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A Methodological Framework for Integrating Systems Thinking and System Dynamics

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Abstract

This paper discusses a methodological framework for integrating the fields of systems thinking and system dynamics. A discussion of the four levels of thinking and their implications for organisations and management is followed by the core of the paper, which presents a methodology for systems thinking and modelling. The methodology includes five major phases: problem structuring; causal loop modelling; dynamic modelling; scenario planning and modelling; and implementation and organisational learning. These phases follow a rigorous systematic process, each involving a number of steps. Some general and specific applications of systems thinking are then discussed, and hard and soft modelling approaches are compared and contrasted. Finally, some cases are provided to illustrate applications of the systems thinking and modelling methodology.

Introduction

Daily, we are exposed to information from a multitude of sources: the news media, newspapers, radio, TV, and the Internet. Generally this kind of information reports events what happened, where, when, how, who was involved, etc. This is a snapshot view of the world because this level of information is very shallow; the reports only touch the surface of what actually happened. For example, the stock market information that is reported daily gives a snapshot of the day's activities. It tells us whether stocks, on average, went up or down (often the index goes both up and down within one day) and by how much. We also get information on the volume of shares traded, the dollar value of stocks traded (capital turnover) and much more. All of this information is at event level.

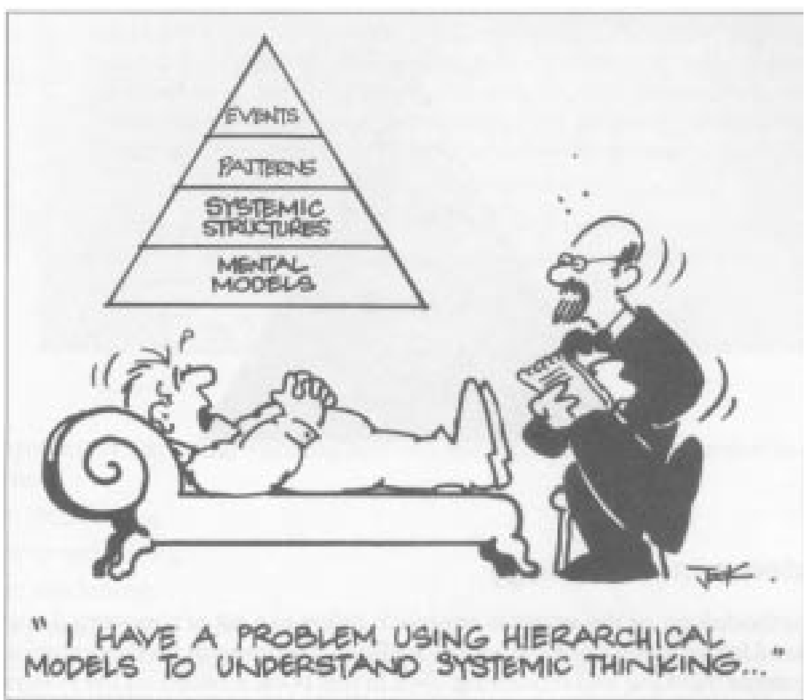
Sometimes there is commentary about a news item or an issue, and this allows one to look back and examine the trends and patterns of events and data. This provides a richer picture of reality and gives more insight into the 'story'. In the stock market example, this means looking at the trends over past months or years, observing the fluctuations and trying to explain what caused 'pulses' in the system - for example, news of a merger, a quarterly economic report or a political scandal.

However, it is rare to see a study of how such trends and patterns relate to and affect one another. This represents a much deeper level of thinking that can show how the interplay of different factors brings about the outcomes that we observe. In the stock market example, this would mean trying to relate a host of factors that systemically cause the fluctuating patterns. These factors could be economic, social, political or structural. The critical thing at this level of thinking is to understand how these factors interact.

Furthermore, there is yet another, much deeper level of thinking that hardly ever comes to the surface. This represents the 'mental models' of individuals and organisations that influence why things should/do or should not/do not work. Mental models are based on the beliefs, values, and assumptions that we (privately) hold, and underlie our reasons for doing things the way we do them. Harvard educationalist Chris Argyris (1990, pp.25-27) calls these the 'undiscussables'.

The four levels of thinking described above are depicted in Figure 1. This figure uses the analogy of an iceberg, where the event level of thinking is represented by the tip and yet most of us are satisfied with this level. However, this level is clearly completely inadequate for understanding the dynamics underlying change and complexity in the world around us. This paper outlines a systems thinking and modelling (ST&M) methodology, which is fully described in a recent book by Maani and Cavana (2000) on '*Systems thinking and modelling: understanding change and complexity*'.

Figure 1 Four levels of thinking



Source: Cartoon provided by Jock Macneish in Maani and Cavana (2000, p13).

Systems methodology

Systems methodology or the systems approach refers to a set of conceptual and analytical methods used for systems thinking and modelling. The general methodological approach towards systems thinking and modelling used in this paper is based on the system dynamics method. The field of system dynamics was developed by Jay Forrester (1961) and others at the Massachusetts Institute of Technology in the late 1950s, based on developments following World War II in:

- the theory of information feedback systems;
- the understanding of decision-making processes;
- the use of mathematical models to simulate complex systems; and
- the development of high-speed electronic digital computers as a means of simulating mathematical models.

Many other people have contributed to the development of systems thinking and system dynamics including Coyle (1977, 1996), Randers (1980), Richardson and Pugh (1981), Roberts *et al*. (1983), Senge (1990), Wolstenholme (1990), Richardson (1991), Mohapatra *et al*. (1994), Morecroft and Sterman (1994), Vennix (1996), Richmond and Petersen (1997), Sterman (2000), and many others! However, several authors have provided definitions of the system dynamics methodology, but we consider the one recently provided by Eric Wolstenholme (1997) as most appropriate. Wolstenholme's description of the scope of system dynamics is set out below.

What: A rigorous way to help thinking, visualising, sharing, and communication of the future evolution of complex organisations and issues over time;

Why: for the purpose of solving problems and creating more robust designs, which minimise the likelihood of unpleasant surprises and unintended consequences;

How: by creating operational maps and simulation models which externalise mental models and capture the interrelationships of physical and behavioural processes, organisational boundaries, policies, information feedback and time delays; and by using these architectures to test the holistic outcomes of alternative plans and ideas;

Within: a framework which respects and fosters the needs and values of awareness, openness, responsibility and equality of individuals and teams.
(Wolstenholme, 1997)

The development of a systems thinking and modelling (Maani & Cavana, 2000) intervention involves five major phases:

1 problem structuring;
2 causal loop modelling;
3 dynamic modelling;
4 scenario planning and modelling;
5 implementation and organisational learning (learning lab).

These phases follow a process, each involving a number of steps, as outlined in Table 1. However, it must be emphasised that a ST&M intervention does not require all phases to be undertaken, nor does each phase require all the steps listed in Table 1. Rather, these phases and steps are presented as guidelines, and which phases and steps are included in a particular ST&M intervention depends on the issues or problems that have generated the systems enquiry and the degree of effort that the organisation is prepared to commit to the intervention.

Table 2.1: Systems Thinking & Modelling Process

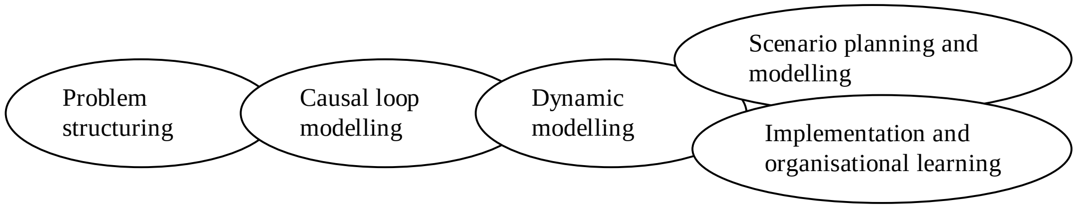
Phases	Steps
1. *Problem structuring*	1. Identify problems or issues of concern to management 2. Collect preliminary information & data
2. *Causal Loop modelling*	1. Identify main variables 2. Prepare behaviour over time graphs (reference mode) 3. Develop causal loop diagrams (influence diagrams) 4. Analyse loop behaviour over time 5. Identify system archetypes 6. Identify key leverage points 7. Develop intervention strategies
3. *Dynamic modelling*	1. Develop a systems map or rich picture 2. Define variable types and construct stock-flow diagrams 3. Collect detailed information and data 4. Develop a simulation model 5. Simulate steady-state / stability conditions 6. Reproduce reference mode behaviour (base case) 7. Validate the model 8. Perform sensitivity analysis 9. Design & analyse policies 10. Develop & test strategies
4. *Scenario planning and modelling*	1. Plan general scope of scenarios 2. Identify key drivers of change & keynote uncertainties 3. Construct forced & learning scenarios 4. Simulate scenarios with the model 5. Evaluate the robustness of the policies and strategies
5. *Implementation and organisational learning*	1. Prepare a report and presentation to management 2. Communicate results and insights of proposed intervention to stakeholders 3. Develop a microworld and learning lab based on the simulation model 4. Use learning lab to examine mental models and facilitate learning in the organisation

Source: Maani and Cavana, 2000, Table 2.1, p16.

Phases of the methodology

Figure 2 shows the progression of the phases. As mentioned earlier, although these phases can be used individually, their cumulative use adds more value and power to the investigation. These phases are described below.

Figure 2 Phases of the systems thinking and modelling methodology



Problem structuring

In this phase, the situation or issue at hand is defined and the scope and boundaries of the study are identified. This is the common first step in most problem-solving approaches. The problem structuring phase consists of the following steps:

(1) Identification of the problem area or policy issues of concern to management. This step requires that we clearly establish the objectives, taking into account multiple stakeholders and perspectives.
(2) Collection of preliminary information and data including media reports, historical and statistical records, policy documents, previous studies, and stakeholder interviews.

Causal loop modelling

During this phase, conceptual models of the problem, known as causal loop diagrams (CLDs) will be created. This is a major component and the most commonly used part of the systems thinking approach. The following steps are used in causal loop modelling:

(1) Identify main (key) variables.
(2) Draw behaviour over time charts (or reference modes) for the main variables.
(3) Develop causal loop diagrams (influence diagrams) to illustrate the relationships among the variables.
(4) Discuss behaviour over time of the dynamics implied by the causal loop diagrams.
(5) Identify system archetypes that would describe high-level causal patterns.
(6) Identify key leverage points.
(7) Develop intervention strategies.

Dynamic modelling

This phase follows the causal loop modelling phase. Although it is possible to go into this phase directly after problem structuring, performing the causal loop modelling phase first will enhance the conceptual rigour and learning power of the systems approach. The completeness and wider insights of systems thinking is generally absent from other simulation modelling approaches, where causal loop modelling does not play a part. The following steps are generally followed in the dynamic modelling phase:

(1) Develop a high-level map or systems diagram showing the main sectors of a potential simulation model, or a ‘rich picture’ of the main variables and issues involved in the system of interest.
(2) Define variable types (e.g. stocks, flows, converters, etc.) and construct stock flow diagrams for different sectors of the model.
(3) Collect detailed, relevant data including media reports, historical and statistical records, policy documents, previous studies, and stakeholder interviews.
(4) Construct a computer simulation model based on the causal loop diagrams or stock-flow diagrams. Identify the initial values for the stocks (levels), parameter values for the relationships, and the structural relationships between the variables using constants, graphical relationships and mathematical functions where appropriate. This stage involves using specialised computer packages like STELLA, ithink, POWERSIM, DYNAMO, DYSMAP, COSMIC or VENSIM.
(5) Simulate the model over time. Select the initial value for the beginning of the simulation run, specify the unit of time for the simulation (e.g. hour, day, week, month, year, etc.). Select the simulation interval (DT) (e.g. 0.25, 0.5, 1.0) and the time horizon for the simulation run (i.e. the length of the simulation). Simulate model stability by generating steady state conditions.
(6) Produce graphical and tabular output for the base case of the model. This can be produced using any of the computer packages mentioned above. Compare model behaviour with historical trends or hypothesised reference modes (behaviour over time charts).
(7) Verify model equations, parameters and boundaries, and validate the model’s behaviour over time. Carefully inspect the graphical and tabular output generated by the model.
(8) Perform sensitivity tests to gauge the sensitivity of model parameters and initial values. Identify areas of greatest improvement (key leverage points) in the system.
(9) Design and test policies with the model, to address the issues of concern to management and to look for system improvement.
(10) Develop and test strategies (i.e. combinations of functional policies, for example operations, marketing, finance, human resources, etc.).

Scenario planning and modelling

In this phase, various policies and strategies are postulated and tested. Here ‘policy’ refers to changes to a single internal variable such as hiring, quality, or price. Strategy is the combination of a set of polices and as such deals with internal or controllable changes. When these strategies are tested under varying external conditions, this is referred to as scenario modelling:

(1) Develop general scope, time frame and boundaries of external environment for scenarios. Prepare stories of possible futures or theme scenarios.
(2) Identify key drivers of change, uncertainties and factors that could have a significant impact on the decisions, policies and strategies being evaluated. Determine ranges for external parameters and graphs.
(3) Construct forced scenarios by placing all the positive outcomes in an optimistic

scenario and all the negative scenarios in a pessimistic scenario. Check the forced scenarios for internal consistency. Modify these scenarios as learning scenarios (based on Schoemaker, 1995).

(4) Simulate the scenarios (either the individual scenarios varying the key uncertainties or the learning scenarios) with the model. Redesign scenarios if necessary.

(5) Evaluate the performance of the policies and strategies with the model for each scenario. Assess the performance against a range of relevant performance measures for overall robustness. Select the policies or strategies that meet management's objectives for the investigation.

Implementation and organisational learning

One of the most beneficial and enduring outcomes of systems thinking and modelling is organisational and team learning. Once simulation models have been developed, they can be enhanced by extending them into a microworld. Microworlds (also known as management flight simulators) provide an interactive and user-friendly interface for managers to experiment with the model. The learning laboratory uses microworlds in a structured process, akin to a scientific environment, to test hypotheses and mental models designed to create individual and group learning. The following steps summarise this phase:

(1) Prepare a report and presentation to the management team and other stakeholders. This should document the background and development of the systems thinking project, the challenges faced and lessons learned.

(2) Communicate results and insights of the study and the reasons for the proposed intervention to all stakeholders.

(3) Develop a microworld and design a learning lab for the simulation model. This involves adding necessary features (i.e. from computer software) to convert the simulation model into an interactive and user-friendly microworld. Then design a learning lab process for the microworld.

(4) Use the learning lab process to diffuse and facilitate learning in the organisation.

Systems thinking and modelling applications

The systems thinking and modelling methodology outlined above has a wide range of general and specific applications. The general applications are:

- design of new systems;
- re-engineering or improvement of existing systems;
- prediction of behaviour of complex systems under varying conditions;
- understanding the interaction of component sub-systems;
- strategy development and testing;
- scenario modelling and testing;
- group and organisational learning.

The specific applications of systems thinking cover both strategic and functional aspects of business and organisations. Some of these are outlined below.

Strategy and policy

Systems thinking is widely used for strategy formulation and testing. This occurs at the level of government and industry (e.g. health care, communication, regulation, etc.) as well as at the organisational level (e.g. marketing, production, human resources, finance and their interfaces). Systems thinking highlights the following areas of strategy, which are often ignored or missed by other methodologies:

- internal contradictions in a strategy;
- hidden strategic opportunities;
- untapped strategic leverages.

Operations and design

Systems thinking also has widespread applications in operations and design. Traditionally, manufacturing systems have been a prominent area of application. Service industries such as health care, communications and logistics are the upcoming areas that readily lend themselves to the application of systems thinking and modelling. Some of the specific applications are:

- new product and service development;
- supply-chain management;
- enterprise resource planning (ERP);
- network design and management.

Functional modelling

In addition to the areas mentioned above, the systems thinking and modelling methodology can be used to model functional areas such as finance, marketing, information technology and human resource management. In Maani and Cavana (2000) we discuss these applications and illustrate how to integrate them using systems models.

Hard and soft modelling

As the terms model and modelling are frequently used, it is important to clarify their meaning in this context. A model is defined as being a representation of the real world. Models can take on different forms, physical, analog, digital (computer), mathematical, and so on. This sense of the word model is the more traditional one and is sometimes referred to as quantitative or 'hard'. More recently, the concept of soft modelling has been developed by Checkland (1981) and others. Soft modelling refers to conceptual and contextual approaches that tend to be more realistic, pluralistic and holistic than 'hard' models. Hard and soft models are sometimes referred to as 'quantitative' and 'qualitative', respectively. The differences between the hard and soft approaches are summarised in Table 2.

Table 2 Hard versus soft approaches

	Hard approaches	**Soft approaches**
Model definition	A representation of the real world	A way of generating debate and insight about the real world
Problem definition	Clear and single dimensional (single objective)	Ambiguous and multi-dimensional (multiple objectives)
People and organisation	Not taken into account	Are integral parts of the model
Data	Quantitative	Qualitative
Goal	Solution and optimisation	Insight and learning
Outcome	Product or recommendation	Progress through group learning

Source: Maani & Cavana (2000, p21) adapted from Pidd (1996, p121)

The systems thinking and modelling methodology presented in this paper covers both hard and soft approaches, because we regard these approaches as complementary and mutually reinforcing. Systems thinking tends to fall in the category of soft approaches, while dynamic modelling gravitates toward the category of hard modelling.

Systems thinking and modelling cases

A number of systems thinking and modelling (ST&M) cases are fully discussed in Maani and Cavana (2000). However, only a few of them will be briefly outlined here to illustrate the various ways the ST&M methodology can be utilised, depending on the specific systems intervention. Table 3 summarises the ST&M steps used in each case. A tick indicates that the step was used. However, it should be re-emphasised that although the steps appear in a linear fashion, in some cases an earlier step in the Table is carried out at a later stage in the investigation. For example in the Beer case (case 4), a causal loop diagram was constructed after a simulation model had been developed to help explain the dynamic behaviour that the model generated.

However, in most cases the steps are followed in a 'sequential' fashion. Interventions that required a 'soft' systems approach (ie cases 1, 2 & 3) tended to draw upon phases 1 and 2 of the ST&M process. However, in cases that developed into 'hard' modelling projects tended to utilise the later stages of the ST&M process. In addition, the telecommunications business unit case (Case 5) utlised all phases of the process.

Table 3: Applications of the Systems Thinking & Modelling Process

***Phases* & Steps**	Case 1	Case 2	Case 3	Case 4	Case 5
1. Problem structuring					
1. Identify problems or issues of concern to management	√	√	√	√	√
2. Collect preliminary information & data	√	√	√	√	√
2. Causal Loop modelling					
1. Identify main variables	√	√	√	√	√
2. Prepare behaviour over time graphs (reference mode)	√	√			√
3. Develop causal loop diagrams (influence diagrams)	√	√	√	√	√
4. Analyse loop behaviour over time	√	√			√
5. Identify system archetypes	√	√			
6. Identify key leverage points	√	√			
7. Develop intervention strategies	√	√			
3. Dynamic modelling					
1. Develop a systems map or rich picture				√	√
2. Define variable types and construct stock-flow diagrams				√	√
3. Collect detailed information and data				√	√
4. Develop a simulation model				√	√
5. Simulate steady-state / stability conditions				√	√
6. Reproduce reference mode behaviour (base case)				√	√
7. Validate the model				√	√
8. Perform sensitivity analysis				√	√
9. Design & analyse policies				√	√
10. Develop & test strategies					√
4. Scenario planning and modelling					
1. Plan general scope of scenarios					√
2. Identify key drivers of change & keynote uncertainties					√
3. Construct forced & learning scenarios					√
4. Simulate scenarios with the model					√
5. Evaluate the robustness of the policies and strategies					√
5. Implementation and organisational learning					
1. Prepare a report and presentation to management	√	√	√		√
2. Communicate results and insights of proposed intervention to stakeholders	√	√			
3. Develop a microworld and learning lab based on the simulation model					√
4. Use learning lab to examine mental models and facilitate learning in the organisation					

Case 1: Public health reform - the case of New Zealand

In July 1993, New Zealand's health system fundamentally changed, splitting the health care provider from the purchaser, whereas previously Area Health Boards had assumed both these roles. The providers, Crown Health Enterprises, were in future to compete amongst themselves for funding from the purchasers, Regional Health Authorities. Private sector managers were brought in to run the hospitals in a business-like manner, increasing efficiency, and even returning a profit to the Government. The objectives of the reforms (Upton, 1991) were:

- to reduce hospital waiting times;
- to improve access for all New Zealanders to an effective, fair and affordable health care system;
- to emphasise health promotion and illness prevention.

However, in reality and despite increased government spending on surgery, waiting list numbers have soared. This case study used a systems thinking approach to investigate the effects of the reform, and to determine whether the new system was consistent with government's stated objectives. The study revealed a number of inconsistencies and gaps in current policies and proposed intervention strategies for reversing the adverse trends.

Case 2: Lowering the legal drinking age[1]

Alcohol is a key feature of New Zealanders' social and sporting activities. Eighty-nine per cent of men and 85% of women consume alcohol regularly. When this case study was undertaken, the legislation stated that '… to legally consume alcohol in New Zealand an individual must be 20 years or older. An individual can also consume alcohol if between the ages of 18-20 and consuming food or accompanied by a parent/guardian.'

Various members of the Parliament were pushing for changes to these laws. A number of changes have been proposed, including Sunday liquor sales and permitting supermarkets to sell liquor. One proposed change that caused considerable debate within the government and in public circles, was the idea of lowering the legal drinking age from 20 to 18 years.

The use of systems thinking methods provided a much clearer understanding of the complex issue of lowering the legal drinking age and its effects, implications, and unintended consequences. The study concluded that the lowering of legal drinking age would push the *actual* drinking threshold downward and would, in effect, create a new 'under-age' drinking group. Only a few months after the introduction of the new policy, this 'unseen' consequence is already occurring which has caused surprise and disappointment by the policy makers and the public alike.

Case 3: Drivers of Quality in Health Services

This case describes how an exploratory project at the New Zealand Ministry of Health, using a qualitative system dynamics approach to identify the factors that interact to drive quality in the health and disability sector, revealed sound evidence for the much cited different worldviews (mental models) of medical/health clinicians and policy managers. (Cavana *et al.*, 1999)

Case 4: Mainland Beer Distribution Model

This case illustrates model conceptualisation, model construction, and an introduction to policy analysis. It is based on the famous beer game first developed in the 1960s at the Massachusetts Institute of Technology's Sloan School of Management (see Senge, 1990). The version of the beer distribution system presented here is derived from Clark (1988). Details of this case are: The distribution system for Mainland beer consists of a retail store and brewery; each managed independently under a centralised inventory policy. The case uses systems thinking and modelling to assist with the design of inventory control policies.

Case 5: Strategy Development for a Telecommunications Business Unit

This case demonstrates all the phases and nearly all the steps in the systems thinking and modelling process. It is based on a consultancy project for a business unit in the telecommunications industry in New Zealand (Cavana and Hughes, 1995). However, the issues, data and names have been changed to preserve client confidentiality. The major issues dealt with in this case are how to design policies and strategies to help managers' turnaround a business unit that is experiencing a declining market share and eroding profitability.

Conclusions

This paper has presented a methodological framework for understanding change and complexity using a systems thinking and modelling approach. The phases and steps of this methodology have been outlined, and we have indicated how we have used aspects of this methodology in specific systems interventions (cases).

The methodology outlined combines a range of soft and hard modelling/systems approaches, which can be used in various combinations depending on the specific systems intervention being considered. We expect that this methodology will be further developed and tested with other applications over time. The full treatment of the methodology and the five cases outlined in this paper can be found in authors' new book Systems Thinking and Modelling - Understanding Change and Complexity (Maani & Cavana 2000).

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[1] This case was based on a project prepared by David Todd for the graduate course in systems modelling at the University of Auckland