210. How to build a dynamical model

Dynamical modelling shifts problem-solving from a blame-frame to an outcome-frame

Every SD project starts with a problem: a system that exhibits some unsustainable behaviour. The goal of the dynamical modelling project is to make ***policy recommendations*** for improving this situation. In other words, the project should discover how the system generates the unsustainable behaviour, and recommend actions that make this behaviour more sustainable.

Conventional problem-solving uses a *structural* approach. It asks what event or action caused this behaviour to occur, then seeks to fix that event or action. Structural problem-solving operates from a ***blame-frame*** that regards behaviour as being caused by an external event or action.

By contrast, SD uses a *narrative* approach to problem-solving that regards behaviour as arising not from individual events, but from a reciprocally causal story of interactions *within* a system. Rather than seeking to blame, SD adopts an ***outcome-frame*** of discovering how the unsustainable narrative emerges from the existing system structure, and how we might realign that structure to support more sustainable narratives.

Procedure for implementing a modelling project

Specify the dynamical problem

1. Describe the system's structure by listening to *all* stakeholders: *What are the important variables? What are the policy variables? What are their interrelationships? Who has the power to influence them?*
2. Ask stakeholders: *What exactly is the problematic, unsustainable behaviour?* Write down their problem statement in 5-6 words, and draw at least one ***reference narrative*** (***RN***) describing it. This narrative will define your entire project: our dynamical model is simply our hypothesis about what causes the RN. Usually, the RN combines one or more of the six archetypal narratives: growth, decay, goal-seeking, overshoot, oscillation or switching. Stakeholders' reaction to the RN should be: "*Yes! That is <u>exactly</u> the nature of our problem!*"
3. *What are the **stocks** of the reference narrative?* Stocks are state variables that change incrementally over time – if the system has no stocks, it is driven only by external events, and there is no point in building a dynamical model!
4. *What are the processes, parameters and relations that link the stocks into a coherent dynamical system?* ***Processes*** change the stocks; ***parameters*** are either ***given*** (e.g. chemical constants) or they are ***policy*** parameters representing policies that stakeholders have used in the past to try to solve the problem; ***relations*** are quantities that depend on other stocks, processes or parameters.

Design the dynamical model <u>iteratively</u>

5. *Construct the SPD.* Construct an internally consistent system from the stocks, processes, relations and parameters. At a minimum, the SPD contains the reference variable and its relations to policy parameters. Keep your eyes open for new stocks, processes, etc. that nobody thought to mention before.
6. *Draw the feedback loops.* If these are not sufficient to explain the RN, return to step 5 to extend the SPD. In general, system behaviour tends to shift quickly in response to positive causal loops, while negative loops make the current behaviour resistant to change.
7. *Estimate the parameter values* from all possible sources of data. Some will be easy to define, some you will need to calculate, but others (such as 'expert intuition') will just be guesses. These parameters are important for the model – even if you have to guess them. Just insert these values into the SPD, and if they lead to problems in step 8, we will iterate back to

resolve the problem. An important tool for calculation and estimation is to reproduce the equilibrium situations of the system you are modelling.

Implement the reference narrative iteratively

8. *Does our model reproduce the reference narrative?* Build and run the model and compare its BOTG with the RN; if they do not match, return to step 7, 5, 4, 3 or 2 to adjust the model and your information to get a match. *This is very important:* What distinguishes scientific theory-construction from magical Trumpian thinking is that a scientific theory generates results that we can test – *the reference narrative is this test!*
9. *Is our model robust?* Remember that it is not the trajectory that is important, but the attractors lying behind the trajectories. The power of dynamical models lies not in an individual simulation result, but in the ability of the model to provide a causal explanation of the RN even in situations where we vary the parameters' values. We call this testing of the model's robustness ***sensitivity analysis***. If our modelling results are sensitive to changes in some parameter P, then P is a highly important parameter and we must return to its estimation in step 7.
10. *What policies do we recommend for solving the dynamical problem?* Run the model with varying values of the policy parameters. If these reduce the problem, use sensitivity analysis to check how robust this reduction is. If the real-life system contains randomness, build it into the model to check whether our reductions remain stable under random variations.
11. *Report your policy recommendations to customers.* The title of your report should refer directly to the RN, for example, "Suggested policies for handling the problem …". Explanations in your report should be fairly short, and refer mainly to causal loop diagrams, since these are easier than SPDs for lay people to understand.

Case-study: The Rapa-nui project

Sources:

- Wikipedia: https://en.wikipedia.org/wiki/Easter_Island . Accessed 14/4/2024.
- National Geographic: https://www.nationalgeographic.com/history/article/everything-to-know-about-easter-islands-iconic-statues . Accessed 15/4/2024.

Iteration 1-1: What is the system structure?

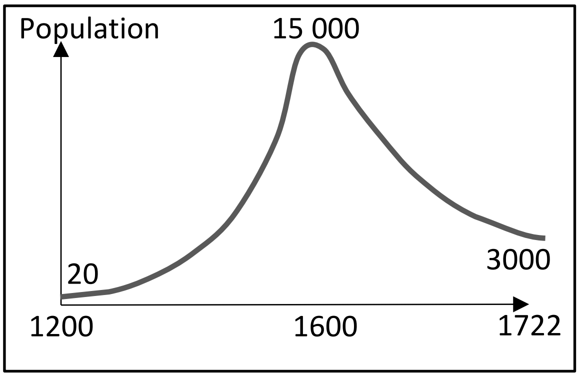
Rapa-nui (*Easter Island*) is a small, isolated island in the Pacific Ocean with an area of about $380\,\mathrm{km}^2$. Oral tradition and radio carbon dating suggest that the island was first settled around 1200 CE by a two-canoe expedition of about 30 settlers from Marae Renga (*Cook Islands*). Due to extreme temperatures and lack of fresh water, the land was difficult to farm, and fishing around the island was poor. The settlers needed to travel further out to sea in order to catch fish. At that time, the island possessed rich forests, and they used the trees to manufacture huts, canoes and rope, and for cooking and heating.

The settlers' activities were highly social – they divided into clans and conducted rituals that resulted in these clans competing to create over 1000 huge stone sculptures over the period from 1300–1600 CE. They presumably used trees and ropes to move the large rocks involved from the volcano Rano-raruku to the coastal areas where most of the statues are still to be seen today. It appears that the size of the statues became greater towards the end of this 300-year building period.

The population grew to between ten and fifteen thousand by 1600 CE, and radiocarbon data suggest that there were almost no trees were left on the island at this time. A Dutch expedition in 1722 CE estimated the population at about 3000.

Iteration 1-2: What problem do we want to solve?

Researchers agree that the central problem of the Rapa-nui population was their extreme growth and crash over the 500-year period from 1200-1722 CE. The sketch on the right illustrates a reference narrative (RN) for this problem. This seems to be an example of Overshoot.



What caused the Rapa-nui population to collapse? We will build an iterative sequence of models to explain how the population might grow up to 15 000 in 1550 CE, and then collapse to 3000. Possible policy variables are growth and change rates of the human and tree populations on the island.

Notice that this RN is common to many ecosystems that collapse – including the World Dynamics model of the Limits to Growth report. Through understanding what went wrong with the Rapa-nui population, we may learn something that is of value for mitigating the mass extinction event currently taking place in the world today.

Iteration 1-3: What are the stocks?

There appear to be three stocks associated with Rapa-nui problem: Humans, trees and statues:

- *Humans* form the centre of the reference narrative – they are the population that grows and crashes. We also assume that this growth and decline is driven by internal factors within the Rapa nui ecosystem, so humans form a stock, or phase variable, that incrementally changes by both reacting to, and acting upon, the entire system.
- *Trees* clearly play a role in the island's ecosystem. Their change depends upon the size of the human population, and their number reciprocally influences growth of the human population. Trees therefore also constitute a stock.
- *Statues* certainly change incrementally over time, reflecting changes in the human population. However, it is difficult to see how the number of statues might reciprocally influence the growth of the human population. We will include the statues as a stock in our model, but we are also aware that this stock might not play any causal role in the system's dynamics.

Iteration 1-4: What are the processes, parameters and relations

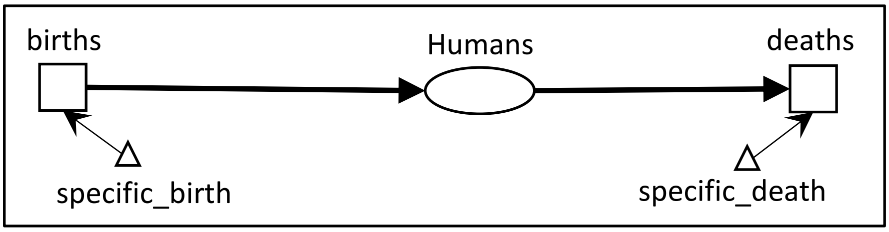
We must now decide how we will build our model. This process is *iterative*: we start with a highly constrained model, then gradually extend it into a more complete model. I therefore suggest the following sequence of models:

1. Our first iteration models the growth of the human population from 1200–1600 CE.
2. Our next iteration models the disappearance of trees from 1200–1600 CE.
3. Our final iteration links these two components to explain the collapse of the population.

The model components for iteration 1 are:

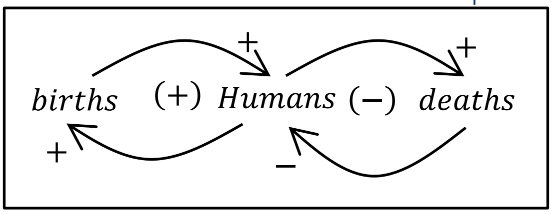
- Stocks: Humans
- Processes: births, deaths
- Parameters: specific birth rate, specific death rate

Iteration 1-5: Construct the SPD



- births = Humans * specific_birth
- deaths = Humans * specific_death

Iteration 1-6: Draw the feedback loops



Iteration 1-7: Estimate parameter values

This is where we need to be imaginative!

- The number of Humans starts at 30 in 1200 CE and reaches 10–15 thousand by 1600.
- The lifespan of settlers was probably only 40 years, giving a specific death rate of $1/40 = 0.025\ \mathrm{yr}^{-1}$.
- We have no precise data on birth rate, but we can make some assumptions. Assume that half the population are female, and that they can bear children from the age of 15–35 years. If each female gives birth every four years (typical for working class communities in 1800), the specific birth rate becomes:

$$\frac{1}{2} \times \frac{20}{40} \times \frac{1}{4} = \frac{1}{16} = 0.0625$$

Iteration 1-8: Compare simulation results with the reference narrative

(i) The method **RapaNui.demo(1)** runs my first iteration of the Rapa-nui model (Growth model 1). Run this method now and study its output. Do these simulation results match our RN?

(ii) Clearly our model is missing some important aspect of settlers' life on Rapa-nui. If we investigate the data, we find that infant mortality in such communities is extremely high. A typical value is that 35% of all children fail to reach 15, but if they reach this age, they will usually live a full lifespan of 40 years. In Growth Model 2, I have implemented this change by multiplying the birth rate by 0.65. Check these simulation results against our RN.

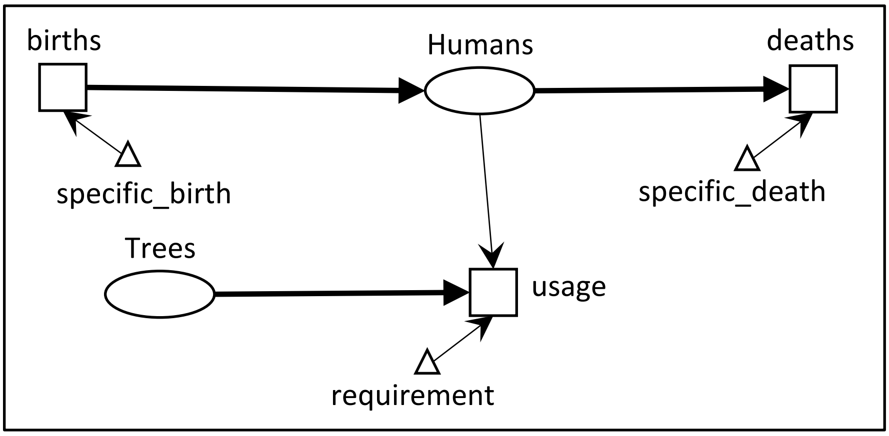
Our results match the RN, so we will iterate our model design by implementing the Trees stock …

Iteration 2-4: What are the processes, parameters and relations

To introduce the Trees stock, we must reassess the processes, parameters and relations. The settlers did not replant the trees, so we assume them to be a non-renewable resource: *no regrowth!*

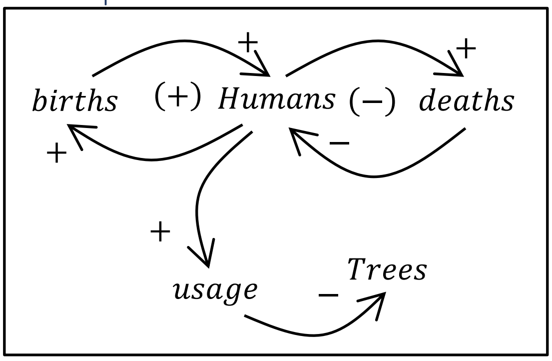
- Stocks: Humans, Trees
- Processes: births, deaths, tree usage
- Parameters: birth rate, death rate, usage rate
- Relations: tree usage rate depends on current human population

Iteration 2-5: Construct the SPD



- usage = Humans * requirement

Iteration 2-6: Draw the feedback loops



Iteration 2-7: Estimate parameter values

- Allowing for coastal and volcanic areas where no trees grow, estimate one tree per $100\ \mathrm{m}^2$ area, or 100 trees per square kilometre. This gives an initial value of about 40 000 trees on the island in 1200.
- Regarding specific tree requirement, suppose each tree provides one canoe for 10 people, and that this canoe has a service life of 4 years. Then 40 people together need one tree per year, and the specific requirement rate is $r = 1/40 = 0.025$ trees per person per year.

Iteration 2-8: Compare simulation results with the reference narrative

(iii) Implement a third model (**Tree consumption**) in the module **RapaNui** that implements the new SPD, using the value 0.025 for the requirement r. Run this model, then compare your simulation results to the RN. Does this value of r eliminate all trees by 1600?

This model of tree usage is clearly missing something important, and indeed, it does not take into account *wastefulness*: our tendency to use more resources than we actually require. Studies on sustainability suggest that unless we perceive a resource to be in short supply, we will consume up to twenty times our actual requirement of that resource. We can model this using the following wastefulness function $w(\,)$:

$$w(s,d) \equiv d \cdot hill(s,d,n) = \frac{d\, s^n}{d^n + s^n}$$

where $d = 20r$ is the desired amount of the resource. This saturation function consumes resources at rate zero when the supply s of resources is zero; at rate $d/2$ when the supply s is equal to d, and will consume resources up to a maximum rate d as the supply rises even higher.

(iv) Implement the function $w(s)$ in your **Tree consumption** model. Choose a suitable cooperativity value n and define the current supply of trees as $s \equiv Trees/Humans$. Finally, use the resulting wastefulness value $w(s,d)$ as the new specific resources consumption rate. In what year does the number of trees now fall to zero?

(v) We know that the population of Rapa-nui lay between 10 and 15 thousand in 1600, so the trees could not have been consumed much before this time. In your **Tree consumption** model, define a new parameter greediness (g) that links the desired usage rate d to the required rate r: $d = gr$. Now modify the value of g so that trees disappear just before 1600 CE. What greediness factor generates results consistent with the historical record?

Important: *Notice that the settlers are in fact not at all greedy – they are merely a little wasteful in their canoe production, and they drop even this wastefulness as soon as the supply of trees runs low. Nevertheless, even this low-level wastefulness makes a significant difference to the survival of their ecosystem! This unintended breakdown of ecosystems through slight wastage has a name:* ***The Tragedy of the Commons****.*

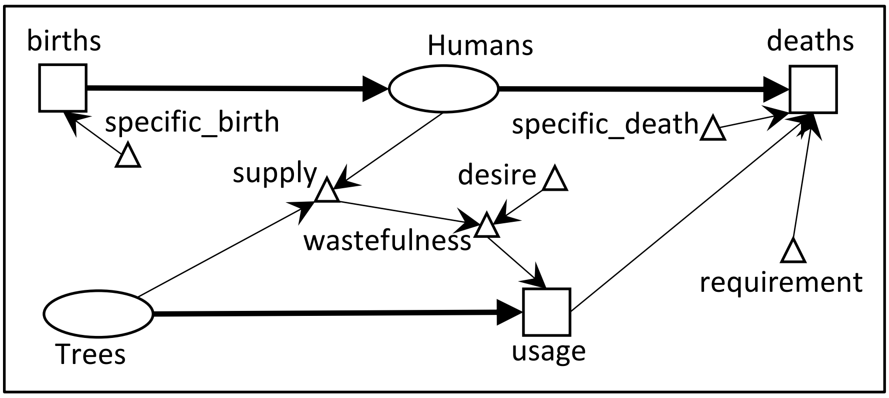
Notice that our model does not yet display the collapse of the ecosystem, since we have not yet linked the collapse of the trees to human deaths. That is what we must do in the next iteration of our modelling process.

Iteration 3-4: What are the processes, parameters and relations

To tie human deaths to the number of trees, we reconsider the processes, parameters and relations:

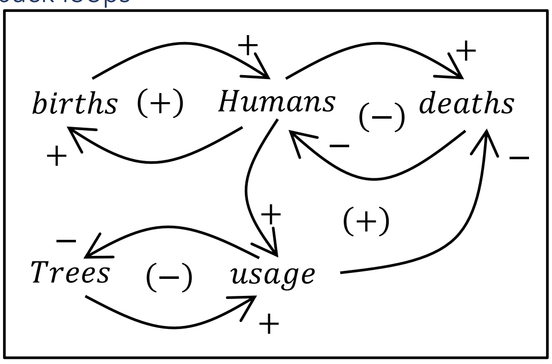
- Stocks: Humans, Trees
- Processes: births, deaths, tree usage,
- Parameters: birth rate, death rate, required usage rate, desired usage rate
- Relations: Human growth rate depends upon the relationship between required and actual tree usage rate

Iteration 3-5: Construct the SPD



- usage = Humans * wastefulness

Iteration 3-6: Draw the feedback loops



Iteration 3-7: Estimate parameter values

- To link tree usage to deaths, we note that usage lowers the death rate, so lower usage leads to higher surplus mortality m:

$$m(usage, r) = hill(usage, -r, n)$$

- This mortality modifies the death rate: deaths = specific_deaths * Humans * (1 + m)

Iteration 3-8: Compare simulation results with the reference narrative

(vi) Implement a fourth model (**Overshoot**) in to implement the new dynamics linking deaths to usage. Run this method from 1200 to 1750 and compare your simulation results to the RN. Your results should indicate that the collapse of the trees leads to a sharp decline in the number of humans. Well done!

Iteration 3-9: Robustness

(vii) We have succeeded in demonstrating how the overshoot of the Rapa-nui population leads to the collapse of the ecosystem, but we have only demonstrated this for a specific value of the greediness g. Experiment with the values of g to find out how it affects two aspects of your **Overshoot** model: the year of the collapse and the maximum size of the human population. Can you achieve a human population peak of 10-15 thousand together with a tree population that crashes in 1600?

(viii) You should find that overshoot is a robust property of your model. However, if humans use the trees too greedily, their population never rises above 10 thousand, and if they use the trees less greedily, the collapse comes much later than 1600. This seems to suggest that humans use the trees more wastefully when the trees are running out. Look back now at our information on Rapa-nui, and think of a mechanism by which this extreme usage might occur as the collapse happens. Create a new model (**Collapse**) that implements this mechanism to achieve correct population numbers and dates.

Iteration 3-10: Policies

(ix) By reproducing the collapse of the Rapa-nui ecosystem, we have discovered the mechanisms that might have caused it. Think about what policies could avoid this collapse of the ecosystem, and demonstrate the effectiveness of these policies by implementing them in a new model **Sustainability**.

Iteration 3-11: Communication

(x) We still need to convince the Rapa-nui population of the necessity of implementing these policies. Imagine it is the year 1400, and create a Powerpoint poster to convince the settlers that they should change their habits in ways that make the Rapa-nui ecosystem sustainable.