LIMITS TO GROWTH AND INDUSTRIALISATION

Insights from small and metaphorical system dynamics models and simulators

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Abstract

In this paper I develop a small system dynamics model of the fishing industry to explore sustainability and limits to growth. I then use the same model as a metaphor to think about limits to global growth and industrialisation and to appreciate the structure and dynamics of more complex models of industrial society. Since my aim is also to communicate about dynamic complexity, the paper and accompanying talk illustrate basic concepts of stock accumulation, feedback structure and dynamics.

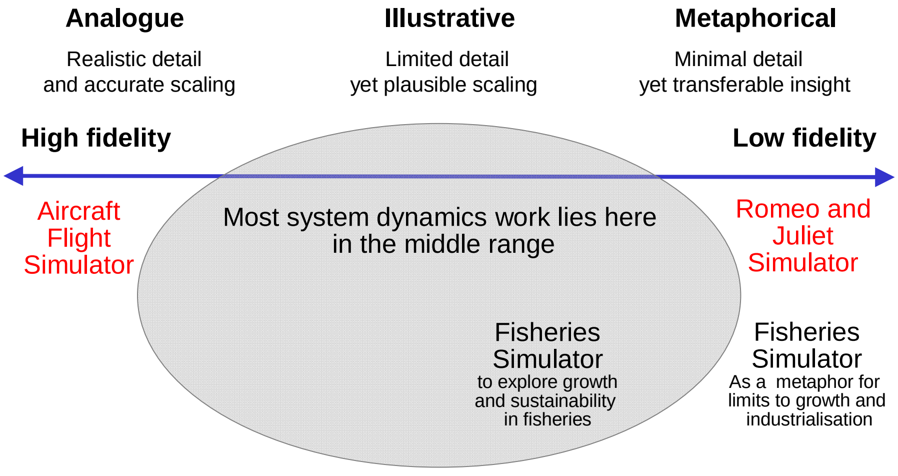
Keywords: growth and industrialisation, sustainability, unintended decline, fishery dynamics, resource coordination, behavioural decisionmaking, capital investment, metaphorical models

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. 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 other end of the spectrum, on the far right, is a low fidelity Romeo and Juliet simulator, containing 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 metaphor or transitional object[i] to help undergraduates and high school students to engage with 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 engage people's attention, to encourage them to reflect and debate - that I wish to illustrate for the interlocking issues of growth, sustainability and industrialisation.



Adapted from Chapter 10 of *Strategic Modelling and Business Dynamics* by John Morecroft, Wiley 2007.

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

I first develop a small system dynamics model of the fishing industry to explore sustainability and limits to growth. 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. This famously concise (yet dynamically intricate) model represents an industrial society whose growth is eventually curtailed. I also consider how the conceptual framework from *World Dynamics* might be adapted to address the societal effects of global warming.

Asset Stock Coordination in Fisheries

Asset stock accumulation is at the heart of any system dynamics model. All business and social systems contain a variety of asset stocks or 'resources'. Stocks capture the inertia of organisations and society, the time consuming process of building and deploying assets (both tangible and intangible) necessary to achieve goals and strategic objectives.

As a prelude to fishery dynamics first consider a simple visual model of fish stock that illustrates the (often counterintuitive) concept of asset stock accumulation. The fish population or fish stock, shown as a rectangle, accumulates the difference between the inflow of new fish per year and the outflow in terms of the catch or harvest rate. (Note that here and in later models the inflow is defined as births minus deaths). At the left end of the inflow arrow is a pool or cloud depicting the source from which the flow arises – in this case fish eggs. We assume at the start there are 1900 fish in the sea and that both the inflow of new fish and the outflow catch are set at 200 fish per year. The time horizon is 40 years. During this period we further assume, for illustration, that the inflow of new fish remains constant at 200 fish per year and that the outflow undergoes a temporary increase. The harvesting scenario is as follows: the catch is constant at 200 fish per year until year 10 and then rises from 200 to 300 fish per year in the interval between years 10 and 15. The catch remains at 300 fish per year between years 15 and 20, and then returns to 200 fish per year in the interval between years 20 and 25. Thereafter, from year 25 to year 40, the catch remains constant at 200 fish per year.

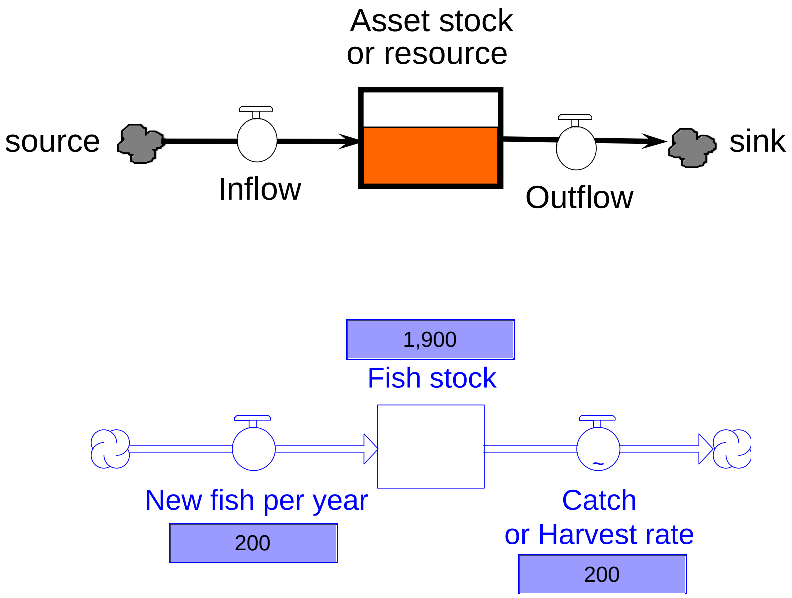


Figure 2: Asset Stock Accumulation and Fish Stock

A simulation of this scenario is shown in Figure 3. Line 1 is the fish stock plotted on a scale from zero to 4000. Line 2 is the inflow of new fish per year and line 3 is the catch, both plotted on a scale from zero to 400. The inflow and outflow rates reflect the scenario assumptions described above. The precise trajectory of the fish stock is the numerical result of accumulation. Note the lack of visual correlation between the stock and the catch rate. The catch rises and falls, while the fish stock simply declines. As Sterman (2008) notes, commonly used correlational reasoning fails in such situations. Note the particular shape of the fish stock trajectory. While the inflow and outflow are equal (a constant 200 fish per year in this case) the number of fish remains constant – an intuitively obvious outcome. In year 15, when the catch begins to rise, the fish stock begins to fall – gradually at first and then more steeply. In years 20 through 25, when the catch stabilizes at 300 fish per year, the fish stock continues to fall – but now following a steady linear path. Years 25 through 30 are the most counterintuitive (for correlational reasoners). During this interval, even though the catch is falling, the fish stock still continues to fall. The trajectory gradually becomes less steep until, in year 30, equilibrium is once again re-established when the catch equals the inflow of new fish per year.

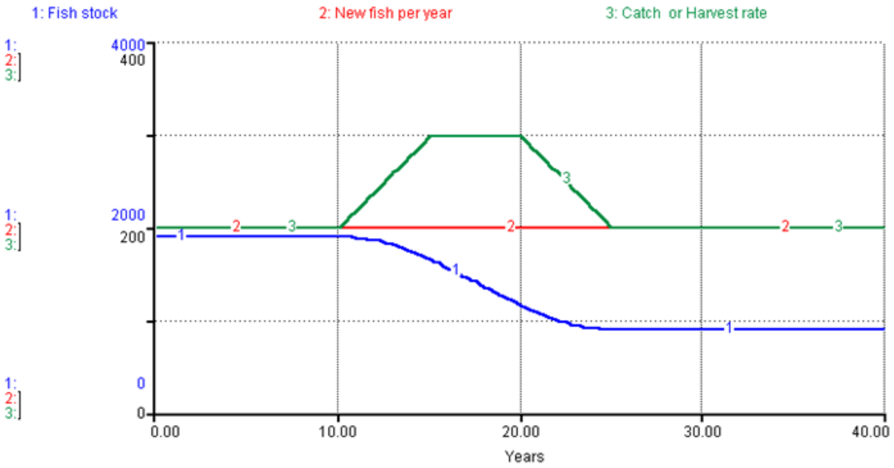
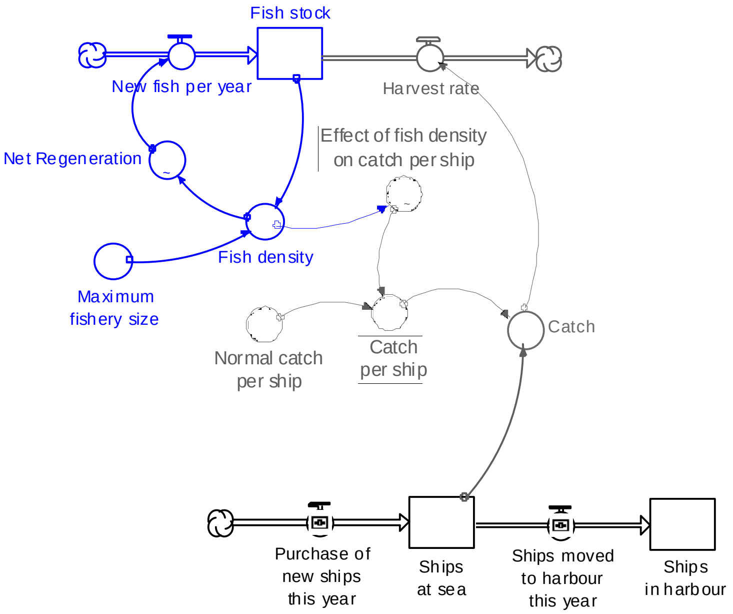


Figure 3: The Dynamics of Asset (Fish) Stock Accumulation

So far we have seen the important dynamics of stock accumulation. Now we add a single feedback loop and some other dynamic complexity to arrive at a small model of a fishery and fishing firm shown in Figure 4. The top left quadrant of the diagram represents fish population and regeneration in a ‘natural’ fishery as though free from human intervention. The size of the inflow varies according to conditions within the fishery, as explained below. 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 tons of given species and an assumed maximum fishery size of 400 thousand tons would generate equivalent results.

A very important relationship is the effect of fish density on net regeneration. 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[iii]. The relationship is non-linear[iv]. When the fish density is small 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, providing the population is far below the presumed theoretical carrying capacity of the ocean region.



Source: Chapter 1 of *Strategic Modelling and Business Dynamics* by John Morecroft, Wiley 2007.

Figure 4: A Small Model of a Fishery and Fishing Firm

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. Marine biologists say there is increasing 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 1 and net regeneration falls to zero. The population is then at its maximum natural sustainable value. Left alone this small yet dynamically complex system will reach a long-term equilibrium in which the fish stock equals the maximum fishery size.

The rest of the diagram represents, in aggregate, a local fishing industry comprising firms that purchase new ships and uses them to harvest fish. 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.

You or I can step into this imaginary world and make ship purchasing and deployment decisions. Let's see it in operation.

Simulated Dynamics of a Natural Fishery

Figure 5 shows the dynamics of a 'natural' fishery over a period of 40 years, starting with a small initial population of 500 fish. By assumption there are no ships and no investment. Fishermen are not yet part of the system. The result is smooth S-shaped growth. For 10 years the fish stock (line 1) grows exponentially. The population grows from 500 to 2200 fish and regeneration (new fish per year, line 2) also increases until year 10 as rising fish density enables fish to reproduce more successfully. Thereafter crowding becomes a significant factor according to the non-linear net regeneration curve described above. 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.

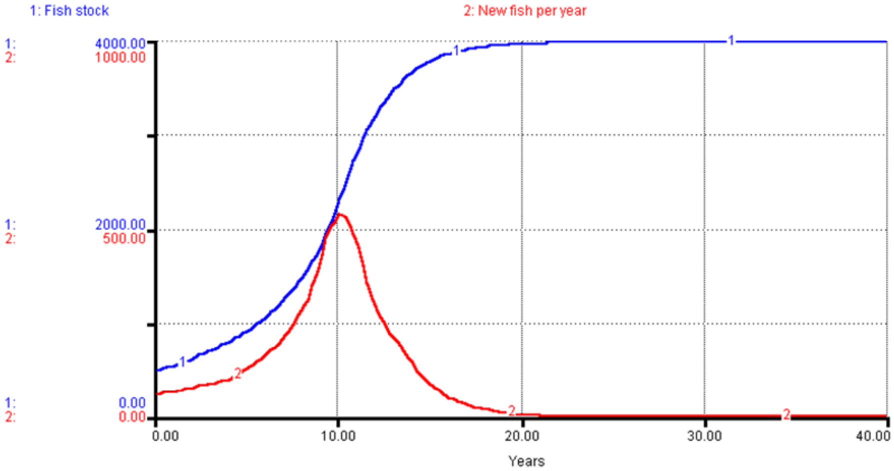


Figure 5: Dynamics of a Natural Fishery

Thought Experiment in a Harvested Fishery

Now imagine a harvested fishery in which new ships can be purchased and sent to sea to catch fish. It is best to run this simulation for yourself (which can be done by opening the file called 'Fisheries Gaming Simulator' in the CD folder for Chapter 1 of *Strategic Modelling and Business Dynamics*). If you do not have access to the simulator you can nevertheless read about the thought experiment and study the time charts in this section.

Although there may be plenty of fish, in reality the precise number is unknown. To replicate this fundamental uncertainty of fisheries it is necessary to 'hide' the trajectories for fish stock and new fish per year so they blend into the background of the time chart. If you are using the gaming simulator then some playing around with the software is necessary to bring about this change, but the result is important and worthwhile. The instructions can be found in the attached endnote [v].

Press the Run button once, and then again, to recreate 10 years of natural fishery growth. At first glance the simulated chart will appear quite blank and uninteresting, as shown in the first panel of Figure 6. That's how it should be! Now move the slider for 'Purchase of new ships this year' to a value of 2 by clicking, 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 at sea. Press the Run button three times in succession to simulate fleet expansion for years 10-25, a period of historical growth for the imagined fishery. In Figure 6 ships at sea (line 2) increase linearly from zero to 30 as you would expect from an investment policy that adds two new ships per year over 15 years. The catch (line 1) 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 follow the same relentless linear expansion. But notice a dramatic change in the trajectory of the catch (line 1). 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 click, hold and drag).

In year 27 the catch declines for the very first time in the fishery's simulated history. By the third quarter of year 28 the catch is down to 690 fish per year, a decline of 12 percent from the peak. Imagine the situation in a real world fishery. The local fishing industry 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.

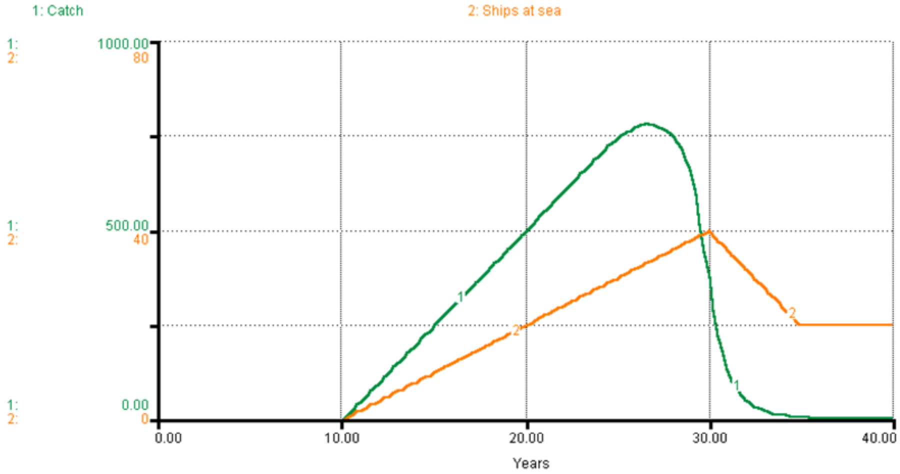


Figure 6: A Typical Time Chart from the Fisheries Gaming Simulator

At this point in time you can imagine pressure building in the industry 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 that the decline is due to a run of exceptionally bad luck and that, sooner or later, the catch will return to normal. And remember that 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 industry or business to cause itself to shrink deliberately. There are bound to be more losers than winners.

Nevertheless imagine the various stakeholders in the fishery agree a conservation policy involving a total ban on the purchase of new ships for the next five years and an effective reduction in the fleet size to be achieved by moving four ships per year into the harbour. Note that in its first year of operation this policy idles 10 percent of the active fleet (4 ships out of 40), then 11.1 percent in the second year (4 ships out of 36), then 12.5 percent in the third year (4 ships out of 32). After 5 years a total of 20 ships have been idled, which is fully 50 percent of the original fleet – a huge reduction in a short time.

If you are using the gaming simulator, 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 clicking 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 4 appears in the centre box. Press the Run button to see the results of the policy.

You will notice that ships at sea (line 2) decline steeply as enforced idling takes place. By year 35 of the simulation the active fleet size is 20 ships at sea, back to where it had been in the early growth heyday of the fishery 15 years ago in year 20. But, despite the cuts and huge economic sacrifices, the catch has declined to less than 10 fish per year, scarcely more than 1 percent of the peak catch in year 26. In a decade our imagined fishery has gone from productive prosperity to extreme hardship. Each day the fishing community awakes to see half 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 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. In Figure 6 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 overfishing in real fisheries[vi]. And 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 industry and community.

Interpreting the Metaphor

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 7. 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 depicted in greyed-out blue: fish stock and new fish per year.

System dynamics can provide insight into the fisheries coordination problem and a theory of resulting unintended dynamics. We have already seen in Figure 5 a natural limits-to-growth structure in the reinforcing feedback loop that connects fish stock to new fish per year. To better understand the coordination of fish and ships we also need to endogenise the purchase of new ships (investment). In other words we need to 'close the loops' surrounding investment policy to find enduring feedback structure that gives rise to observed dynamic behaviour. 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 more ships. The second assumption is that economic forces will curtail investment if the 'return' (in this case the catch per ship) is deemed to be too low. The full formulations can be found in chapter 9 of *Strategic Modelling and Business Dynamics* (Morecroft 2007). Let's see what happens in a fishery when these assumptions (rather than a game-slider) are used to determine the purchase of new ships.

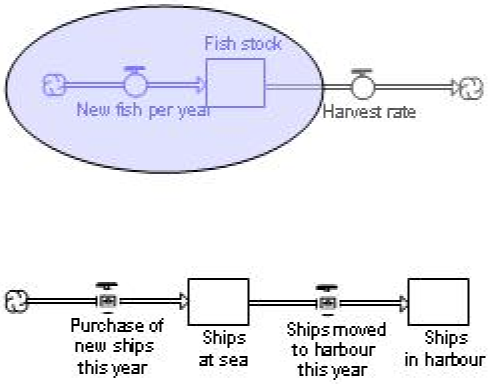


Figure 7: Interpreting the Metaphor: Visible and Invisible Asset Stocks in Fisheries

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. This harvest rate is below the maximum sustainable yield to allow room for growth and to investigate the dynamics of boundedly rational investment and the resulting coordination in the 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 8. You can recreate this chart by running the model called Fish and Harvesting – Endogenous Investment in the CD folder for chapter 9 of *Strategic Modelling and Business Dynamics*.

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 steady, suggesting 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.

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.

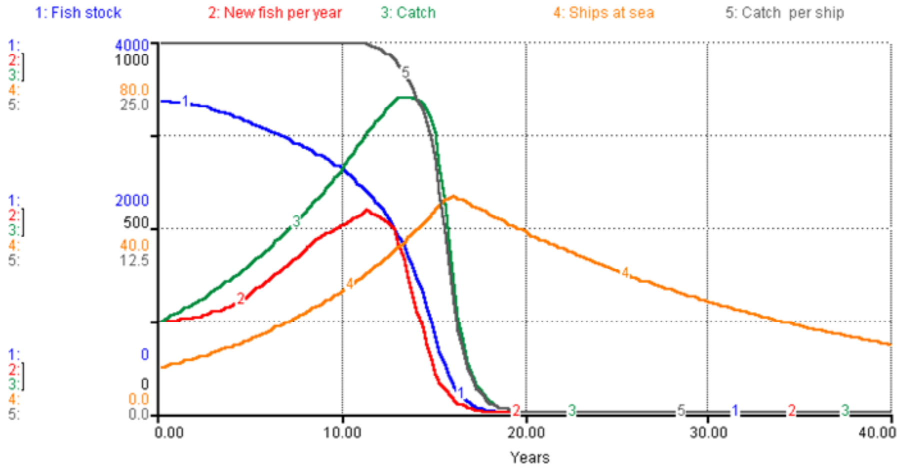


Figure 8: Growth and Unintended Collapse in a Closed-Loop Harvested Fishery (with endogenous investment)

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 boundedly rational 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 deep-rooted 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 (somehow) 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[vii].

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: 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 somehow be replenished, then surely growth can continue and the demise of industrial society is forestalled. Or is it? Could some other 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 9. 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.

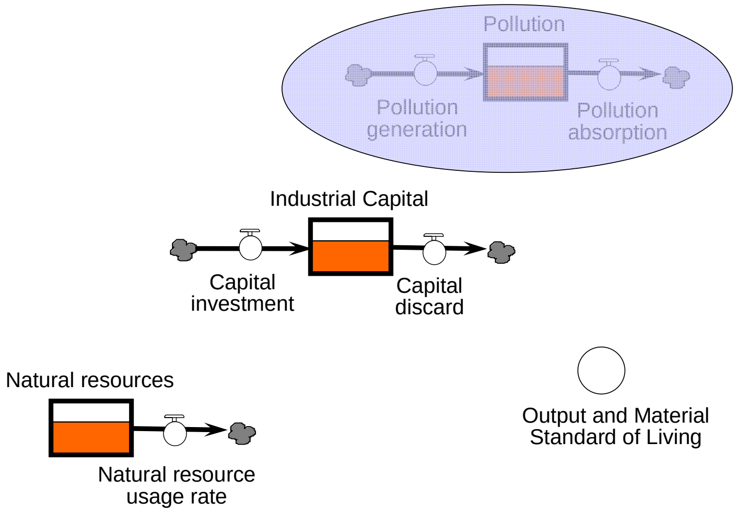


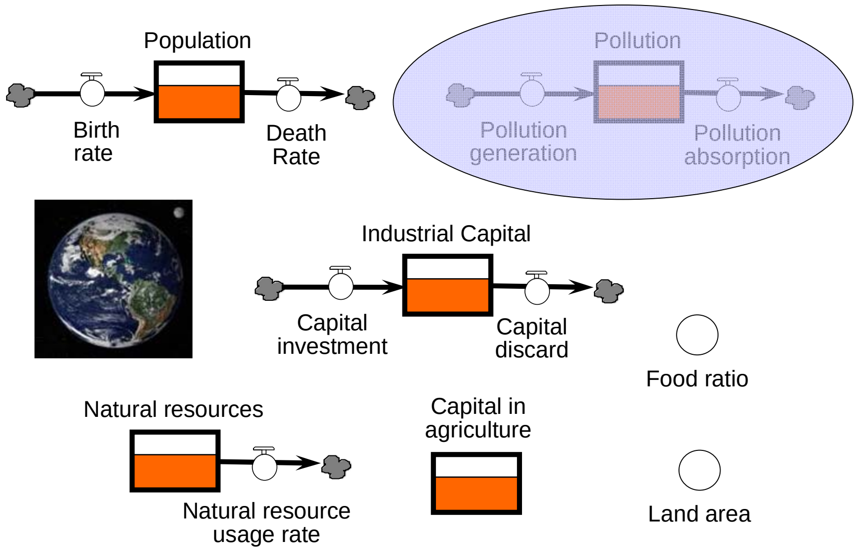
Figure 9: Developing the Metaphor – Visible and Invisible Stock Accumulations in an Industrial Society

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.

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 conceptual model used in the study provides a remarkably compact visual framework for thinking about sustainability of a global industrial society. The accompanying simulator 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 10. Behind the scenes 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.



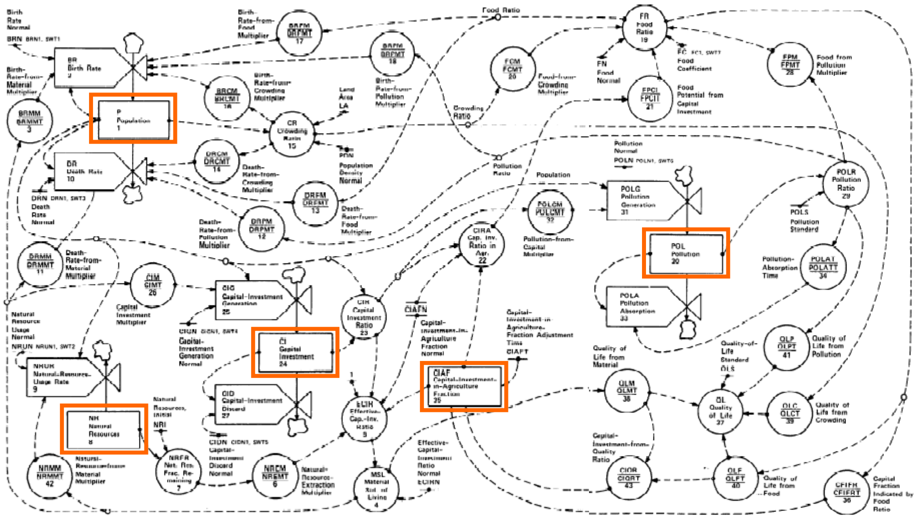
Adapted from pages 20-21 of *World Dynamics* by Jay Forrester, Pegasus Coomunications, Waltham MA 1973.

Figure 10: Stock Accumulations in Jay Forrester's World Dynamics Model

Figure 10 also includes a space-shot of planet earth, a very different and emotive world model, available only to a technologically advanced civilisation capable of taking such a picture. At this distance the accumulations of industrial society are all invisible, yet it is clear we live in a bounded world with limited land area and a finite supply of natural resources.

Scenarios from the World Dynamics Model

The structure of the complete World model is shown in Figure 11. 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[viii]. The full visual detail of the coordinating network is shown, revealing a complex interlocking web of relationships that embody the assumptions mentioned above. Two simulation scenarios are now presented from chapter 4 of *World Dynamics.* I have chosen these particular scenarios because they reveal, 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 interpretation of the simulations[ix]. I have adopted the convention of US-English spelling for the quotes. The rest of the paper uses UK-English spelling.



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

Figure 11: 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.

Basic World Model Behaviour

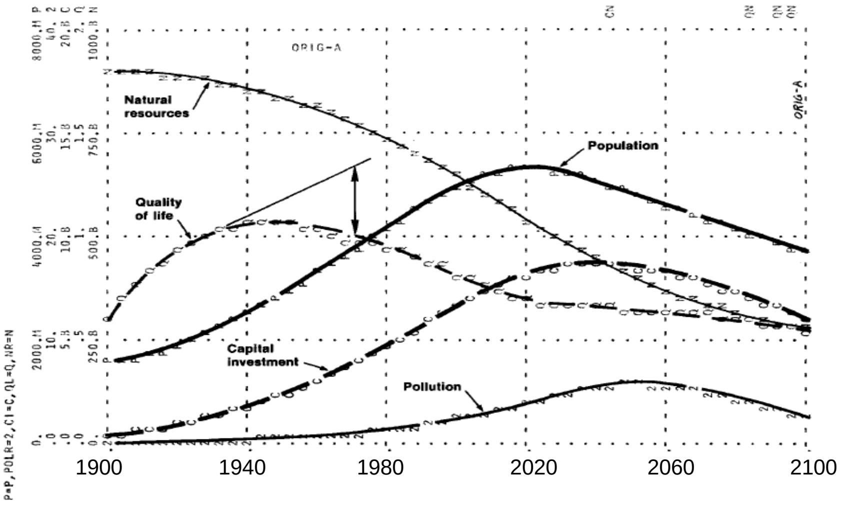
Figure 12 shows the behaviour of the original world model. Quoting from *World Dynamics* (pages 69-71):

"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.

[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 12 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.



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

Figure 12: Archive Simulation of the World Model – base case showing the mode in which industrialisation and population are suppressed by falling natural resources

Many industrialized nations are now growing rapidly and placing ever greater demands on world resources. Many of those resources come from the presently underdeveloped countries. What will happen when the resource-supplying countries begin to withhold resources because they foresee the day when their own demand will require the available supplies? Pressures from impending shortages are already appearing. Will the developed nations stand by and let their economies decline while resources exist in other parts of the world? Will a new era of international conflict grow out of pressures from resource shortage?

In Figure 12, pollution peaks in the year 2060 at some 6 times the level in 1970 but not enough to cause a regenerative increase of pollution [the mirror image of the degenerative decrease in fish stock seen in the fisheries model].

Quality of life in Figure 12 peaks around the year 1960. It has declined very little by the year 1970 and is near its all-time high. Is this reasonable? How can one explain a historical maximum in quality of life at a time when the world shows rising social unrest? The two become consistent if we compare expectations with actuality. Figure 12 shows an extension beyond 1940 of the quality-of-life curve prior to that year. The extension continues to rise along the slope that had characterized the first part of the century. But the actual curve has fallen away from the extended slope. The gap between expectation and reality is shown by the arrow. A gap has opened between the extension of earlier trends and the actual quality-of-life curve, which has reached a peak and is starting to decline slightly. In fact, it is always at a peak or minimum of a varying quantity that the discrepancy between expectation and reality is greatest. The sense of disappointment is explained by Edward Banfield (1970) in arguing that although our cities are actually in better condition than ever before in history, yet they fall the furthest short of where we expect them to be".

Technology Breakthrough to Reduce Resource Usage

Quoting from *World Dynamics* (pages 74-76):

"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.

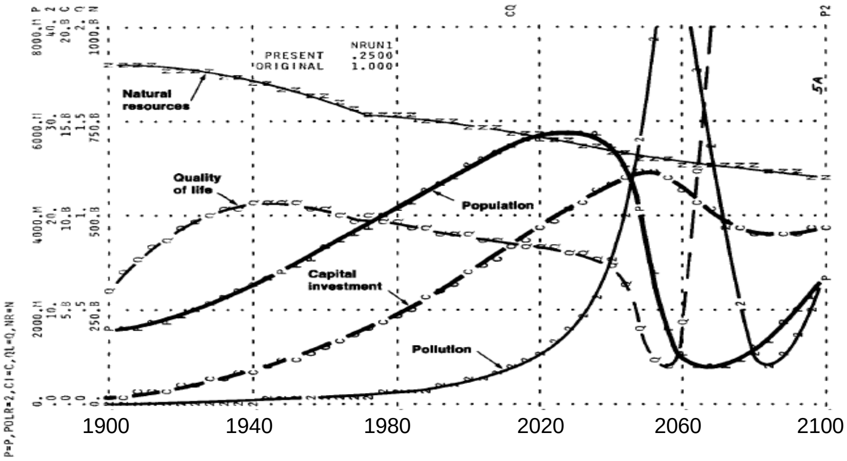
Suppose we wish to assume that in the year 1970 the usage rate of natural resources were to be sharply curtailed without affecting any other part of the system. This might correspond to either an altered estimate of the actual rate of consumption relative to the available stocks in the earth, or it might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

In Figure 13 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.

Figure 13 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 13 should be compared with Figure 12 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 13 population drops in 20 years to only one-sixth of its peak value.

The processes of pollution generation were not altered in the model by the reduced usage rate of natural resources. Some people argue that pollution is related directly to resource usage, but that seems only partly justified. A technology that is conserving rare metals might turn to chemicals and plastics with equivalent or higher pollution danger.



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

Figure 13: Archive Simulation of the World Model – showing the mode in which reduced usage of natural resources leads to a pollution crisis.

Whether or not the population collapse would be as severe as in Figure 13 depends on which sector of the world population were most affected by the consequences of pollution. The highly aggregated model in Figure 11 does not distinguish between industrialized and underdeveloped societies. In calculating the material standard of living, the total population is divided into the total capital investment. If population drops suddenly, the model formulation assumes that the capital is available and used by the remaining population. This is equivalent to assuming that the population decline from a pollution crisis afflicts those populations that are not using the capital investment. Such is probably not correct. It is most likely that the disruption of social systems and agriculture would occur in a way that the industrialized societies would suffer the greatest population declines. If that were to happen, the pollution-generation processes would probably stop before the world population has dropped as far as shown in Figure 13. In other words, if the pollution crisis works its greatest hardship on the pollution-generating nations, the more numerous underdeveloped populations would survive with less reduction in population. Assumptions within the model will need to be carefully re-examined before substantial dependence is placed on the dynamics that follow the population peak.

It has been asserted by some who examine Figure 13 that the onset of the pollution crisis would cause people to reconsider their ways and to stop the pollution-generating processes before a catastrophe had occurred. But that may not happen. Reaction to a pollution crisis depends on its dynamic nature and on the steps necessary to stop it taking the course shown in the figure. If [as happens in fisheries] prevention requires a major cutback of industrial activity, the treatment will at first seem as serious as the disease. Pollution might indeed be recognized [by some] as destroying the developed countries , but so would shutting off industry, power plants and fertilizer factories. [Just as in fisheries, low fish stock is recognized by marine scientists as a precursor to population collapse, while shutting off fishing activity is fiercely resisted by fishermen whose livelihood depends on the catch]. The high density of population is possible only because of the industrialization. Without industrialization the population could not be sustained. A point may be reached where continuing the

> industrial process means a population collapse from failure of the technical support systems of the society. Faced with this dilemma, the most probable course of action is to wait and to hope that the pollution threat has been exaggerated. As a consequence of such indecision, the pollution cycle would continue.
>
> In Figure 13 the quality of life dips suddenly and deeply as conditions become severe enough to drive down population. The rapid rise in quality of life after the year 2060 may be fictitious and is dependent on assumptions in the model that may not be valid for such severe conditions [as implied earlier in this section]. The reasons for the rise in the quality of life [can be further explained in terms of the material standard of living].
>
> Material standard of living [not shown] turns steeply upward when the population begins to decline. This happens because of the assumption that all of the capital investment is available to and usable by the remaining population. Such might not be true under the catastrophic conditions that are depicted. If the population decline occurs mostly in the industrialized nations, capital investment and the remaining world population would be geographically separated. Also the differences in culture and education would prevent a population in an underdeveloped country from making effective use of capital investment that might be idle".

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. There is not space here to fully reproduce the explanation and supporting simulations from *World Dynamics.* However, the gist of the analysis is captured in the following synopsis. 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. During this period the pollution absorption time rises to a peak of 13 years compared to the 1 year that was assumed for the 1970 absorption time.

Quoting from *World Dynamics* (pages 78-79):

> "It is the failure of the rate of pollution absorption to rise as total pollution rises which triggers the pollution crisis. Is such a phenomenon possible? It means that cleanup processes are disrupted by the pollution itself. Many of the processes that have already been observed seem to have this character. The eutrophication of lakes progresses to a point where the purifying processes no longer keep up with rising contamination. In oceans and forests, sufficient interference with plant life and bacteria can slow their capability of restoring nature to its original balance. Our ecological systems show a high stability in the face of minor disturbances. Such stability is characteristic of multiple-loop nonlinear systems. But when pushed far enough, the equilibrium-seeking processes can break down. Beyond the breakdown point cumulative and self-generating changes are possible.
>
> [Simulation shows that] at about year 2040 a large gap has developed between pollution generation and pollution absorption. To stop the rise in pollution requires that the rate of pollution generation be dropped to less than the rate of pollution absorption. To be safely under the absorption rate, the generation rate would here need to be cut in half. That means discounting half of the industrial activity of the world. And only ten years elapse [in simulations] between 2030 when the rapid buildup starts and 2040 when only the most drastic action would suffice. It is doubtful that world organizations could respond with sufficient speed and vigor".

This 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 – Metaphorical and Illustrative Models for Sustainability and Climate Change

In chapter 1 of my book *Strategic Modelling and Business Dynamics* I issued a challenge to readers who finish the book. The task, as originally described, was to “rebuild the *World Dynamics* model to incorporate 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” (see page 27, footnote 7). I must admit that back then, in 2007, I was not particularly clear about the likely direction and extent of reconceptualisation, except to stress the need for a compact and vivid model, accessible to policymakers and the public. I also suggested various sources of ideas for reconceptualising the World model including Sterman’s online interactive climate change simulator (available at http://web.mit.edu/jsterman/www/GHG.html), the 30-year update of *Limits to Growth* (Meadows et al 2002) and *The Revenge of Gaia* (Lovelock 2006)[x].

I have always thought the reconceptualisation challenge applied to me as well as to my readers. My interest was spurred in February 2010 during the 12th Annual Gathering of the UK Chapter of the System Dynamics Society held at London’s South Bank University. The theme for the two-day event was ‘Environmental Challenges’. There were three keynote speakers. Details can be found in the Proceedings (editor, Kennedy 2010) and on the UKSD Chapter website www.systemdynamics.org.uk. I was pleasantly surprised to hear appreciative talks about the 1972 Limits to Growth study (David Fisk, BP/Royal Academy of Engineering Chair, Imperial College), climate change and Gaia Theory (Dennis Sherwood, Consultant and Founder, Silver Bullet Machine Manufacturing Company) and systemic approaches to energy and climate security (Nick Mabey, UK Government Policy Adviser and Founder Director of E3G). There were also two interactive workshops. The first, led by Kim Warren (Teaching Fellow, London Business School and Founder of Global Strategy Dynamics), was entitled the “Copenhagen Climate Change Exercise”, based on the C-ROADS simulator and learning materials (Jones et al. 2008) created to enable policy makers to explore climate stabilisation (Sawin et al. 2009).

I led the second workshop, entitled “Metaphorical Models for Simulating Limits to Growth and Industrialisation” - which brings me back to the challenge of reconceptualising *World Dynamics.* Since 2007 I have made some progress on this task, but I have not (yet) changed the original World model. Instead I have re-read the book and studied the model’s equation formulations. My conclusion, as reported here in this paper, is that the conceptual model still provides a versatile framework for thinking about limits to growth and industrialisation, particularly when approached through the structural metaphor of fisheries. Moreover, the accompanying simulator generates vivid alternative futures that remain relevant to debate about overindustrialisation and climate change.

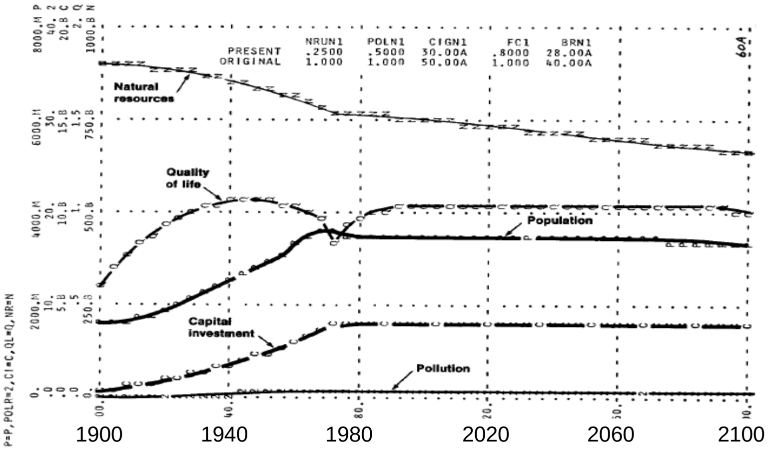
When first published, the World model was illustrative of a global industrial society calibrated to the times. The model’s parameters could of course be re-calibrated to better fit the world situation in 2010. But arguably, even without re-calibration, it remains a useful metaphorical model to evoke critical thinking about industrialisation, limits to growth and climate change. To illustrate I first present an archive simulation relevant to debate about sustainable equilibrium. Then I review some ideas for conceptual ‘fine-tuning’ of the original World model. These ideas, though still evolving, are intended to align the model’s terminology more closely with contemporary concerns about carbon emissions and climate change, while retaining its concise, compelling and intricate feedback structure.

Sustainable Equilibrium

Figure 14 is a simulation of one set of conditions that establishes a world equilibrium at a high quality of life. The following changes were made by comparison with the base case simulation in Figure 12. In 1970 normal capital investment rate is reduced 40 percent, normal birth rate is reduced 30 percent, normal pollution generation is reduced 50 percent, normal natural resource usage rate is reduced 75 percent, and normal food production is reduced 20 percent.

Quoting from *World Dynamics* (pages 120-122):

> “The result is to drop population slightly below the 1970 value and increase the quality of life. Because of the direct influence on birth rate, the system pressures of hunger and low standard of living need not rise as high as before in order to stabilize population. Quality of life stabilizes at a value slightly higher than the 1970 value. Resources are still declining slowly and in time will depress the system unless there is sufficient recycling of waste products and substitution of less critical materials.
>
> Would the world shown by Figure 14 be accepted? It seems more attractive than the system pressures created in the earlier simulations. But is it attractive enough to gain acceptance for the changes in world social values that are implied?
>
> Figure 14 means an end to population growth and to rising standard of living. It suggests a reversal of the emphasis on economic development. Reduction of investment rate and reduction in agricultural productivity are counterintuitive and not likely to be accepted without extensive system studies and years of argument – perhaps many more than are available.



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

Figure 14: Archive Simulation of the World Model – showing one set of conditions that establishes a world equilibrium at a high quality of life

> The reduced normal birth rate introduced in Figure 14 may not be achievable, particularly if the population growth rate should appear to be coming under control. Pressures on the individual and the family would not seem threatening. Each family and even each nation would feel it could expand, if others were holding steady. The result would be incentives and psychological pressures to increase birth rate and to resume population growth. A birth-control program may become merely a substitute for present psychological and social pressures that are limiting population, and, if so, the result may not be the increased quality of life that appeared in Figure 14. Instead, the birth-control program might cause a shift in various goals and traditions sufficient to counteract its own good effects. On the other hand, if the birth-control program becomes mandatory and is based on legal force, then the consequent loss of personal freedom is a loss in a component of quality of life that is not represented in the present model. Forcible imposition of population control would be seen by most people as a sufficiently unfavourable change in the social environment that they might prefer that the forces take the tangible forms of lowered material standard of living and reduced food supply.
>
> This [analysis] suggests that a global equilibrium is conceptually possible. Whether it can be achieved is another matter. The actions that appear to be required are not apt to be accepted easily. Probably more pressure on mankind from the environment will be required before the issues will be addressed with enough concern and seriousness. But by then time will be even shorter".

Climate Change and Industrialisation – Conjectures on Adapting World Dynamics

World Dynamics in the early 1970s offered a compact and compelling representation of limits to growth and industrialisation. But can this conceptual framework and simulator, almost 40 years old, be adapted to address our pressing contemporary concerns about industrialisation and climate change? This is the implicit question behind my 2007 challenge to system dynamics modellers (whether they are new to the field or well-established).

When I first reviewed the original World model it seemed obvious that several conceptual adjustments would be required. After all, the World model makes no explicit mention of fossil fuels, carbon emissions or atmospheric CO_2. Yet it does capture the enduring drivers of industrialisation and the resulting growth dynamics. However I eventually concluded, to my own surprise, that no conceptual or structural change at all is required, at least for the time being. Below is the reasoning that led me to this conclusion in terms of both the concepts that should be invariant and those considered for change but where change was subsequently rejected.

Surely we still need population and capital accumulation as the foundations of our industrial society and as the well-spring of our collective propensity for growth. We also need a pollution-like concept (along with its non-linear regenerative feedback) to capture the invisible side-effects of industrialisation and the potential for a surprise spiral of decline. But now, 40 years later, we know that CO_2 is a particularly potent yet invisible form of pollution. Perhaps therefore the stock of 'pollution' should be replaced with cumulative CO_2 in the atmosphere and the feedback effects on industrial activity reformulated. Also, since carbon dioxide emissions come from the combustion of coal, oil and gas then finite natural resources could be replaced with finite reserves of fossil fuels.

These are plausible changes, but I rejected them on the following grounds. If CO_2 in the atmosphere were simply assumed to be a re-scaled version of pollution, then the model's feedback structure and dynamics would remain the same (or at least similar). The model would become a slightly better analogue (depicting a fossil-fuel using society) but not necessarily a better metaphor.

However it is much more likely that feedback structure and formulations will need to be changed, though precisely how is an empirical matter requiring study, observation, measurement and logic. Formulations for CO_2 generation, regeneration and absorption surely differ from those used for aggregate pollution. Moreover, despite a scientific consensus on global warming, the impact of climate change on industrial activity is not widely understood. The representation of climate feedback structure, connecting cumulative atmospheric CO_2 to society, requires careful thought. Variations on the original structure surrounding aggregate pollution are therefore to be expected. For example, feedback effects from pollution in the World model are deterministic, whereas extreme weather events, that damage society and are thought more likely under global warming, are partly stochastic. Deterministic processes differ too. Compare the inflow rates to cumulative CO_2 versus pollution. CO_2 emissions are proportional to usage of fossil fuels. The greater usage, the more emissions. But, in the World model, usage of natural resources does not directly determine pollution generation (for reasons given in the 'technology breakthrough' scenario). This is an important difference, especially in renewable energy scenarios. Why?

In a model where pollution is replaced by cumulative CO_2, a successful transition to renewable energy would (in principle) solve global warming. However, frugal use of fossil fuels would not necessarily fix the broad pollution problem if such frugality also sustained industrial growth. In particular if CO_2 were stabilised, and there were no alternative pollution concept in the model, then simulated scenarios would lose the important idea in *World Dynamics* of 'hidden pollution' as a latent limit to growth. At least that is my concern about simply substituting CO_2 for pollution in the World model. Further work is needed to capture the joint effects of CO_2 and other forms of industrial pollution without compromising the conceptual clarity of the original model.

I will continue to look for incremental changes to the World model that can refresh its applicability and message in an era of anthropogenic climate change. But my main conclusion/recommendation so far is to re-learn, re-use and re-communicate the original World model; and only then to reconsider and revise it to address climate change. It was never intended as a high fidelity analogue. It was a characterisation of industrial society; a bold sketch on a compact canvas. The passage of time has not diminished its value as a metaphor (or transitional object) for thinking about limits to growth and industrialisation[xi].

Simulators and Interactive Learning Materials

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[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. 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] 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 7 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.

[iv] The functional relationship chosen is recognised in marine science as a combination of Ricker's density dependent stock-recruitment relationship and a density dependent S-shaped natural morality rate (Stouten 2010; Nikolskii 1969).

[v] 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. Click 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. Click 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. Click and the phrase will turn from blue to grey and will, as intended, 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.

[vi] A vivid example of overfishing comes from the Pacific Sardine fishery (Meadows et al 2001, debriefing slides). The annual catch grew remarkably between 1920 and 1940, starting around 50 thousand tonnes and peaking at 700 thousand tonnes – a fourteen fold increase. Over the next four years to 1944 the catch fell to 500 thousand tonnes, stabilised for a few years and then collapsed dramatically to almost zero in 1952. Since then it has never properly recovered. It's a dramatic story. A business that created prosperity for twenty years then collapsed to nothing in little more than a decade. See also Charles Clover's acclaimed book about overfishing *The End of the Line* (Clover 2004).

[vii] 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. More details can be found in Morecroft 2007 (chapter 9) and Stouten 2010. These two references also cite articles by marine biologists and fisheries economists and thereby provide a bridge to the mainstream fisheries management literature.

[viii] The terminology for capital accumulation differs slightly between Figures 10 and 11. In Figure 10 the asset stock is called 'Industrial Capital', the inflow is 'Capital Investment' and the outflow is 'Capital discard'. In Figure 11 the asset stock is called 'Capital Investment', the inflow is 'Capital-investment generation' and the outflow is 'Capital-investment discard'.

[ix] 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.

[x] I would also now add Ford 2010 to my list of sources to browse.

[xi] My suggestion for re-using and re-communicating the World model applies specifically to World 2, the final documented model of 42 equations that appears in *World Dynamics*. There is also World 3, developed by the *Limits to Growth* team (Meadows et al. 1972 and 1992). This is a much larger model of 149 equations, more analogue and less metaphorical than World 2. World 3 has already been revised and re-communicated in two follow-up books, *Beyond the Limits* and *Limits to Growth: The 30 Year Update* (Meadows at al. 1992 and 2002). In these sequels the model's parameters were updated while retaining the original feedback structure. Incidentally, World 1 was the prototype model first sketched out by Jay Forrester in response to The Club of Rome's enquiry about interconnections among global trends and problems. The sketch is reproduced in Lane 2007.