
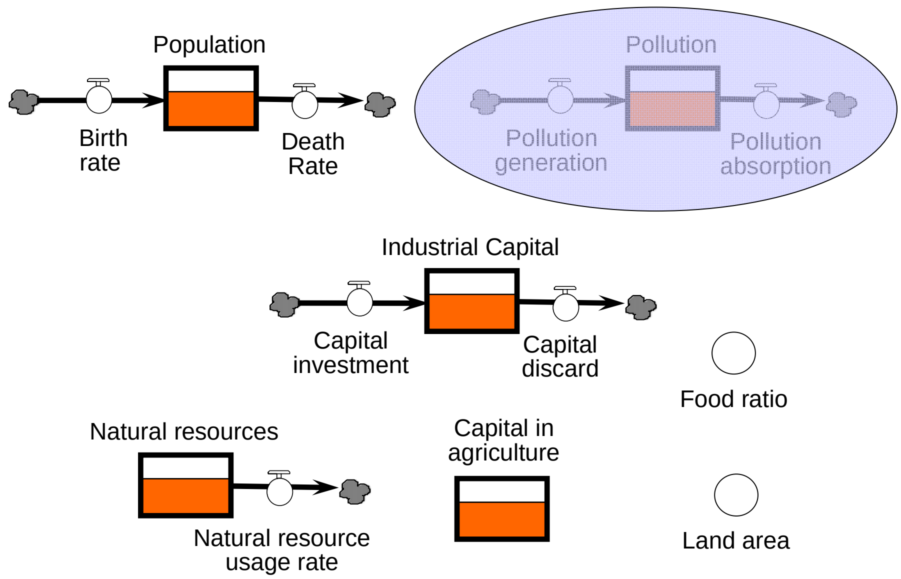


Figure 4: Developing the Metaphor – Visible and Invisible Stock Accumulations in an Industrial Society

World Dynamics and the World Model – A Concise Model of Limits to Growth and Industrialisation

The developed metaphor above brings us close to one of the most famous and influential studies in the field of system dynamics: Jay Forrester's *World Dynamics* (1973). The World model provides a remarkably compact visual and conceptual framework for thinking about sustainability of a global industrial society. Simulation reveals alternative futures implied by the model's intricate yet concise non-linear feedback structure.

There are the same three stock accumulations already considered and two more besides: population and capital in agriculture. All five stocks are shown in Figure 5.



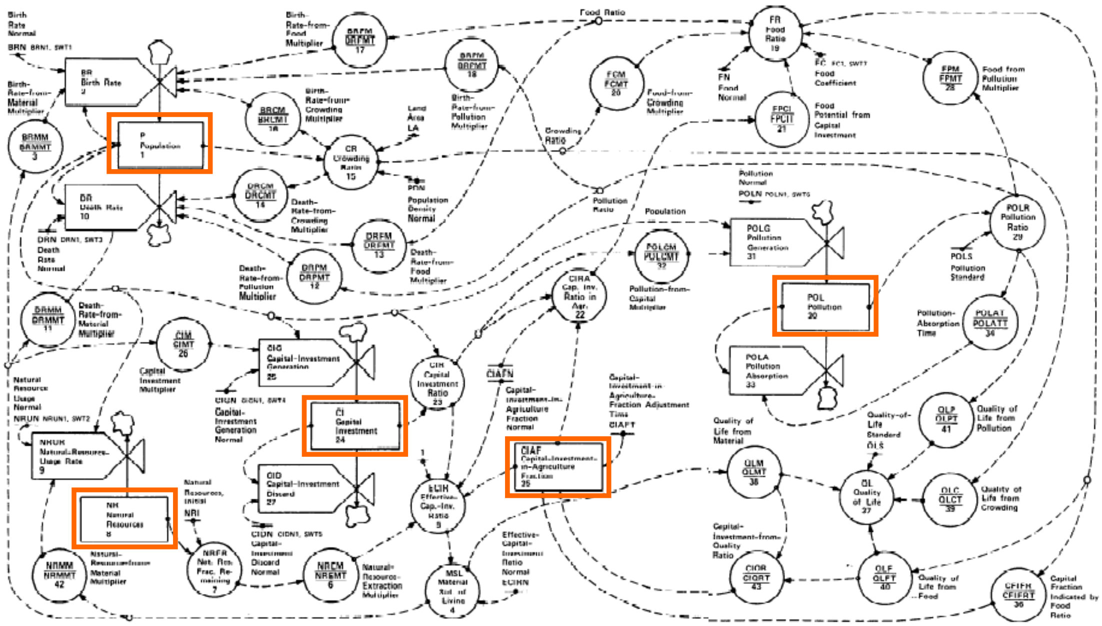
Adapted from pages 20-21 of *World Dynamics* by Jay Forrester, Pegasus Coomunications, Waltham MA 1973.

Figure 5: Stock Accumulations in Forrester's World Dynamics Model

Behind the scenes (and fully documented in Chapter 3 of *World Dynamics*) there are the following additional assumptions, plausible and enduring, about the coordinating network: 1. Population in an uncrowded world tends to grow exponentially through reinforcing feedback - in other words we like to reproduce; 2. Humans have a propensity to accumulate industrial capital; 3. Resource usage rate is proportional to population and the material standard of living; 4. Pollution generation is proportional to population and industrial capital (the determinants of commercial activity); 5. Births and deaths depend on a complex non-linear interaction of pollution, capital, food and population density; 6. The amount of capital in agriculture (as a proportion of industrial capital) declines as food availability rises and vice-versa.

Scenarios from the World Dynamics Model

The structure of the complete World model is shown in Figure 6. The image is an annotated copy of the original to be found on pages 20-21 of *World Dynamics* (Forrester 1973), and uses standard diagramming conventions from *Dynamo*, a popular simulation language at the time. The five main stock accumulations are depicted together with their respective flow rates[v]. The full visual detail of the coordinating network is shown, revealing a complex interlocking web of relationships that embody the assumptions mentioned above.



Source: pages 20-21 of *World Dynamics* (2nd edition) by Jay W. Forrester, Pegasus Communications, Waltham MA 1973.

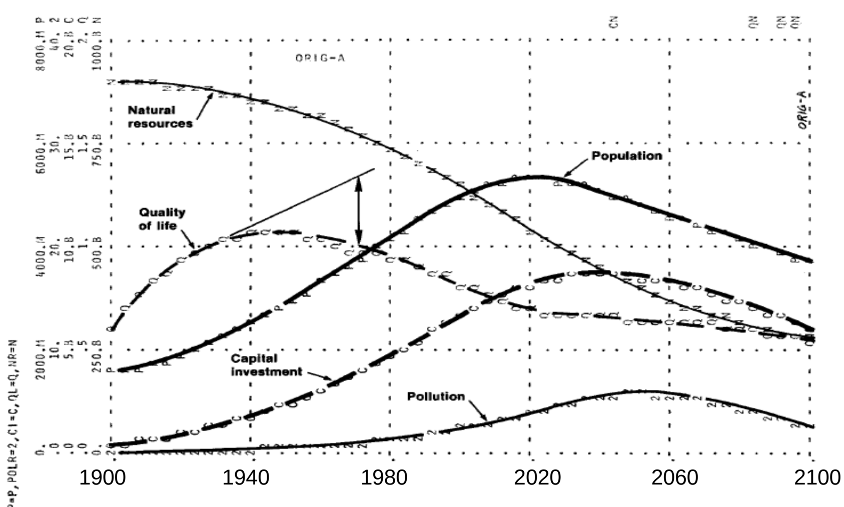
Figure 6: Diagram of the Original *World Dynamics* Model

Two simulation scenarios are now presented from chapter 4 of *World Dynamics.* I have chosen these particular scenarios because they demonstrate, within our industrial society, the same latent dynamics of growth and unintended decline as found in fisheries. For authenticity I have reproduced Forrester's original text[vi]. His clear interpretation of simulated trajectories enables the parallels to fishery dynamics to be easily drawn.

Basic World Model Behaviour

Figure 7 shows the behaviour of the original world model. Quoting from *World Dynamics* (pages 69-70):

> “The horizontal scale shows the time from year 1900 to 2100. Five variables of the system are plotted, giving four of the system levels and the quality of life. Population rises to a peak in the year 2020 and thereafter declines.
>
> The decline in population is caused in this figure by falling natural resources. The falling natural resources lower the effectiveness of capital investment and lower the material standard of living enough to reduce population. At about the year 2000, natural resources are falling steeply. The slope of the curve is such that, if usage continued at the same rate, natural resources would disappear by the year 2150.



Source: *World Dynamics (*2nd edition) by Jay W. Forrester, Pegasus Communications, Waltham MA 1973.

Figure 7: Archive Simulation of the World Model – base case showing the mode in which industrialisation and population are suppressed by falling natural resources.

[In the original formulations] the supply of natural resources was assumed sufficient to last for 250 years at the 1970 usage rate. But in Figure 7 the rate of usage (not plotted) rises another 50% between 1970 and 2000 because of the rising population and the increasing capital investment. Well before natural resources disappear, their shortage depresses the world system because of … the more difficult extraction task resulting from depleted and more diffuse stocks of resources. The effect of rising demand and falling supply is to create the dynamic consequences of shortage, not 250 years in the future, but only 30 to 50 years hence.

Discussions of the world system often rely on comparing present conditions with ultimate limits. By such comparison, present world demand [as observed in 1970] seems well below the capacity of the environment. But two factors are usually overlooked. First, demand is rising with a doubling time of only a few decades. Second, the consequences of impending shortage begin to appear long before an ultimate limit is reached. As we see here, the effect of resource shortage appears far ahead of the time resources are exhausted and within only a quarter of the time that would be required for present [1970] rates to deplete present [1970] supply. The same accelerated pressures can be expected from food shortage, crowding, and pollution.

Technology Breakthrough to Reduce Resource Usage

Quoting from *World Dynamics* (pages 74-75):

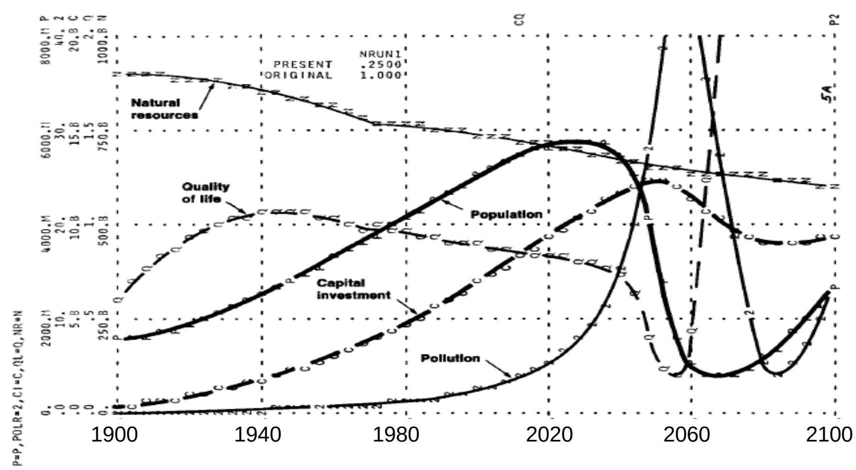
"In the preceding section the decline of natural resources halted the exponential growth of population and capital investment. Because the use of resources is continuous and irreversible, the continued decline of resources not only stopped growth but also reversed the trends and produced declines in world population and industrialization.

But natural resources may not be the most critical aspect of the world environment. It is easy to change the assumptions in the system model to reduce the dependence on natural resources.

Suppose we wish to assume that in the year 1970 the usage rate of natural resources were to be sharply curtailed without affecting any other part of the system. This might correspond to either an altered estimate of the actual rate of consumption relative to the available stocks in the earth, or it might correspond to technology finding ways to be less dependent on critical materials.

In Figure 8 the natural-resource-usage normal has been reduced to 25% of its original value in 1970. That is, if all other things were to be the same, the rate of consumption of resources would be a quarter of the previous value after 1970. Of course, other things do not remain the same. Natural-resource usage is still being affected by population and material standard of living. The latter two continue to change and now move along a different time path than before because they respond to the consequences of a more slowly declining resource pool.

The effect of reducing the demand for natural resources is to take one layer of restraint off the growth forces of the system. If natural resources no longer limit growth, the next growth-suppressing pressure will arise within the system.



Source: *World Dynamics (*2nd edition) by Jay W. Forrester, Pegasus Communications, Waltham MA 1973.

Figure 8: Archive Simulation of the World Model – showing the mode in which reduced usage of natural resources leads to a pollution crisis.

Figure 8 shows pollution as the next barrier to appear. A pollution crisis lurks within the system [in much the same way that a population collapse lurks within fisheries]. The regenerative upsurge of pollution can occur if no other pressure limits growth before pollution does so. Here pollution rises to more than 40 times the condition in 1970. Figure 8 should be compared with Figure 7 to see the effect of a reduced usage of natural resources which begins in 1970. Population continues for a longer time along its growth path. So does capital investment. Population and capital investment grow until they generate pollution at a rate beyond that which

> the environment can dissipate. When the pollution overloading occurs, pollution climbs steeply and continues to grow until it extinguishes the pollution-generating processes This means a [catastrophic] decline in population and capital investment until pollution generation falls below the pollution-absorption rate. [This outcome is the mirror image of overfishing that causes a catastrophic decline in fish population and forces enough ships out of operation to extinguish overfishing]. In Figure 8 population drops in 20 years to only one-sixth of its peak value.

The reasons for the regenerative pollution crisis are of particular interest because of their dynamical similarity to the degenerative population collapse in the illustrative model of fisheries. The regenerative pollution crisis is triggered when rising pollution no longer increases the rate of pollution absorption. The analogy in fisheries is when falling population no longer increases net births of fish. In simulations of the World Model a point is reached in year 2030 when pollution absorption no longer rises even though the total pollution load in the environment continues to increase. In the model's formulations the pollution absorption rate is equal to pollution divided by the pollution absorption time, a kind of decay process. In simple decay processes, decay time is constant. But pollution absorption does not appear to be such a simple process, except at low levels of pollution. At higher levels the time needed for a specified fraction of any existing pollution to disappear seems to depend on the amount of pollution itself; the more pollution the longer the pollution absorption time. This assumption brings about rapid and unexpected growth in pollution. If the pollution absorption time rises more rapidly than pollution itself, the rate of pollution absorption will fall as pollution continues to rise. Such behaviour is observed in simulations between the years 2045 and 2060.

The resulting need for swift and painful cuts in industrial activity to avert regenerative pollution is similar to the need for swift and painful cuts in fishing effort to avoid degenerative collapse in fish stocks. Few commercial fisheries have succeeded when faced with such a crisis of 'local overindustrialisation'. Many have tried and failed. Unlike fisheries, we have only one world in which to achieve sustainable industrialisation.

Conclusion and Discussion

So far I have presented a simple fisheries simulator and the *World Dynamics* model to help understand a complex problem situation - the limits to growth of an industrial society. Both models are small. The fisheries model contains 18 equations and just two stock accumulations (see the Appendix for details). It is a stepping stone to issues and insights in the *World Dynamics* model which, with 43 equations and five stock accumulations, is considerably larger – though still remarkably compact. But why should small models of complex real world situations be useful at all[vii]?

The Credibility of Small Models

A similar question faces theoretical economists and management scientists who often devise compact and highly stylised models of business and society to develop theory and policy. In a thought provoking paper entitled 'Credible Worlds' Sugden (2000) asks how it is that abstract and conceptually sparse models can help explain features of the real world. He analyses two classic papers from the economics literature, Akerlof's 1970 'market for lemons' (potentially flawed goods) and Schelling's 1978 'checkerboard city'.

The model in Akerlof's paper is inspired by the used-car market, yet the underlying assumptions about buyers and sellers are far from a realistic description of all that happens in a used car dealer. It is a low fidelity model. However it captures a common property of trading; that sellers often know more about the quality of goods (used cars in this case) than buyers. This key property of asymmetric information, when put in the context of market forces, sheds new light on trading behaviour, price and the theory of markets that Akerlof uses to interpret a wide range of puzzling market phenomena in the real world.

The model in Schelling's paper is inspired by social segregation. One example he presents is an important case found in American cities at the time. Blacks and whites tend to live in separate areas. The boundaries of these areas change over time, but the segregation remains. For his model Schelling uses a simple checkerboard on which pennies and dimes are placed, one per square, in an intermingled fashion. Some squares are deliberately left empty. The coins represent citizens and the spatial grid allows for neighbourhoods to develop. The assumptions about city life are minimalist and far from realistic. The scaling of model parameters differs entirely from their equivalents in the real world. Again it is a low fidelity model. Yet it captures a common emotional trait of individuals within heterogenous social groups. The assumption is that people are generally content with mixed neighbours, but will move to a new neighbourhood if they feel isolated or self conscious. In other words they exhibit a mild social preference to be among others of the same type. On the checkerboard we assume a dime is 'content' with its neighbourhood provided that at least one-third of its neighbours are dimes. A similar rule applies to pennies. "Then we look for coins that are not content. Whenever we find such a coin, we move it to the nearest empty square at which it is content. This process continues until there are no discontented coins". The surprising result is a very strong tendency for the emergence of sharply segregated distributions of coins, even when the condition for contendedness is quite weak.

Sugden uses these two compelling examples to argue that the appeal and power of such minimalist and stylised models lies in their ability to demonstrate social and economic phenomena in the real world from a very small number of *credible* assumptions that are skillfully set in an abstract yet recognisable context. These models are far too simple to be an accurate description of the real world. They are not so much an abstraction from reality as a parallel reality whose assumptions are stated with sufficient clarity and brevity to be understandable *and* plausible. Sugden then argues that the usefulness of such models depends on inductive inferences that can be made from the self-contained world of the model to the real world. "Thus we see Schelling's checkerboard cities *as possible cities*, alongside real cities like New York and Philadelphia. We see Akerlof's used-car market *as a possible market*, alongside real markets for used cars in a particular city, or the market for a particular type of insurance. We recognize the significance of the similarity between model cities and real cities, or between model markets and real markets by accepting that the model world *could* be real – that it describes a state of affairs that is credible". It is this credibility that enables us, as theorists or policy makers, to move back and forth between model and reality and to make inductive inferences that tell us something, however limited, about the real world.

Inductive Reasoning and Properties of Metaphorical Models

Sugden's examples from economics provide some guidance for desireable properties of small and metaphorical models in other domains, including system dynamics. A small model, though stylised, needs to be both plausible and sufficiently understandable to stimulate comparisons with the real world. It is from such comparisons that inductive reasoning stems. Therefore key assumptions of the model, about traits and characteristics of individuals or institutions, should be clear and recognisable. These traits should be carefully embedded in a context of interactions and constraints that makes sense to the reader/user[viii], even though this context may be abstract and apparently distant from the real world. The resulting model and its interpretation should be presented in a vivid way that slips easily between talking about the real world and talking about the model.

Consider the fisheries model in light of these guidelines. It captures two important human traits. First is a propensity for growth. We all prefer growth to stagnation or decline. This preference is a credible characteristic of commercially-minded fishermen and, more generally, people living in an industrial society. It shapes our investment decisions and biases them in favour of growth. Second is bounded rationality, our inability as decision makers to collect, process and make sense of all the information that is needed to reliably foresee the consequences of decisions and to take pre-emptive corrective action (Simon 1979 and 1982). We observe the world through information filters. We pay attention to only those few factors deemed to be important.

These two traits are embedded in a context of plausible interactions such as reinforcing feedback of fish regeneration, balancing feedback of investment decision making, and various non-linear relationships. The combination of assumptions, few though they are, can be described in a vivid way that invokes the image of a real fishery. Simulations of the model form the basis of plausible stories about the rise and fall of real world fisheries. The ingredients for inductive reasoning are present – a fishery like the one in the model *could* exist and does give rise to dynamics like those in real fisheries.

Consider now the *World Dynamics* model. It captures exactly the same two human traits as the fisheries model – our propensity for growth and our bounded rationality. It embeds these traits in a more complex feedback setting that is recognisable as an industrial society complete with interlocking population, capital, natural resources and hidden pollution. The fisheries model is a metaphor for the more complex *World* model which is itself a small and metaphorical model of a global industrial society.

Building Confidence in Assumed Traits

Some readers may feel the assumed traits are merely assertions. What evidence demonstrates such traits are indeed credible and enduring? Take the assumed growth bias in fisheries. One source of supporting evidence is time series data from numerous real-world fisheries. Such data may span periods of 50 years or more. What is important, for the credibility of our stylised model, is the typical *pattern* showing rapid growth in the catch followed by collapse (see for example the debriefing materials for *Fish Banks* (Meadows et al. 2001). Sustainable fisheries are a rare exception. There are also empirical results from gaming simulation experiments. Numerous plays of the Fish Banks simulator demonstrate that participants tend to overinvest, no matter what their background and experience. They expand capacity of the virtual fishing fleet much faster than they get reliable information about the state of the fish population, thereby inducing collapse – eventually. Back in the real world there is another recognised and enduring pressure for growth: rapid development of fishing technology to provide trawler skippers with a competitive edge in the hunt for fish (Clover 2004). Although technology is not explicitly represented in the stylised model, its widespread adoption in fishing fleets illustrates the enduring desire for more capacity and better ships.

Turning to industrial society, there is plenty of time series data charting the growth of industrial output and resource usage over the past century. In some cases the data goes back to the start of the industrial revolution in the 1800s. A particularly relevant collection of time series can be found in work of the Limits to Growth team (Meadows at al. 1973 and 1992). For example, Chapter 2 of *Beyond the Limits* is devoted to the driving force of exponential growth. Selected time series show exponentially rising population, consumption and GNP. Chapter 3 provides evidence of limits, arguing that population and capital are sustained by flows of fuels and non-renewable resources from the planet which in turn produce outflows of heat and waste that contaminate the air, waters and soils of the planet.

World Dynamics takes a rather different approach to evidence about, and quantification of, key assumptions and traits. There is a subtle mixture of observations, insight into dynamics and psychology, and facts and figures from the mental database, all combined with logical argument, attention to dimensional consistency and a sprinkling of hard numerical data. There is not space here to scrutinize the assumptions. However, they are fully documented in Chapter 3 (A World Model – Structure and Assumptions) and the interested reader is invited to study this source material and find the detailed reasoning that lies behind the traits of industrial society used in Forrester's original work and in this paper. Importantly the mental database is mined as a vital source of information for model building (Forrester 1980). A sample from the equation description in *World Dynamics* shows the style of reasoning. The topic is capital investment. Here we glimpse how the growth bias of our industrial society is formulated and quantified.

> At extremely low levels of capital the standard of living is low and the ability to accumulate capital is low. Under such conditions, almost all output must be for immediate consumption. But as capital accumulates, production in excess of current need permits some of the output to be allocated to further increase in the capital pool.

There follows a description of a graphical function that justifies and numerically specifies this relationship in terms of the effect of material standard of living MSL (the horizontal scale) on a concept called the capital investment multiplier CIM (the vertical scale). The shape of the function is upward sloping and convex.

> Both MSL and CIM have values of 1 for 1970 conditions. At zero capital, which would mean a zero value for material standard of living, the ability to accumulate capital is taken as only 0.1 as great as for the average intensity of capital in 1970. The shape of the curve assumes that capital is not uniformly distributed in the hands of the population. As capital begins to accumulate, it is assumed to concentrate in the hands of a few people who can then rise above immediate consumption needs and thereby begin to accumulate more capital. At extremely low levels of capital the standard of living is low and the ability to accumulate capital is low. Under such conditions, almost all output must be for immediate consumption. But as capital accumulates, production in excess of current need permits some of the output to be allocated to further increase in the capital pool. Were the capital equally

> distributed at all times, the shape of the curve might have a horizontal section at the left end before upward curvature begins. Such might keep the capital-regeneration process from starting. At the right side of the figure, the capital accumulation per person per year rises no further after capital accumulation reaches a point where more capital does not contribute to still greater human satisfaction. On the horizontal scale, a value of MSL of 5 would mean a world average of capital per person about equal to that of the United States in 1970. Even this non-rising rate of capital generation would cause capital to continue to accumulate to very high values before capital generation comes into equilibrium with the rate of capital discard.

This style of reasoning, combining descriptive and numerical information, is particularly appropriate for stylised and metaphorical models and is consistent with Sugden's views about credible worlds. If one were building the World model today it would be natural to further illustrate the predominance of growth in human activity in practical terms such as the spectacular rise of China and India, and the huge expansion of the oil and gas industry (Yergin 2011). Well-grounded observations and vivid cases are useful when interpreting and justifying a stylised model.

Modelling for Learning

If a model is constructed to make easy comparisons with the real world, to slip back and forth almost seamlessly from one to the other, then it achieves another vital purpose. It influences mental models. Sugden does not address this point, but it is important. Through mental models we interpret and make sense of the world around us. In business and social systems, mental models shape decisions and actions. Modelling is for learning, for aiding understanding rather than replicating reality. The idea there is a singular objective world out there to be modelled is replaced with the softer notion that a formal model can help to improve mental models. This property of a formal model as a transitional object, a playful interface between mental models and the real world, is well recognised by educational and cognitive psychologists (Winnicott 1971, Papert 1980) and by system dynamicists (Morecroft and Sterman 1994). It is appreciated by business leaders too (de Geus 1999). Akerlof's lemons model and Schelling's checkerboard city are effective transitional objects. They invite *and enable* thoughtful reflection on the causes of real-world social and economic phenomena. They are models for learning.

Credibility, transparency and interactivity are all important properties of small and metaphorical models for learning. In system dynamics this means aiming for a model with few assumptions and recognizable traits embedded in a clear feedback structure.

One final thought is about the relative importance of these properties. If a model is interactive and transparent, how credible do its assumptions need to be for it to be useful as a learning model? Might a model with implausible assumptions work too? This question is anathema to serious academics, conjuring images of poor quality and misleading models. But it deserves some attention because it probes the source of insight from metaphorical models. According to *Webster's Dictionary* "A metaphor is a figure of speech in which one thing is likened to another *different* thing by being spoken of as if it were that other". Schelling's checkerboard city, and the tendency it reveals for sharp segregation, is spoken of as if it were a real city. But is its main value that it *engages* us with the issue of racial segregation in cities? It makes an entertaining exercise that sets us thinking and gently challenges the pre-conception that sharp segregation stems from strongly segregationist preferences. The terminology of the model, the board and the pieces can be matched to cities. The mild preference assumption is plausible. It may or may not be true. The rules for relocating coins are clear, whether or not they are realistic. The point is that the exercise sparks new insight into a real-world phenomenon. The model is a transitional object.

A more distant metaphorical model is the Romeo and Juliet simulator I mentioned at the start of the paper. With just four interlocking concepts - Romeo's love for Juliet, Juliet's love for Romeo and the rate of change of their love for each other – it engages students with Shakespeare's play. It makes an entertaining exercise that sets students thinking. The terminology of the model matches the play, but only in a minimalist and fleeting way. The assumption about the relationship between Romeo and Juliet is plausible, but it is *not* the same as in the play. Yet this unrealistic and plainly wrong simulator can lead students to study the play closely and thereby learn. The model is still a transitional object.

As a professional modeller I am intrigued yet wary of distant metaphorical models. Perhaps they are valuable in situations where the 'real world' of interest can be studied closely in its own right, as in a careful reading of Shakespeare's play. But in the murky realm of business and society it seems important to strive for credible metaphorical models that are simple and playful yet skilfully grounded in reality.

Generic Feedback Structure and Cognitive Limits to Growth

To end the paper I return once more to fisheries and the *World* model. Both models illustrate a deep-rooted tendency of decisionmakers to inadvertently overinvest while pursuing the beguiling objective of growth. I have established, drawing on a variety of source material, that these traits are common and realistic. My approach then investigates investment policy and the information feedback structure that coordinates growth and contains the seeds of overinvestment. I argue that this feedback structure is generic; it occurs in many other areas of business and society. Moreover it reveals cognitive limits to growth that stem from the way we make the strategic investment decisions that enable growth.

The reason that coordination is so difficult to achieve is at the heart of a feedback view of business and society, a view that incorporates behavioural decisionmaking and assumes bounded rationality (Morecroft 1985, Sterman 1989). Figure 9 summarises the essential idea. Operating policies guide the accumulation of asset stocks that underpin growth. Any operating policy is bombarded by information originating from asset stocks throughout the system. But most of the available information is ignored by decisionmakers. It is too complex for them to process. Instead each policy is imagined to sit amid filters that represent people's bounded rationality; their natural cognitive limits for processing information overlaid by a variety of organisational factors. As a result of these filters only a handful of information flows penetrate to the policy core leading to action and stock accumulation. Information overload is avoided, but asset stocks are only loosely coordinated and it is this property that leads to unintended consequences in growth management[ix].

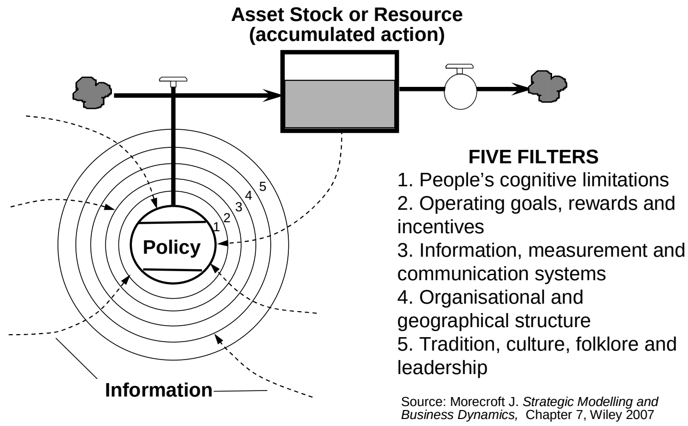


Figure 9: Behavioural Decision Making Leading to Stock Accumulation Based on Sparse Information Feedback.

The implication is that some of the limits to growth in business and industrial society are cognitive, not physical. This is a vital distinction, particularly for engaging in public debate about growth and sustainability. Physical limits are commonsense. Industrial growth *will* cease if we run out of natural resources[x]. But cognitive limits are more subtle. They arise from our collective inability to foresee and act-on the 'tipping-point' implications of too much growth, too fast. Overcoming these cognitive limits, with the help of modelling and simulation, is a continuing and worthy challenge arising from the 2011 European System Dynamics Workshop in Frankfurt and for the field of system dynamics as a whole[xi].

Cognitive limits to growth have long been an implicit focus of system dynamics, originating in firm-level studies of business policy and strategy. For example, the well-known Market Growth model (Forrester 1968) demonstrates the difficulty of coordinating capital investment and sales effort in a new product market. In the wake of rising sales, delivery delay increases and delivery standards fall. Promising growth in early years is transformed into premature stagnation and decline. Yet the model assumes market size is very large relative to production capacity of the supplying firm. So the ultimate decline of sales is not due to a market limit per se but rather to cognitive limits (of normally competent managers) that, in this particular case, lead to overinvestment in sales force relative to production capacity. Only a fraction of the potential market is exploited and growth strategy fails as sales unexpectedly collapse.

Business examples provide useful insight into cognitive limits to growth that extend metaphorically beyond the firm to industrial society. Consider the rise and fall of the pioneering low-cost airline People Express in the 1980s. The situation is described in a vivid Harvard Business School case study about the airline (Holland and Beer 1990; Whitestone 1983) and further developed in an accompanying business simulator (Sterman 1988). At first glance the troubled airline seems far removed from fisheries and global industrial society. But the same hubris of growth is to be found and the same managerial difficulties of coordinating the factors underpinning growth. In real life People Express grew from obscurity to industry prominence in a period of only five years against powerful rivals. Dramatic growth was followed by equally dramatic demise.

The latent inevitability of the unfolding tragedy has proven attractive to study. In *The Fifth Discipline*, Senge (1990) outlines a feedback 'story' of what happened at People Express. At the heart of the story is underinvestment in service capacity and overinvestment in planes. Service capacity, in terms of experienced staff, failed to keep pace with the growth of flights and passengers and so, ultimately, the service reputation of the business was destroyed. However, one is left wondering why the company persisted in its aggressive fleet expansion and why, in its hiring policy, the company did not better appreciate the need to boost service capacity.

To examine these anomalies we turn to investment policy and the coordination of the fleet size with staff and passengers as shown in Figure 10. In this figure bounded rationality in decisionmaking is symbolised by filters, as explained earlier. The filters restrict the flow of information to represent a realistically sparse coordinating network. The most influential information flows, those that penetrate to the core and lead to action, are depicted as dotted lines in bold. Their existence is inferred from descriptions of business operations in the case study.

First consider fleet expansion. Investment in new planes at People Express was shaped by CEO Don Burr's ambitious personal growth target stemming from his vision for the company and industry. This expansionary vision is just like the propensity for growth found in fisheries and in *World Dynamics*. Indeed the formulations for investment in planes are essentially interchangeable with those shown in the appendix for investment in ships. The result is reinforcing feedback (R1 in figure 10) in the stock of planes.

The rationale for hiring staff is quite different. From the case one gathers the impression of a Human Resource VP insistent on high-quality recruits, carefully selected by the top management team and trained on the job. This rationale leads to reinforcing feedback in which the stock of experienced staff is the principal determinant of hiring and acts as a constraint on the growth rate (R2 in figure 10).

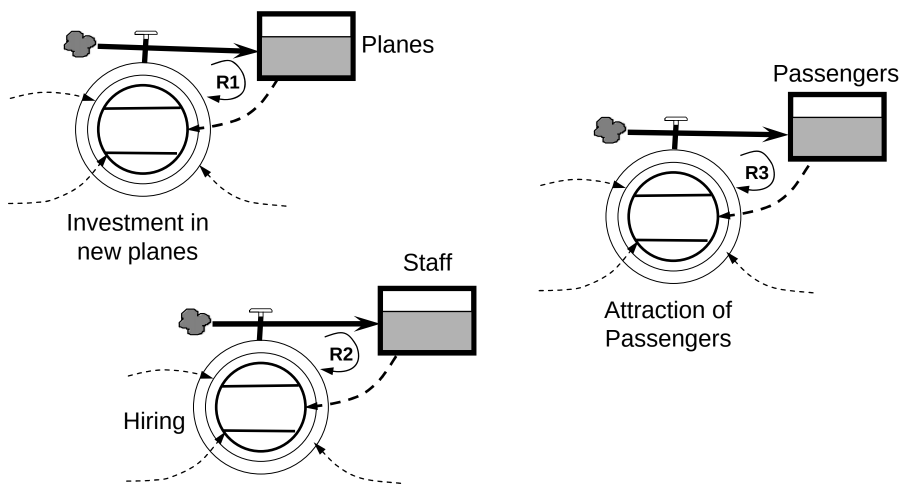


Figure 10 Tangible Assets and Operating Policies in People Express

The factors influencing passenger growth are also noteworthy at People Express. Deep price discounts coupled with targeted advertising unleashed a powerful word-of mouth effect that caused a very rapid build-up of potential passengers (those fliers willing to try People Express should the opportunity arise). The result is reinforcing feedback in passengers (R3 in figure 10).

The system of tangible assets contains three reinforcing feedback loops (R1, R2 and R3) operating almost independently to produce expansion of planes, staff and passengers. Partial model simulations reveal the power of these feedback loops to underpin the kind of spectacular growth achieved by People Express in reality[xii].

The dynamic complexity of the situation is compounded by two vital yet intangible assets: service reputation and staff motivation. From the case it appears that neither service reputation nor staff motivation is overtly managed. They are rather like the hidden fish stock in the fisheries model and invisible pollution accumulation in the World model. It is difficult to read the minds of customers and measure service reputation, or register the emotions of staff to discern motivation. So reputation and motivation just evolve from operating conditions. Motivation responds to a range of dynamic factors such as company growth rate, share price and profitability. Motivation influences staff productivity which, in combination with experienced staff, determines service capacity. Reputation responds with a time lag to the balance of passenger miles and service capacity.

When the three reinforcing feedback loops driving growth of the firm's tangible assets differ in strength then problems begin to accumulate in the intangibles. No management action is taken to fix these problems because: 1. the unmanaged intangibles provide only weak signals to the rest of the organization of latent growth stresses; and 2. the powerful policy rationale governing tangibles is insensitive to such weak signals.

A full model simulation of People Express' growth strategy reveals the mounting strategic problem. As Figure 11 shows, service reputation declines steadily for six years between 1980 and 1986 when the airline was growing rapidly. The apparent recovery of reputation in the last two years results from an unintended abundance of staff as disillusioned passengers switch to competing airlines. Motivation, though invisible and beyond direct management, remains both steady and high for the first six years, underpinning People's competitive cost advantage.

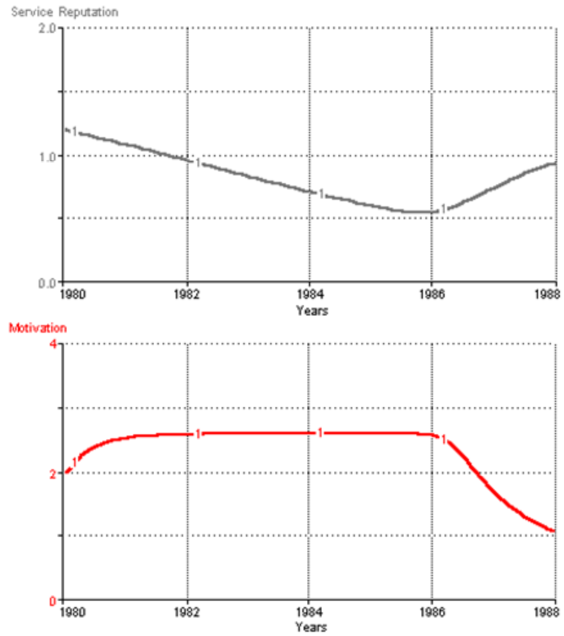


Figure 11 Time Charts for Service Reputation and Staff Motivation at People Express

Meanwhile, as shown in figure 12, the number of passengers grows rapidly for five years, falters and then collapses. In the final years of the simulation the excitement and profit-lure of a fast-growth enterprise evaporates. Motivation plummets (see figure 11) and employees become demoralized. Planes fly half-empty, as reflected in the falling load factor. The company dies with a configuration of assets, both tangible and intangible, that is inferior to its major competitors. There is no commercially viable route of recovery from this dire situation. It is a vivid example of unintended consequences from ambitious growth strategy based on seemingly sound policies and precepts. Yet, after a promising start, the strategy results in poorly coordinated growth; in this case overinvestment in planes and underinvestment in staff. Moreover, just as in fisheries and *World Dynamics*, problems from the hubris of growth accumulate in hidden variables that are difficult to measure and therefore go unnoticed until it is too late to take corrective action. The syndrome of growth and unintended collapse plays out once more, this time in the airline industry[xiii].

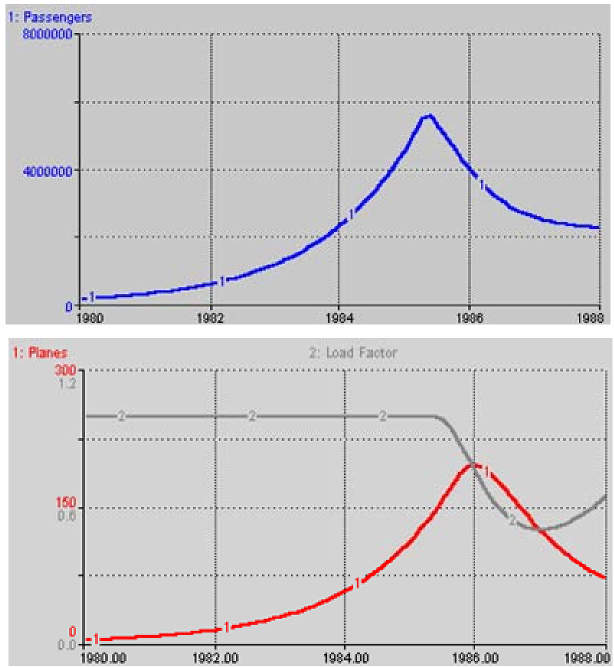


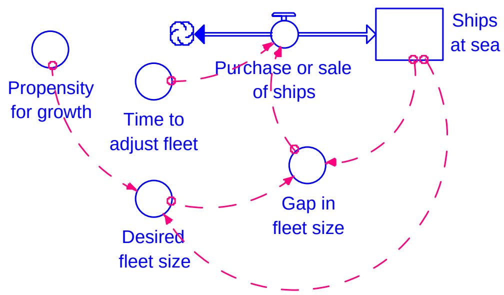
Figure 12 Unsustainable Growth Strategy at People Express

Appendix: Formulations for a Harvested Fishery with Endogenous Investment (edited excerpts from Chapter 9 of *Strategic Modelling and Business Dynamics*)

Investment in ships is a decision making process (or policy) representing, in aggregate, the judgements of those people most closely involved (fishermen in this case) and the information sources on which their decisions are based. Such decision making processes are behavioural in the sense that they capture the broad intention of investment without necessarily assuming decision makers have perfect information or perfect foresight. Typical investment policy has three main parts: a goal for the intended capacity, monitoring of current capacity, and corrective action to bring capacity in line with the goal (Forrester 1961, Chapter 10). This process of 'asset stock adjustment' applies equally well to investment in fishing fleets.

Figure 13 shows the investment policy for fleet adjustment in the fisheries model. Notice that connections between variables are depicted as dotted lines denoting flows of information rather than 'hardwired' causal links. In other words they are discretionary connections that reflect the information available and deemed most relevant to investment. The desired fleet size (the goal) depends on the number of ships at sea and the propensity for growth. Specifically the desired fleet size is equal to ships at sea multiplied by a growth factor denoted as (1+ propensity for growth). We assume that the normal propensity for growth is 0.1, so the desired fleet size is 10 percent larger than the current fleet size. In other words fishermen normally and collectively want a bigger fleet than they now have, an attribute of human nature - bigger is better, growth is inherently attractive. This is an important behavioural assumption and recognises that fishermen lack the information (or even the inclination) to agree an optimal fleet size. They just want more and better ships. As we will see later the propensity for growth also depends on conditions in the fishery, a poor catch will dampen enthusiasm for a larger fleet, despite an underlying bias toward growth.

The rest of the asset stock adjustment formulation is standard and similar to typical formulations used in system dynamics for inventory control and employee hiring. The gap in fleet size is the difference between the desired fleet size and ships at sea. If there is a large positive gap then conditions for investment are favourable. The purchase or sale of ships closes the gap over an assumed time span of one year which is the time taken to adjust the fleet (including ordering, construction and delivery).

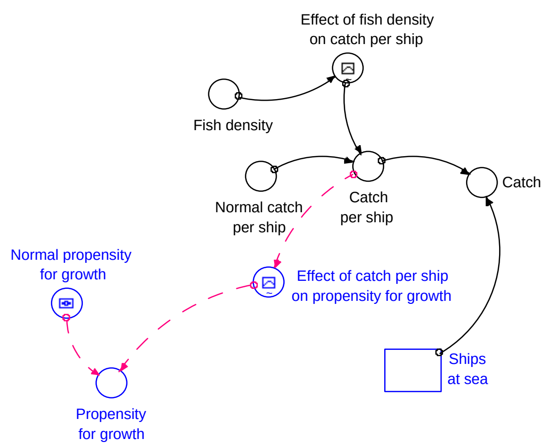


Ships at sea (t) = Ships at sea (t - dt) + (Purchase or sale of ships) * dt
INIT Ships at sea = 4 {ships}
Purchase or sale of ships = Gap in fleet size/Time to adjust fleet {ships/year}
Gap in fleet size = Desired fleet size – Ships at sea {ships}
Desired fleet size = Ships at sea * (1 + Propensity for growth) {ships}
Propensity for growth = …. See figure 14 for this important formulation, for now just assume that normally the propensity for growth is positive and non-zero
Time to adjust fleet = 1 {year}

Figure 13: Fleet Adjustment in a Harvested Fishery

A crucial formulation in the model is the propensity for growth and the factors that determine it. As mentioned above fishermen do not know the optimal fleet size and so they prefer, more simply and pragmatically, to grow the fleet until there is compelling evidence to stop. In a real fishery the most persuasive information is catch per ship. Fishermen know this number from each fishing trip and it is vital to their livelihood. Significantly they do not know the fish population or the fish regeneration rate - because the fish are under water. Moreover they do not believe scientific estimates of low fish stocks unless confirmed by the catch. Such practical considerations suggest that propensity for growth is curbed by low catch rather than by objective evidence of fish stocks. As a result investment is boundedly rational, sensing only indirectly the true balance of the fish population on which the long-term sustainability of the fishery depends.

Figure 14 shows one possible formulation that captures the essential limited information characteristic of fishermen’s boundedly rational decision making. Propensity for growth depends on the normal propensity for growth multiplied by the curbing effect of catch per ship. This curbing effect is non-linear and captures another typical human tendency: to ignore bad news until it is really bad. If catch per ship falls from 25 fish per year to 15 per year (a 40 percent decline) propensity for growth falls from .1 to .09 (a decline of only 10 percent). Thereafter the effect becomes much stronger. If the catch per ship falls to 10 fish per year (less than half the normal value) then propensity for growth falls to zero and fishermen stop purchasing ships. If the catch falls still further then the propensity for growth becomes negative and fishermen sell ships because they realise it is futile to retain a large and unproductive fleet.



Catch = Ships at sea * Catch per ship {fish/year}
Catch per ship = Effect of fish density on catch per ship * Normal catch per ship {fish per ship/year}
Normal propensity for growth = .1 {fraction}
Propensity for growth = Normal propensity for growth * Effect of catch per ship on propensity for growth
Effect of catch per ship on propensity for growth = GRAPH (Catch per ship)
(0.00, -0.48), (2.50, -0.45), (5.00, -0.37), (7.50, -0.27), (10.0, 0.00), (12.5, 0.64), (15.0, 0.9), (17.5, 0.995), (20.0, 0.995), (22.5, 1.00), (25.0, 1.00)
Effect of fish density on catch per ship = GRAPH (Fish density)
(0.00, 0.00), (0.1, 0.4), (0.2, 0.68), (0.3, 0.8), (0.4, 0.88), (0.5, 0.96), (0.6, 1.00), (0.7, 1.00), (0.8, 1.00), (0.9, 1.00), (1, 1.00)

Figure 14: Formulation of Propensity for Growth and Catch per Ship

Catch per ship is essentially a measure of ships’ productivity and is modelled here as a deterministic function of fish density. The scarcer are fish, the lower is productivity. But the relationship is non-linear. For moderate to high fish density (between .5 and 1) catch per ship remains close to normal. The assumption is that fishermen do not really notice a difference in the catch if the sea is teeming with fish or only half-teeming with fish, because fish tend to school or cluster. Catch per ship is still 68 percent of normal when the fish density is only .2, or in other words when the fish population is 20 percent of the maximum sustainable. But thereafter catch per ship falls quickly to zero as schools of fish become increasingly difficult to find and are hotly contested by rival ships.

An overview of the model with endogenous investment is shown in figure 15. In the top left quadrant is the natural fishery with its non-linear reinforcing loop depicting population dynamics. In the lower right quadrant is the fishing fleet. Investment is represented as a stock adjustment process in which a balancing loop adjusts the number of ships at sea and a reinforcing loop drives the desired fleet size. Fish biology and capital investment are linked through the catch, harvest rate and propensity for growth resulting in a dynamically complex non-linear feedback structure.

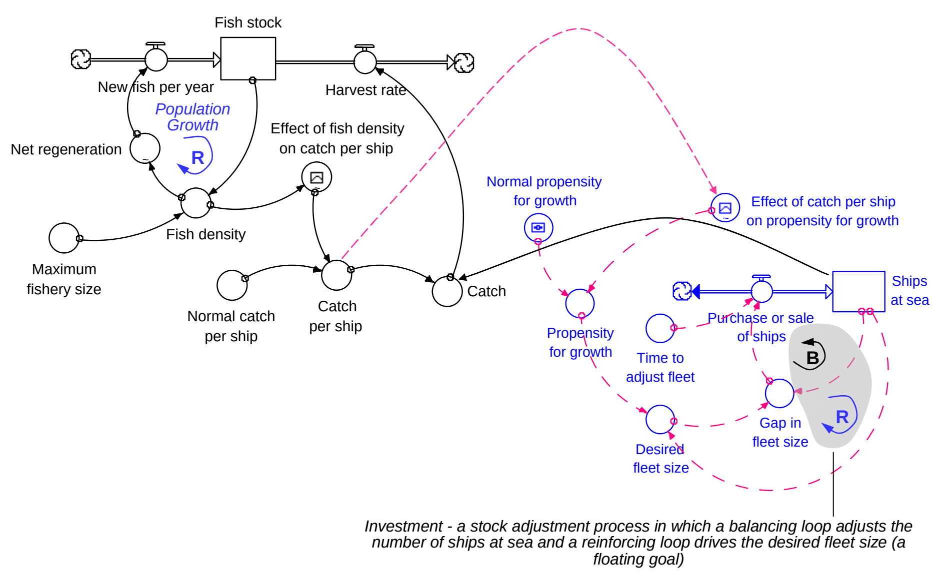


Figure 15: Overview of a Simple Fisheries Model with Endogenous Investment

Simulators and Interactive Learning Materials

Meadows Dennis, Tom Fiddaman and D Shannon 2001. *Fish Banks Ltd. A Microcomputer Assisted Group Simulation (3rd ed.)* Laboratory for Interactive Learning: University of New Hampshire, Durham NH 03248.

Morecroft John 2007. Fisheries Gaming Simulator, in Chapter-1-Models on the CD that accompanies *Strategic Modelling and Business Dynamics*, Wiley, Chichester UK.

References

Akerlof GA 1970. The Market for 'Lemons': Quality Uncertainty and the Market Mechanism, *Quarterly Journal of Economics,* 84: 488-500.

Arnason R 2005. Property rights in fisheries: Iceland's experience with ITQs, *Reviews in Fish Biology and Fisheries* 15(3): 243-264.

Booth Sweeney L and Sterman JD. 2000. Bathtub dynamics: initial results of a systems thinking inventory. *System Dynamics Review* 16(4):249-286.

Clover C. 2004. *The End of The Line,* Ebury Press, London. (see especially Chapter 5 'Mighty Seaman')

de Geus A. 1999. *The Living Company,* Harvard Business School Press, Boston MA.

Forrester JW. 1961. *Industrial Dynamics,* MIT Press, Cambridge MA. Currently available from Pegasus Communications, Waltham MA.

Forrester JW. 1968. Market Growth as Influenced by Capital Investment, *Industrial Management Review,* 7(1): 5-17.

Forrester JW. 1973. *World Dynamics (2nd ed.)* Pegasus Communications, Waltham MA. The 1st edition of *World Dynamics* was published in 1971 by Wright-Allen Press, Cambridge MA.

Forrester JW. 1980. Information Sources for Modeling the National Economy, *Journal of the American Statistical Association* 75, 371, 555-574.

Lane DC, Grossler A and Milling PM. 2004. Rationality in System Dynamics: Modeling Human and Organizational Decisionmaking, *Systems Research and Behavioral Science,* 21 313-317.

Meadows DL and Meadows DH (editors) 1973. *Toward Global Equilibrium: Collected Papers*, Wright-Allen Press, Cambridge MA.

Meadows DH, Meadows DL and Randers J 1992. *Beyond the Limits*, Earthscan Publications, London.

Meadows DH, Fiddaman T and Shannon D 2001. *Fish Banks, Ltd. A Micro-computer Assisted Group Simulation That Teaches Principles of Sustainable Management of Renewable Natural Resources (3rd ed.)* Laboratory for Interactive Learning: University of New Hampshire, Durham, NH 03284.

Morecroft JDW. 1985. Rationality in the Analysis of Behavioral Simulation Models, *Management Science,* 31 (7): 900-916.

Morecroft JDW. 2007. *Strategic Modelling and Business Dynamics*, Wiley, Chichester UK.

Moxnes E 1998. Not Only the Tragedy of the Commons: Misperceptions of Bioeconomics, *Management Science* 44(9): 1234-1248.

Nikolskii GV. 1969. *Theory of Fish Population Dynamics as the Background for Rational Exploitation and Management of Fishery Resources*, Oliver | Boyd Ltd, Edinburgh.

Papert S. 1980. *Mindstorms:Children, Computers and Powerful Ideas*, Basic Books, New York.

Schelling TC. 1978. *Micromotives and Macrobehavior,* Norton, New York.

Senge PM. 1990. *The Fifth Discipline: The Art and Practice of the Learning Organization,* Doubleday, New York.

Simon HA 1979. Rational decisionmaking in business organizations, *American Economic Review* 69, 493-513.

Simon HA 1982. *Models of Bounded Rationality*, MIT Press, Cambridge MA.

Special Edited Collection 2010. *Tracing Connections: Voices of Systems Thinkers.* (In tribute to Barry Richmond), isee systems, inc., Lebanon, NH and The Creative Learning Exchange, Acton, MA.

Sterman JD. 1989. Misperceptions of feedback in dynamic decisionmaking, *Organizational Behavior and Human Decision Processes* 43 (3): 301-335.

Sterman JD. 2008. Risk Communication on Climate: Mental Models and Mass Balance, *Science*,322: 532-533.

Stouten H. 2010. Learning from a Microworld in Fisheries Management, PhD Thesis, University of Gent, Faculty of Economics and Business Administration.

Sugden R. 2000. Credible Worlds: The Status of Theoretical Models in Economics, *Journal of Economic Methodology* 7: 1-31.

Winnicott DW. 1971. *Playing and Reality,* Tavistock Publications, London.

Yergin D. 2011. *The Quest – Energy, Security and the Remaking of the Modern World,* Allen Lane, London.

[i] A metaphor is an evocative figure of speech, to fire the imagination, in which one thing is likened to another different thing by being spoken of as if it were that other. A transitional object is an artefact or conceptual device whose creation and use helps people make sense of something abstract and complex in their world (Winnicott 1971 and Papert 1980). In this paper a metaphorical model is viewed as a conceptual device to trigger imagination, learning and reflection and is therefore a kind of transitional object. For further discussion see chapter 10 of *Strategic Modelling and Business Dynamics* entitled ‘Model Validity, Mental Models and Learning’.

[ii] More information about the Romeo and Juliet simulator can be found in a Special Edited Collection 2010 in tribute to Barry Richmond.

[iii] The initial value and maximum size can be re-scaled to be more realistic without changing the resulting dynamics.

[iv] More information about fishery dynamics can be found in Moxnes 1998, Morecroft 2007 (chapter 9) and Stouten 2010. These references also cite articles by marine biologists and by fisheries economists thereby providing a bridge to the fisheries management literature, including work by Arnason 2005 on Iceland’s successful and sustainable commercial fishery.

[v] The terminology for capital accumulation differs slightly between Figures 5 and 6. In Figure 5 the asset stock is called ‘Industrial Capital’, the inflow is ‘Capital Investment’ and the outflow is ‘Capital discard’. In Figure 6 the asset stock is called ‘Capital Investment’, the inflow is ‘Capital-investment generation’ and the outflow is ‘Capital-investment discard’.

[vi] There are minor changes to the quoted text from *World Dynamics.* My editorial comments are enclosed in square brackets. Figure numbers are altered to fit the sequence in the paper. Otherwise the text is identical to Forrester’s original.

[vii] These are important questions about model validity. I will not attempt to review the full topic of validity here. Interested readers are referred to Sterman 2000, chapter 21 on ‘Truth and Beauty: Validation and Model Testing’ and related literature he cites. My purpose is narrower. It is specifically about the usefulness and ‘validity’ of very small and metaphorical models.

[viii] Whether a model is credible and makes sense depends partly on the reader/user. Akerlof's market for 'lemons' makes sense and appeals to trained economists who recognise, within the model's formulations, the market setting in which potentially flawed goods are traded. However, it is inaccessible to the intelligent layman. In contrast Schelling's model, and its theory of segregation, is accessible to anyone with a checkerboard. The fisheries model and *World Dynamics* model lie somewhere in between.

[ix] This pragmatic perspective on decisionmaking distinguishes system dynamics sharply from traditional microeconomics in which 'economic man' makes objectively rational decisions, weighing-up all available sources of information to arrive at an optimal (profit maximising) configuration of assets.

[x] If there are recognised physical resource limits to growth then the sustainability debate naturally focuses on the likelihood of resource depletion.

[xi] Notions of cognition, rationality and sensemaking were the theme of the first European System Dynamics Workshop held in 2003 at Mannheim University and reported in *Systems Research and Behavioral Science* (Lane, Grossler and Milling 2004).

[xii] The partial model simulations can be generated with models from Chapter 6 of *Strategic Modelling and Business Dynamics* (Morecroft 2007) on the CD that accompanies the book.

[xiii] It is not unreasonable to suppose that a similar explanation of growth hubris and hidden variables can be found for the rise and fall of the financial sector. But that's another story for another time.