Review of Literature on Systems Thinking and System Dynamics for Policy Making

Prepared for Department for Environment, Food and Rural Affairs

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1.0 Executive Summary

This literature review sets the stage for the Defra project titled:

Systems thinking and system dynamics modelling to support policy development using waste prevention and recycling as case studies

The objective of this literature review is to provide evidence of existing knowledge and experience related to the project, with examples of where systems thinking (ST) and System Dynamics (SD) have been used to support policy making, explain complexity in systems that policy makers are working within, and especially where these methods have been used in the waste system.

"Systems thinking" is a general term that describes an approach to understanding and working with complexity in the real world and it covers a range of different formal methodologies. System Dynamics is a specific system modelling and system practitioner methodology.

The intended audience for this literature review is experts, policy makers and analysts at Defra. For those not already familiar with systems thinking, the introduction section in Section 2 provides a general overview of the field and its methods.

There are three sections within this literature review, each with a different focus:

[1] Systems thinking to support policy making
[2] An introduction to System Dynamics
[3] The use of System Dynamics in policy making for the waste system

2.0 Systems Thinking to Support Policy Development

This section reviews literature on the general approach of systems thinking and how it is applied to government policy development.

2.1 Introduction to Systems Thinking

Firstly, we present three definitions of the term "systems thinking". They reflect the slightly different perspective of the writers but all refer to the key elements of dealing with complexity, seeing interconnectedness, identifying emergence, and working in an interdisciplinary way.

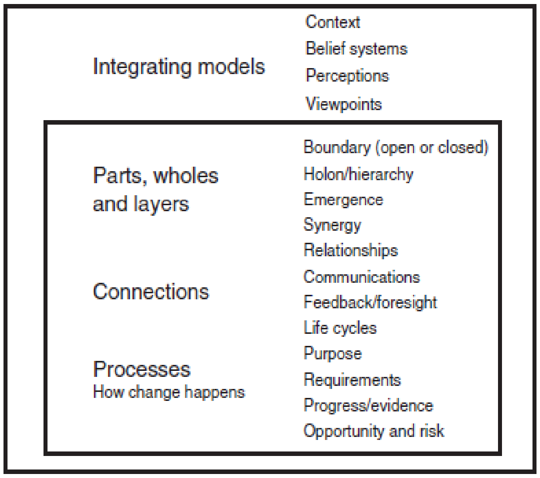
- (Open University 2012): *'Systems thinking enables you to grasp and manage situations of complexity and uncertainty in which there are no simple answers. It's a way of "learning your way towards effective action" by looking at connected wholes rather than separate parts'*.
- (Richardson 2011): *'Systems thinking is the mental effort to uncover endogenous sources of system behavior'.*
- (Senge 1990)*: 'Systems thinking is a framework for seeing interrelationships rather than things, for seeing patterns rather than static snapshots. It is a set of general principles spanning fields as diverse as physical and social sciences, engineering and management.'*
- (INCOSE UK 2010): *'Systems thinking is a way of thinking used to address complex and uncertain real world problems. It recognises that the world is a set of highly interconnected technical and social entities which are hierarchically organised producing emergent behaviour.'*

2.2 Systems Methodologies

Within the systems thinking field there is a range of formally defined methodologies, each with methods and tools for working with real world systems. Essential ideas used in these methodologies have been classified as "parts, wholes and layers, connections, or processes" (Godfrey 2010), as shown in Figure 1. Systems methodologies are generally oriented more towards soft (i.e. people) or hard (i.e. physical) systems, and they can be applied at any level, from a single case (e.g. a particular organisation or piece of equipment) up to the global (e.g. climate science models of the Earth). In his paper on creative holism (Jackson 2006) provides a map of applied systems methodologies, shown in Figure 2, with methodologies positioned along two axes. The vertical axis defines the nature of systems as ranging from simple to complex, and the horizontal axis defines systems as unitary, pluralist, or coercive. Systems approaches positioned in the complex area of the map, such as System Dynamics, try to *'manage greater complexity and change by getting "behind" the numerous surface relationships apparently impacting on the system'* (ibid) and identifying those key mechanisms or structures that cause system behaviour. In contrast, a more interpretive stance is taken in soft systems methodologies and *'attention is given to ensuring sufficient accommodation between different and sometimes conflicting world-views.'* (ibid)

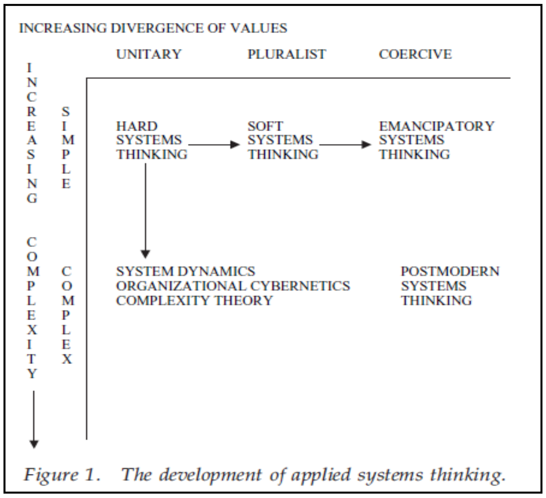
The practice of applying systems methodologies varies according to the system being worked with and the methodology being used. There are commonly several steps involved in applying systems thinking methods: problem exploration and structuring, model building, scenario development, model validation, and application of model results to the real world. The last few steps are often done within an iterative learning process, with several rounds of model building, testing, and model revising as evidence is gathered and compared against the model.

Figure 1: Essential Ideas in Systems Thinking



Source: (Godfrey 2010)

Figure 2: Applied System Thinking



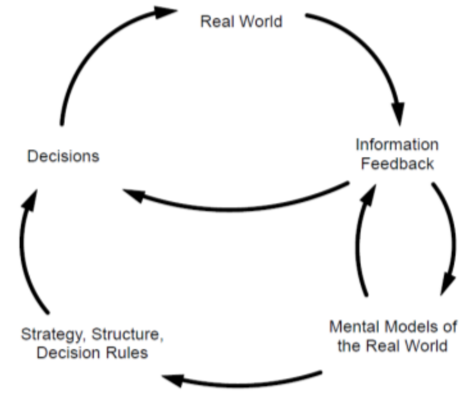
Source: (Jackson 2006)

2.3 Systems Modelling

System modelling is the primary tool of systems thinkers. Models are *'the means by which a systems thinker comes to terms with complex real-world problems.'* (Godfrey 2010) Systems modelling is a way of making a mental model of the world specific; it is a structural account of real world systems. The function of a model is to act as a proxy for a real system so that it can be understood better and the possible impact, or consequences, of possible interventions can be explored before implementation. Implicit in the modelling process is that decision-making affects the system, which in turn affects decision making. (Sterman 2000) names this "double loop learning", depicted in Figure 3, and describes this as a process in which feedback from the real world stimulates changes in people's mental models, which leads to new understandings and reframing of the situation, new goals and decision rules, and new decisions.

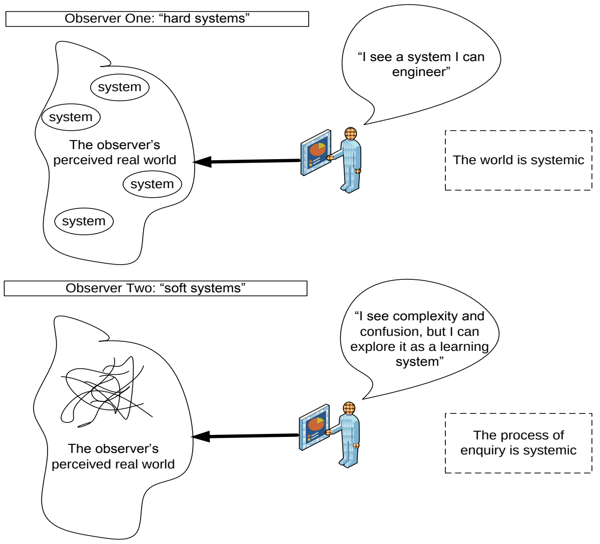
An important part of the modelling process is to identify what the position of the systems modeller is in relation to the actual system. Any model is naturally subjective, and all stakeholders will have their own unique perspective on the system. (Checkland & Scholes 1999) depicts this relationship between the modeller and the system in his book Soft Systems Methodology in Action, as shown in Figure 4. He compares the difference between a hard systems understanding with that of soft systems. In the secondary one complexity and confusion can be explored through a systemic process of enquiry whereas in the first the modeller views the system as something to be engineered.

Figure 3: Double Loop Learning (Sterman)



Source: adapted from (Sterman 2000)

Figure 4: The Hard and Soft Systems Stances (Checkland)



Source: adapted from (Checkland & Scholes 1999)

The benefits and characteristics of systems modelling include:

- System modelling enables a what-if analysis of potential interventions in existing systems to be done through scenario analysis.
- System modelling allows us to consider perspectives not usually included in more traditional analysis for policy making (such as cost-benefit analysis) including: endogeneity, positive and negative feedback, delays, and mutual causality.
- Systems thinking views the system of concern in a systemic way, meaning that systems thinkers have to consider the ethical and moral issues around how much to view the system as interconnected with the rest of the world, or parts of it, and what the effects of intervening in the system will be to any concerned stakeholders.
- System modelling doesn't model individuals, but empirical quantities that are associated with aggregates of individual behaviours (e.g. market confidence).
- Systems models are structural accounts of the real world system, with the format of the structure hinging on which relationships within the system are the most crucial. The dynamic behaviour of the system, as simulated in the model, is seen as a consequence of that structure.[1]

2.3.1 Modelling Sociotechnical Systems

Universally available systems such as waste, water and power include interacting and interdependent subsystems of both physical and social infrastructure, and modelling such systems is not a straightforward task. A sociotechnical system such as the waste system can be described as a "system of systems." An essential feature of a system of systems in that it grows by composition. Sub-systems are integrated, combined, or just come together in ways in which the designers of the original systems may not have planned. (Abbott 2006) defines this term as follows*: 'A system of systems is best viewed not as a hierarchy built of component systems but as an environment within which other systems operate and which can support the addition of new systems that build on systems already in the environment.'*

When modelling a system of systems that includes physical, political, and social factors, so-called "soft variables" will be needed, which are those for which there are no available numerical metrics. (Sterman 2000) stresses that variables known to be important to the system should be included even when numerical data are not available because leaving them out would be even more inaccurate, and soft variables such as

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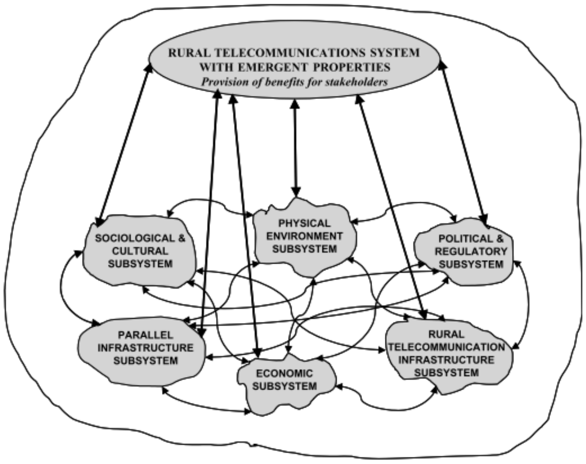
[1] Notes from discussions with Mike Yearworth at University of Bristol, October 2012

employee morale, investor optimism and political values can be quantified with tools such as content analysis, surveys and focus groups; in fact, the process of quantification of soft variables can yield important insights into the dynamics of a system.

Case Study: (Andrew & Petkov 2003)discuss the need for a systems thinking approach in the planning of a Rural Telecommunications System (RTS). They see the RTS as evolving from *'the interdependent relationships between the subsystems.'* Tensions between financial investment, socio-economic development, return on investment and, the impact of the physical environment on infrastructure all influence the conception of the RTS and the dynamics of the system. The authors' conceptualisation of the whole system is shown in Figure 5.

Figure 5: Systems Diagram of Rural Telecommunications System



Source: (Andrew & Petkov 2003)

Due to the complexity and heterogeneity of the system the authors proposed to use a multi-methodology approach, based on the work of (Mingers & Gill 1997), which combines more than one methodology, or techniques taken from different methodologies. Their approach mixes Interactive Planning (Ackoff 1993), Interpretive Structural Modelling/Interactive Management (Warfield & Cardenas 1994), and Critical Systems Heuristics(Ulrich & Reynolds 2010), within a critical systems thinking approach.

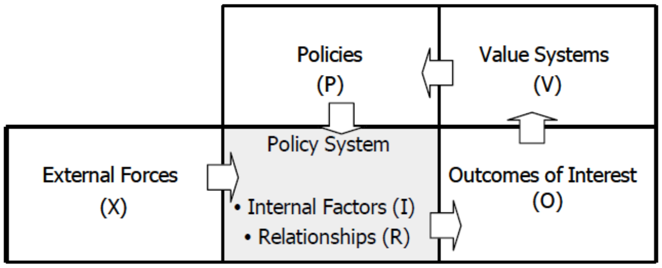
(Lane & Husemann 2008) see System Dynamics as a suitable tool for modelling social structures. They describe social structures as evolving through forms that include customs, laws, and the way that resources are allocated. These social structures are encountered by individuals in their daily lives and experienced as discouraging or encouraging certain acts. There is an ongoing feedback between individuals and social systems: *'Human agents interpret such influences in terms of attitudes, values and roles which become part of the mental models informing their behaviour. Such mental models are expressed as social actions which then create new structural effects, or replicate existing ones'.* (ibid) This ongoing feedback can be represented in a SD model by defining stocks of patterns of human behaviour that accumulate through social acts.

Case Study: (Agustinata 2008) specifies a system of systems model for policy making in the Dutch energy sector, an example of problem structuring for a universal system that includes the effects of policy. His approach includes consideration of several influencing factors on policymaking, along with their possible effects on system performance and the required societal conditions for their implementation. The paper presents a framework for understanding the system, termed XPIROV, which contains six elements:

- X = External forces: factors that are beyond the influence of policymakers (i.e., exogenous).
- P = Policies: instruments that are used by policymakers to influence the behaviour of the system to help achieve their objectives.
- I = Internal factors: factors inside the system (i.e., endogenous) that are influenced by external forces and policies.
- R = Relationships: the functional, behavioural, or causal linkages among the external forces, policies, and internal factors that produce the outcomes of interest.
- O = organizing the available information as well as for the process of elicitation and discovery of such information.
- V = Value system of policymakers and stakeholders, which reflects their goals, objectives, and preferences. The value system contains the criteria for indicating the desirability of the various policy outcomes based on the resulting outcomes of interest.

When applied to the Dutch energy sector, use of the framework produced a model of the sector as a system of systems (Figure 6). The model highlights interactions between actors within the vertical and horizontal hierarchies. At the national level, there is horizontal interaction between the policy system on both the supply side and the demand side. For example, the share of renewable influences the energy emissions factor. The model indicates the need for communication and coordination between decision makers working on the supply side and the demand side. The paper concludes that both vertical and horizontal interactions between subsystems combine to determine the behaviour of the whole system.

Figure 6: Policy Analysis with the XPIROV Structure



Source: (Agustinata 2008)

2.3.2 The Modelling Process

The way modelling is done in practice varies by practitioner, budget, and situation. Models can be initiated through a group model building session and then developed further and in more detail by individuals, initiated by individuals and then presented to groups of stakeholders for a reality check, or any combination of these in an iterative way. The low-level mechanics of the model are not usually suitable to present to stakeholders and so a simplified version will often be used for presentation purposes. Two modelling procedures are shown here as examples.

(Wolstenholme & Coyle 1983) developed a procedure for modelling, based on their experience of teaching methods of system description. The procedure is based on a taxonomy of modules, which is intended to provide two benefits:

[1] A fairly automatic procedure that leads directly from the observed symptoms of a real world system to a suitable degree of model complexity, and

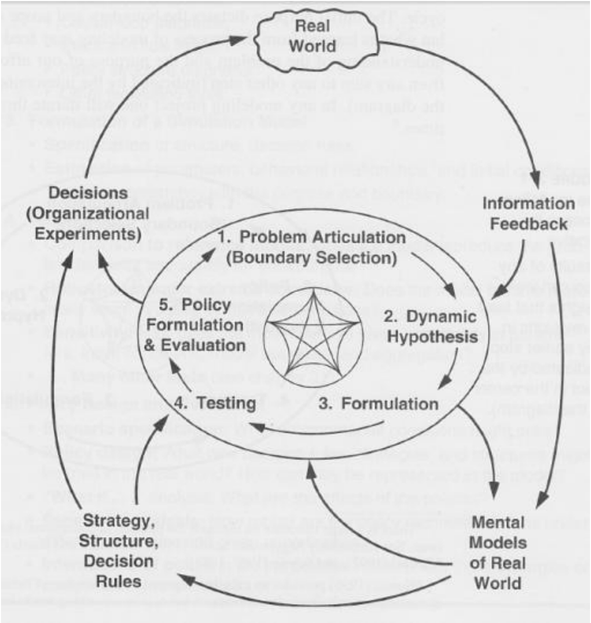
[2] An analysis framework that summarises all the perspectives on all the problem areas related to the problem being modelled and available ideas for improving the system behaviour.

The procedure has nine steps: (1) recognise the key variables giving rise to the observed symptoms of concern; (2) identify some of the initial system resources associated with the key variables; (3) identify some of the initial states (levels) of each resource to be used; (4) construct physical flow modules associated with each state of each resource, containing the physical processes or rates which affect these; (5) if more than one state of a resource is involved, cascade flow modules together to produce a chain of resource conversion or transfer; (6) identify the intra module behavioural information and control (policy) links by which the levels affect the rates; (7) identify similar behavioural, information and control links between modules of different resource types; (8) identify any new states of existing or new resources which affect the rates of the modules created, and add these to those recognised at stage 1 and 2; and (9) carry out a qualitative analysis of the model to identify: further key variables contributing to the symptoms of concern; specific relationships in the system that need further analysis; controllable variables; systemic impacts of changes to controllable variables; and the vulnerability of the system to changes in uncontrollable variables.

A more comprehensive and somewhat simpler process is presented in (Sterman 2000) and represented diagrammatically in Figure 7. The model creation is done through a basic five step process, shown in the inner circle (note: not shown here are the several sub steps involved in each of the five steps). This model building is embedded within single- and double-loop learning feedbacks.

Outputs from the modelling process revise the modellers' mental models and lead to revised action in the world. In turn, observed effects of this revised action lead to improvements in the formal and mental models in use. Sterman states that *'Modelling is not a one shot activity that reveals The Answer, but an ongoing process of the continual cycling between the virtual world of the model and the real world of action.' (ibid.)*

Figure 7: Sterman's Iterative Modelling Process



Source: (Sterman 2000)

2.3.3 Model Validation

Building models is not useful unless the results and insights can be applied to the real world, and this requires a minimum level of confidence in the structure, use of data, and dynamical behaviour of the model. There are many different formal methods for model validation:

- Direct model structure tests, such as dimensional consistency and parameter confirmation
- Structure-oriented behaviour tests, such as extreme condition tests and modified behaviour prediction
- Behaviour validity tests, such as behaviour pattern tests.

In addition to these more technical checks, an exposure of the model to stakeholders can serve as a check on its appropriateness for use in policy making. (Barlas 1996) discusses the lack of a single definition of model validity in the literature, partly because model validity cannot be judged without also considering the model's purpose. Barlas states that *'once validity is seen as "usefulness with respect to some purpose", then this naturally becomes part of a larger question, which involves the "usefulness of the purpose" itself.'* (ibid) This second question about the validity of the model purpose is a non-technical and qualitative process of judgment.

Case Study: (Wolstenholme et al. 2007) used SD to explore the issue of informal coping policies used at the local level within the NHS. The paper created a hypothesis on the reasons for the difference in the way health and social case organisations are observed to work when coping with high demand and the way these organisations are formally described to work. SD is used to both *'surface and explain these discrepancies in terms of informal structure and policy and to expose the unintended con sequences of such actions.'* The paper also provided sustainable solutions which would enable the organisations involved to return to working within best practice capacity utilisation levels and so avoid the excessive use of coping policies. The authors identified several implications for SD model validation and policy design:

- **Validation:** Data collection and structure validation in SD are often seen as independent activities, but these activities are intertwined; it is fundamental to know what policies were in place during a given period of data collection for the data to have any meaning. If there are informal policies in place they must be incorporated into the model together with the data that reflect them and the consequences they cause.

- **Policy Testing and Design:** The method used to reveal hidden coping policies, was to run a model with them on and then to switch them off, which allowed the true behaviour of the system resulting from working beyond capacity to be unmasked. To identify deviation from best practice, data were required for the policy design stage. The best levers for change in a system are often well removed from the location of the problem symptoms, and in this case the best levers were found to be in social services. Interestingly, these levers are often in the least powerful agency in the value or supply chain and it is often difficult for more powerful players to accept this fact.

2.4 Systems Thinking to Support Government Policy Making

In government policy making, which is most often concerned with intervening with an existing system – be it political, social, financial or physical – systems thinking provides a range of methodologies to deal with the complexities in that system. (Rosenhead 1992) identifies the need for such an approach, saying that *‘the absence of a methodology capable of providing analytic contributions consistent with the complex, interactive process of public policy formation has been a significant deprivation’* and identifying two principle types of complexity in public policy decision making:

[1] The need to handle a large number of factors simultaneously, and

[2] The fact that ‘*decisions on even apparently isolated issues can have repercussions for the programmes and policies of other departments.’* ((Nelson 1974) from (Rosenhead 1992))

2.4.1 Wickedness and Complex Adaptive Systems

Two terms have been used in the literature to describe the public systems that government policy-makers work with – *wicked* and *complex adaptive*. Systems thinking methodologies provide tools and methods for working with these types of problems in a way that recognises these characteristics, although of course they do not provide instant or complete solutions. These terms are described below.

(Rittel & Webber 1973) have described the difficulties involved in public planning and dealing with societal issues as “wicked” problems. They identified ten distinguishing characteristics of a wicked problem:

1) There is no definitive formulation of a wicked problem. The information needed to understand the problem depends upon one's idea for solving it.
2) Wicked problems have no stopping rule. There are no criteria for sufficient understanding and there are no ends to the causal chains that link interacting open systems.
3) Solutions to wicked problems are not true-or-false, but good-or-bad. Many parties are equally equipped, interested, and/or entitled to judge the solutions, although none has the power to set formal decision rules to determine correctness.
4) There is no immediate and no ultimate test of a solution to a wicked problem. Any solution, after being implemented, will generate waves of consequences over an extended--virtually an unbounded-- period of time.
5) Every solution to a wicked problem is a "one-shot operation"; because there is no opportunity to learn by trial-and-error, every attempt counts significantly.
6) Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan.
7) Every wicked problem is essentially unique. Despite long lists of similarities between a current problem and a previous one, there always might be an additional distinguishing property that is of overriding importance.
8) Every wicked problem can be considered to be a symptom of another problem. The level at which a problem is settled cannot be decided on logical grounds.
9) The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution.

10) The planner has no right to be wrong. Planners are liable for the consequences of the actions they generate; the effects can matter a great deal to those people that are touched by those actions.

The term "complex adaptive system" is used by several authors to describe the sociotechnical systems that policy makers deal with. Levin states that although there are many authors who discuss systems such as the biosphere, economies, or brains as complex adaptive systems *'it is much harder to find a formal definition, as if investigators fear that by defining a complex adaptive system (CAS), they will somehow limit a concept that is meant to apply to everything.'* (Levin 1998)

(Miller & Page 2010) describe complex adaptive social systems as *'composed of interacting, thoughtful (but perhaps not brilliant) agents.'* One example of a CAS they give is the stock market, which exemplifies *'the space between anarchy and control'*. They state that it is possible for a political institution to introduce "noise" into a CAS so that it promotes the emergence of beneficial global organisation. (Arthur et al. 1997) identified six characteristics of a CAS in relation to the economy: there are many probably heterogeneous agents interacting only with some of the others possibly over space; there is no global controller or competitor who can exploit all opportunities in the economy or the interactions in the system; there is cross-cutting hierarchical organization with many tangled interactions; there is perpetual novelty as new markets, technologies, behaviours, and institutions create new niches in the system; learning and evolving agents continually adapt; and there exist out-of-equilibrium dynamics, with the possibly of there being no equilibrium at all. (taken from (Oxley & George 2007))

Case Study: (Kreuter et al. 2004) used the concept of wicked problems to investigate the promotion of environmental health. They state that when the inherent complexities in a wicked problem are acknowledged there is more likelihood that the multiple factors and forces making up the problem will be analysed, and that stakeholders will be included in the problem-solving process. This can lead to the wicked problem being broken into more manageable components, which can then be treated with the more usual problem-solving methods designed for "tame" problems. The authors agree with (Conklin 2002) that *'wicked problems are best resolved through a planned process with input from multiple sources in an atmosphere where scientific certainty is tempered by the perspectives of community stakeholders.'* (Kreuter et al. 2004) They conclude that a solution that addresses one aspect of a problem can end up leading to new problems being created, and so public health practitioners should pursue a trans-disciplinary approach to their decision making and continue with stakeholder engagement throughout the decision-making process.

2.4.2 Policy Resistance

The phenomenon of "policy resistance" is described in (Sterman 2002) as the unexpected effects of policy interventions. He describes the unanticipated "side effects" of well-intentioned interventions aimed at solving pressing problems: *'Our decisions provoke reactions we did not foresee. Today's solutions become tomorrow's problems. The result is policy resistance, the tendency for interventions to be defeated by the response of the system to the intervention itself.'* (ibid) Sterman sites examples of this in California's failed electricity reforms, road building programs that lead to increased traffic congestion, and the evolution of antibiotic-resistant pathogens, saying that it occurs partly due to the way we think: *'At the root of this phenomenon lies the narrow, event-oriented, reductionist worldview most people live by... There are no side effects—only effects. Those we thought of in advance, the ones we like, we call the main, or intended, effects, and take credit for them. The ones we didn't anticipate, the ones that came around and bit us in the rear.'* (ibid.) . He states that System Dynamics can enable us to adjust the boundaries of our mental models, so that the feedbacks created by our own decisions can come into our awareness and thus be taken responsibility for.

2.4.3 Evidence Based Policy Making Versus Reflective Practice

In (Parsons 2002) new labour's Evidence Based Policy Making (EBPM) is compared with Schön's reflective practice and systems thinking. The EBPM of that time envisioned public policy being driven by evidence; the EBPM philosophy rebutted Schön's view that the policy process is *'a swampy lowland where solutions are confusing messes'* (Schön 1991) and held the belief that there exists some firm ground upon which can be laid "hard facts" to support modernised policy-making. But because problems are constantly changing and mutating, to Schön the deficit is less to do with information than our capacity for public and private learning. His view is that government and policy-making need to be understood as processes of learning and institutions must be "learning systems", capable of bringing about their own continuing transformation; improving policy-making involves an appreciation of government as a *complex adaptive system*, rather than as a mechanistic and linear process concerned with better techniques of command and control. Schön's approach sees evidence-informed policy making as a process whereby knowledge is transacted and exchanged, rather than pooled and then utilised by policy professionals at the centre.

(Chapman 2004) has practical experience of introducing soft systems methodology into management of the health sector. He states that when entities are managed as if they are linear, mechanical systems but display the characteristics of complex adaptive systems, failures can occur – such as the frequency of unintended consequences increasing, delivery targets not being met, and agents within the system experiencing interference with their daily activities. Regarding the adoption of a systems approach he states that it requires *'a radical reappraisal of what can be achieved by a system, as well as the means whereby it might be achieved'* (ibid) and the prioritisation of the process of improvement rather than a specific goal or target; this requires an increased tolerance of failure, continuous feedback on effectiveness, and a willingness to foster diversity and innovation. Chapman outlines several possible strategies to achieve this in a national system:

- Local agencies can demonstrate improvement on their own terms, rather than there being uniformity in targets.
- Improvement can be increased through diversity and communicating results across different regions.
- Units can earn autonomy by demonstrating certain standards of performance, enabling policy-makers to stay within their own tolerances of risk-taking and facilitating a manageable level of experimentation.

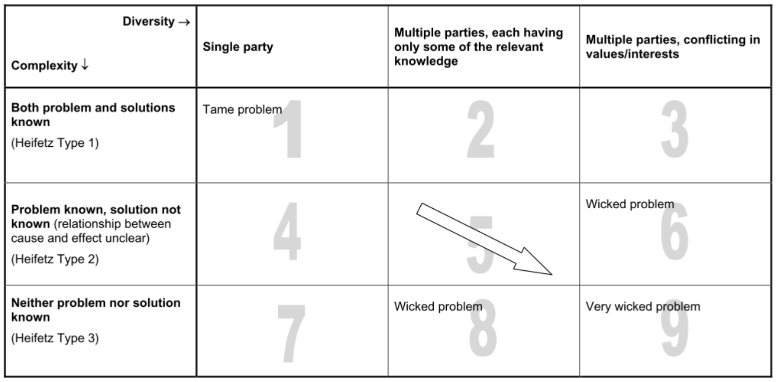
2.4.4 Introducing Interventions in Multi Agency Systems

(Abbott 2006), in his discussion of large systems of systems, outlines concerns for government in designing or intervening in such systems. He cites the example of introducing a new standard for communication, stating that in the case where government systems consist of elements that are all owned and operated by the government, for the government itself to make the change an enormous amount of coordination and expense would be required; in contrast, if participating systems are owned and operated by independent entities that desire continued participation in the overall environment, the owners of these entities will adopt the new standards because it is in their interest to do so. He concludes that *'when the government develops a system of systems environment, it is important to ensure that the participating systems are owned and operated by entities that have enough of a stake in their participation that they will adapt as the environment evolves.'* (ibid)

2.4.5 Dealing with the Wickedness of Public Policy Making

(Head & Alford 2008) discuss the implication of wickedness for public policy making. They describe wicked problems as being linked to *'social pluralism (multiple stakeholder interests and values), institutional complexity, and scientific uncertainty (fragmentation and gaps in knowledge)'* and they state that the uncertainty generated by wicked problems is what makes them *'apparently intractable'*. Their typology of problems, developed along the two axes of diversity and complexity, is shown in Figure 8. Wickedness increases as there is uncertainty about either the problem or its solution or both, and the diversity of parties involved and the amount of existing conflict between them increases.

Figure 8: Typology of Problems in Terms of Wickedness (Head and Alford)



Diversity → **Complexity ↓**	**Single party**	**Multiple parties, each having only some of the relevant knowledge**	**Multiple parties, conflicting in values/interests**
Both problem and solutions known (Heifetz Type 1)	Tame problem 1	2	3
Problem known, solution not known (relationship between cause and effect unclear) (Heifetz Type 2)	4	5	Wicked problem 6
Neither problem nor solution known (Heifetz Type 3)	7	Wicked problem 8	Very wicked problem 9

Source: (Head & Alford 2008)

Of particular relevance when discussing waste management is the authors' discussion of the introduction of "contractualism" within public services, which has three principle effects:

[1] Shifting the focus from outcomes to outputs, even though prescribing how a particular outcome should be achieved through specifying outputs prevents the creation and discovery of other means of achieving outcomes

[2] Introducing competition between providers, and thus reducing cooperation and increasing withholding of knowledge between those with specialist knowledge, and

[3] Introducing a policy/delivery split which fragments knowledge and increases the separation between those parties involved in finding solutions to a problem.

(Head & Alford 2008) agree with the importance of using collaboration as a process solution but say that it alone is not enough as it doesn't address the complexity dimension of wickedness. They propose two additional approaches: systems thinking and adaptive leadership. They describe systems thinking as an approach that considers the whole chain that leads to outcomes: the "web" of inputs, processes and outputs. This is a helpful analysis when dealing with a complex problem – not as a method to solve the problem but as an analytical discipline which can support actions in collaboration and leadership.

A particular systems approach discussed by the authors is backward mapping (originally from (Elmore 1980)). The process starts with identifying a problem in *'tentative terms'* to serve as a starting point, then working backwards to compose a diagram of those factors most likely to be causing the problem, going further to find factors that seem to cause the first set of factors, and so on backwards towards what can be considered *'initial factors'*. This complex analytical task requires judgement and iteration, but they describe it as *'an invaluable discipline'*. Further analysis includes looking for *'tensions and contradictions among factors* '– points at which factors that cause one aspect of the problem are at odds with factors causing others. The authors state that in terms of finding the source of wickedness, these points are the most likely culprits.

Case study: The Munro Review of Child Protection (Munro 2011)is a high profile example of systems analysis being used for policy evaluation. The independent review was commissioned by the Department for Education to help reform the child protection system by first trying to understand why previous well-intentioned reforms did not yield the expected results, enabling these insights to be used in the design of a new approach to child protection. The systems analysis done in the study (Munro 2010) makes use of causal loop diagrams to represent and communicate the causal mechanisms in operation, in particular feedback loops responsible for the current system's focus on single loop learning.

The review uses several systems ideas and illustrates these as CLDs as they apply to child protection:

- Single and double loop learning, derived from the Organizational Development field, specifically the work of (Schön & Argyris 1978)
- Ripple Effects (unintended consequences and feedback loops), derived from the System Dynamics field, specifically the work of (Forrester 1961)
- Requisite Variety, derived from the field of Cybernetics, specifically the work of (Ashby 1957)
- Technocratic vs. socio-technical systems – technocratic systems assume that a given analytical approach is clear, with consensus about aims and that implementation of recommendations will be via hierarchical chains of command; in contrast, socio-technical systems assume individuals and how they work together are part of the problem.

3.0 The System Dynamics Methodology

The System Dynamics (SD) methodology was first developed by Forrester, who defined the four foundations of the methodology in 1961 in his book Industrial Dynamics as:

1. *'The theory of information feedback systems;*
2. *A knowledge of decision-making processes;*
3. *The experimental model approach to complex systems; and*
4. *The digital computer as a means to simulate realistic mathematical models*.' ((Forrester 1961) from (Richardson 2011)).

A more concise characterisation is provided by (Richardson 2011): *'System dynamics is the use of informal maps and formal models with computer simulation to uncover and understand endogenous sources of system behavior'.* He stresses that analyses which fail to uncover the endogenous sources of system behaviour are not really SD applications; such analyses are missing a defining aspect of the SD approach and are prone to *'miss crucial ramifying effects and intricate compensating mechanisms'*. Thus, SD practitioners can be said to use systems thinking, management insights, and computer simulation to '*hypothesize, test, and refine endogenous explanations of system change, and use those explanations to guide policy and decision making'. (ibid.)*

According to (Sterman 2000) all dynamics within a system arise from the interaction of just two types of feedback loops – positive loops reinforce or amplify whatever is happening in the system, and negative, or balancing loops, counteract and oppose change. When many of these loops interact between the agents in a system, dynamic complexity occurs. All natural and human made systems have high levels of dynamic complexity, and it arises because systems are:

- dynamic – changing over time
- tightly coupled – actors interact strongly with one another and with the environment
- nonlinear – effect is often not proportional to cause and what happens locally may not apply in other parts of the system
- history-dependent – taking one road can preclude taking another and determine where you end up
- self-organising – the dynamics of systems arise spontaneously from their internal structure
- adaptive – capabilities and decision rules of agents in complex system change over time
- counterintuitive – cause and effect can be distant in time and space, while we tend to look for causes near the events we seek to explain
- policy resistant – the complexity of systems overwhelms our ability to understand them, meaning many seemingly obvious solutions fail or may even worsen the situation
- characterised by trade-offs – time delays within feedback loops mean the long-run response of a system can be different to its short-run response (adapted from (Sterman 2000))

Crucial to SD is the understanding of structure and its relation to system behaviour. Forrester states that: *'Only if the modelling framework coincides with that of the real system can there be a natural flow of real-world information into the model... I believe that the level-rate-feedback structure in system dynamics is indeed the fundamental and universal structure of real social and physical systems'.* (Forrester 1994) Sterman says that the behaviour of a system arises from its structure – the structure consisting of feedback loops, stocks and flows, and nonlinearities created by the interaction of the physical and institutional structure with the decision-making processes of agents acting within it.

There are several typical patterns of dynamical behaviour that are commonly found within real world systems, and these have been classified as different types of system archetypes. They can be useful in diagnosing the documented behaviour of a real world system and they are effective tools when we are seeking to understand why certain problems are seen to occur over and over again. (Braun 2002) has outlined the characteristics of ten of these archetypes, describing for each its structure, dynamic theory, behaviour over time, prescriptive action, the meaning of the archetype, and action steps that can be taken to take to deal with the problem.

Essential in the practice of SD is the use of simulation modelling. Sterman says that although mapping participants' mental models is necessary through problem structuring methods such as causal loop diagramming, the temporal and spatial boundaries of our mental models are dynamically deficient, omitting feedbacks, time delays, accumulations, and nonlinearities; parameters and functional forms are needed to fully specify and test a model. According to Sterman, computer simulation is the only practical way to test a conceptual model, and without simulation even the best model can only be tested and improved by learning through the real world – a slow and ineffective process.

(Richardson 2011) explores the question of agency of individuals within systems by asking: '*Who are the actors in the dynamics of a complex system and how do their perceptions, pressures and policies interact? Are we parts of the problem, or parts of the solution, or merely bystanders watching difficult dynamics play out over time?'* He describes the range of opinions, with some believing that we are endogenous actors in the grand issues we face while others taking a more fatalistic, exogenous point of view. Lane, in discussing whether SD is a deterministic approach, says that the position of SD on the how much structure influences the behaviour of agents is not behaviouralist but instead partial, involving '*a feedback model of the relationship between agency and structure*'. (Lane 2000) Thus, SD takes neither the view that actors are mere victims of the system nor a view that actors have pure free will. In either case, only a model that shows endogeneity of the problem of interest can be useful in explaining behaviour and such a model will always include both structure and agent decision-making and the dynamical behaviour between them.

3.1 System Dynamics and Public Policy

(Wheat 2010) discusses what SD can learn from the literature on public policy implementation. He describes the process of SD modelling for policy as having two high-level stages:

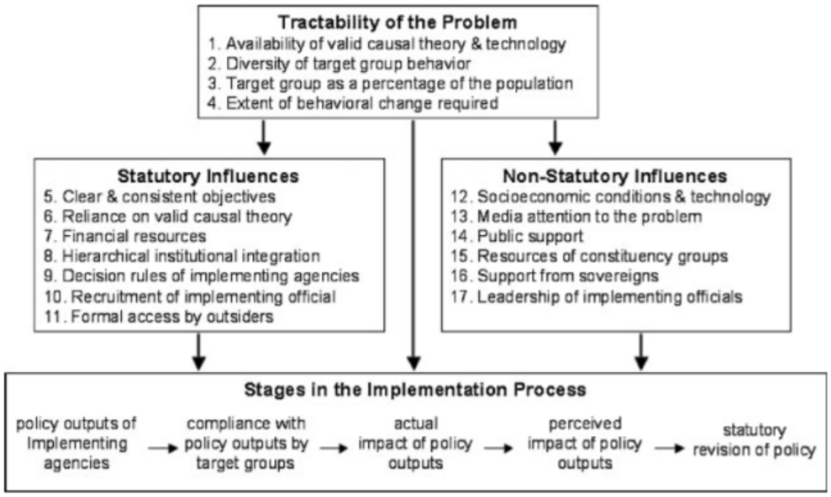
[1] Problem explanation: explaining the reasons for the problematic dynamic behaviour of the system by building an explanatory model

[2] Policy design: designing and testing policies that could improve the dynamic performance of the system by building a policy structure and integrating it with the base model. The policy design structure is a stock and flow feedback structure; it contains decision rules that define when a new policy comes into play, how it works, and what changes are made to it over time that will improve the performance of the whole system.

One danger with this method is if the assumptions made when developing the model's new decision rules are too naive then the model simulation results will provide an unrealistic picture of the efficacy of the policy.

With regards to the practice of this method, Wheat states that if systemic behaviour is to be improved then systemic structure must be improved, and this cannot be achieved through only testing parameter changes in a model. This can be seen, for example, in the amount of time spent discussing incremental rises or falls in social benefits or taxes during elections; people feel that these are going to make a big difference but in fact they have much less impact than a change in structure. However, this type of policy structure design is not easy. It can be made easier by using findings from the literature on public policy that indicate which are the most important feasibility questions to ask.

Figure 9: Implementation Framework for Public Policy

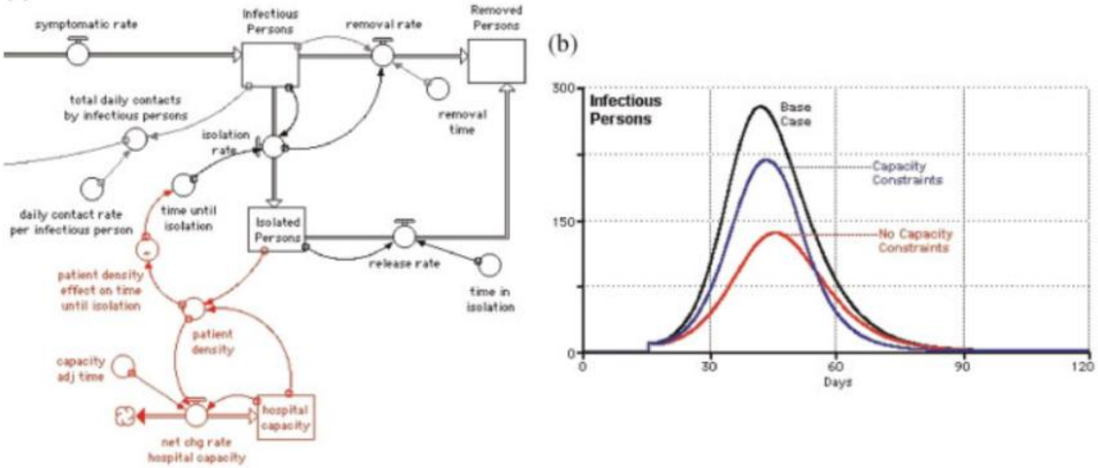


Source: (Wheat 2010), adapted from (Mazmanian & Sabatier 1981)

One such source is the implementation framework (shown in Figure 9) developed by (Mazmanian & Sabatier 1981), which has been used to assess implementation of policies for environmental protection, education reform, urban renewal, and social welfare programs around the world. Although not part of the SD methodology, Wheat recommends use of the framework, which can be transformed into a checklist of important questions, or flags, that are useful when attempting to represent impediments to policy implementation in a policy-design structure.

Case Study: (Wheat 2010) uses Sterman's model of a human epidemic (Sterman 2000) as a base case model, and then applies a policy structure for an isolation policy (relocating infectious persons to a hospital and limiting their ability to have contact with susceptible persons while infectious). When the model is run with several cases for speed of relocation, as anticipated the quicker the relocation occurs, the greater the policy impact. Use of the implementation framework reveals implicit assumptions – for example, that infectious persons would actually go to the hospital soon after symptoms appeared, that health workers would know how to identify infectious persons, etc. Considering the possibility of inadequate hospital capacity, a constrained version of the model was run which produced reduced but possibly more realistic policy impacts. A simplified version of the model, with policy structure shown in red and the base model shown in black, is shown in Figure 10, along with the results from the base, capacity constrained and unconstrained response cases.

Figure 10: Constrained Isolation Policy and Simulation Behaviour (from Wheat)



Source: (Wheat 2010)

Case Study: (Cavana & Clifford 2006) documented learning from a SD study to analyse the relationship of New Zealand Customs Service (NZCS) outputs to desired government outcomes, in relation to the collection of tobacco excise duties and cigarette smoking in New Zealand. The analytic objective was to develop a "toolbox" of analytical tools and techniques to evaluate the impact of policies within the complex environment of border control. Policy analysts involved in the project found it to be *'useful and exacting'* (ibid) and expressed that they felt its best application would be in situations that are well-defined and well controlled, and also on large problems. Reasons for these caveats were the data demands and skills required for working through the logical impacts of the assumptions when model building; there was frequent redefining of requirements for and assumptions about data. Participants found it easier to deal with the system as a whole, the big picture of how price influences the use of tobacco, than to address specific research questions defined in the research plan. Policy analysts found the method of causal loop diagramming useful for drawing out affected and influencing factors and groups, and the method of variables pairing useful for identifying potential outcome indicators. The use of stock and flow diagrams without having to produce data to populate the model was useful in creating a bridge in thinking between the modellers and policy makers. The study provided several useful insights to the policy team and they felt it could be developed into a comprehensive policy tool.

4.0 SD Modelling for Understanding Waste Management

This section summarises eight case studies in the use of SD to understand and create policy for the waste system. Most of these papers include at least some aspects of both the upstream (waste generation) side and the downstream (management of waste streams) side; however, some are more focused on the downstream such as domestic recycling. The papers are concerned with one or more of forecasting, planning, and explanation. Comments on the applicability to the UK waste system introduce each summary.

4.1 Using SD to Inform Policy Making for Solid Waste Management at the Local Level

Purpose	Policy development
Scope	Downstream, domestic recycling
Time focus	Modelling of existing system and policy evaluation
Tools and methods	Stock and flow models, testing of financial levers, framework for human behaviour and public policy
Applicability to the UK waste system	Modelling of the system's dynamics and evaluation of policy levers relevant, actual policies tested not relevant because UK waste is not paid for by individuals directly.

Two papers by Ulli-Beer and colleagues outline the creation and use of a SD model to evaluate policy to encourage household recycling. The first paper details the building of a model that backcasts to reveal reasons for the under-performance of current policy in raising levels of recycling, and the second paper looks at the effects of different pricing systems for encouraging household recycling through financial levers.

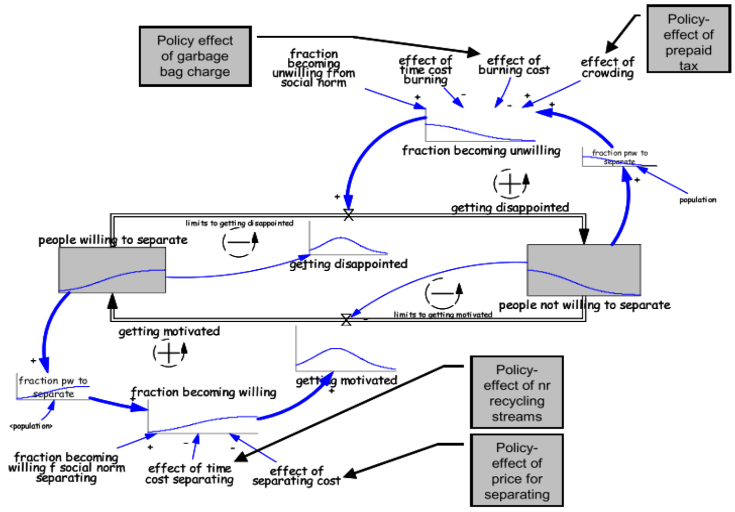
In the first paper (Ulli-beer et al. 2004) the overarching questions the team set out to answer with the SD modelling were: (i) *'How do you motivate the households to participate in solid waste separation?,* (ii) *How do you recover recyclable material in order to produce competitive secondary raw material?,* and (iii) *How do you finance the recovering and disposal activities of local agents?'* (ibid) Several interventions had already been tried to improve recycling behaviour with varying results: The low levels of waste separation by residents led local authorities to introduce a garbage bag charge for non-recyclables; this led to an increase in waste being separated for recycling and less waste being sent for disposal; however, the revenue from the sale of trash bags went down, causing a budget deficit; the garbage bag charge was then increased but this did not improve separation behaviour since the number of recycling streams was the same; eventually, because citizens couldn't avoid the higher disposal costs, they began to put non-recyclable materials into the recycling streams and the quality of that material decreased.

The model's structure is similar to a standard diffusion model such as the Bass model, and has two main feedback loops, as shown in Figure 11. Growth or decline in recycling is limited by first order control loop structures which control factors such as the number of <people not willing to separate> and <people willing to separate>. The second order model includes a tipping point, so that if the diffusion process does not take off a policy initiative is likely to die. The model was calibrated to match historical data on recycling and waste, and four policy experiments were introduced into the model. Analysing the scenario results provided insights into the causes of the current problems, including:

- **Recurrent deficit:** The economic theory underlying a garbage bag policy is the "polluter pays principle" but in reality the price cannot be raised continuously. The price has to settle and then be adjusted depending on changing external conditions such as unit costs or the fraction of material that is recyclable. Delays in the price adjustment process result in a deficit for the authorities, which is a consequence of the structure of the system and not one of mismanagement of solid waste at the local level.
- **Contamination:** The observed dynamics in contamination are a consequence of an initial policy resistance and adjustments delay in personal factors such as <acceptable time for separating> and <acceptable unit cost for burning>. This results in a "first-worse-before-better" dynamic pattern; however, this problem could be largely solved if the whole population would be willing to separate.

The authors find that while local public policies should be able to compensate for unsupportive exogenous market conditions, they should also be designed to improve poor conditions within the local, endogenous system factors that are to do with resident behaviours, such as acceptable separating time. The observed unintended effects of the garbage bag charge used as an economic instrument indicate that a more robust policy should intervene in both the "getting motivated" and the "getting disappointed" loops and ensure good recycling behaviour is encouraged.

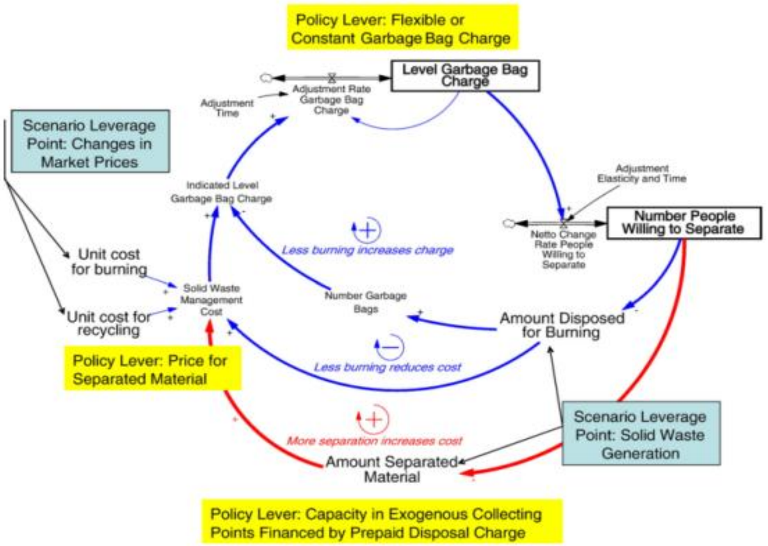
Figure 11: SD Model of Recycling Behaviour in Switzerland



Source: (Ulli-beer et al. 2004)

In the second paper, (Ulli-Beer et al. 2007), the effects of different economic measures on the recycling behaviour of citizens and budget goals were analyzed in a policy laboratory model. An SD model was developed based on a framework for human behaviour and public policy with an evolutionary feedback perspective. The model structure included main driving forces and time delays as well as the realistic satisfying decision rule.

Figure 12: Policy and Scenario Leverage Points Influencing Main Loops



Source: (Ulli-Beer et al. 2007)

The model framework that was used *'emphasizes that human action is a result of the constant interplay between the internal structure of the actor and the structure of the actor's action context, where processes of perception and action mediate between the two structures.'* (ibid) Interventions can be designed to alter either the external structure (e.g. through "command and control" or "service and infrastructure" instruments) or the internal structure (e.g. through "collaborative agreements" and "communication and diffusion" instruments). Within the framework, waste separation behaviour and solid waste management was conceptualized as an evolving system with feedback. Interactions, dynamics and processes explaining the observed phenomena were analyzed during the SD model building, leading to a differential equation model that could explain empirical data from solid waste management in Switzerland. The feedback loops in the model are shown in Figure 12.

The study found that analysis of several policy scenarios revealed what crucial trade offs needed to be made between budget goals at a local level and the achievement of a successful recycling initiative. Additionally, the study found that economic policy instruments are not enough to yield a reliable policy outcome under worst-case conditions.

4.2 Modelling of Electrical Energy Recovery from Urban Solid Waste System: The case of Dhaka City

Purpose	Potential study for policy makers
Process focus	Downstream, solid waste incineration for electricity generation
Time focus	Forward planning (30 years)
Tools and methods	Stock and flow model, population projections
Applicability to the UK waste system	Good example of high level model of the waste system over a long time period.

(Sufian & Bala 2006) present a SD model that predicts population growth and the resulting growth in solid waste generation, and potential for electricity generation from the solid waste for the city of Dhaka, Bangladesh. The results of the base case simulation of solid waste generation compared well with data from the Dhaka City Corporation. The simulation showed that population, solid waste generation and electricity generation potential all increase with time over a 30 year period. The authors state that *'electrical energy recovery from urban solid waste has to address several interdependent issues such as public health, electricity generation potential and present and future costs to society. The electrical energy recovery from urban solid waste system is a complex, dynamic and multi-faceted problem depending not only on available technology but also on economic and social factors.'* The modelling was done because they saw experimental implementation in an existing, complex, real world system – containing economic, social, technological, environmental and political elements – as being costly and time consuming, or even totally unrealistic. The model included simple feedback loops, such as the one that models waste generation increasing with the increase in population, GDP, and per capita income.

The results show a fairly linear relationship between electricity generation capacity and population. Financial data such as the cost of purchasing and running incinerators does not appear to be included in the model, nor changes in incineration technologies in the next 30 years which could affect how much they can generate. The model diagram is shown in Appendix A.

4.3 Zero Waste by 2030: A SD Simulation Tool for Stakeholder Involvement in Los Angeles' Solid Waste Planning Initiative

Purpose	Evaluation of strategic choices to get to zero waste goal by 2030 for the City of Los Angeles
Process focus	Both upstream and downstream, relationships between these
Time focus	Forecasting (20 years)
Tools and methods	Framework, SD model, user interface
Applicability to the UK waste system	Comprehensive model of waste generation and disposal, same goal as the UK, municipality level but universal issues examined, SD model not shown but conceptual framework well presented

(Stave & Ph 2008) built a SD model and user interface to support the City of Los Angeles' desire for *'a model that would demonstrate the benefits and drawbacks of strategic choices over a 20-year period, help stakeholders understand uncertainty in the system, and illustrate the effect of taking no action.'* The ultimate goal of the City's strategic planning process is to reduce waste sent to landfills to zero; cost, environmental effect, and social and political acceptability are also key performance indicators. The model includes both "upstream" sectors (product manufacturing and consumer consumption) as well as "downstream" sectors (consumer disposal, collection of discarded material, processing, and disposal). The basic "recycling loop" incorporates five interconnected sectors: consumption, collection, processing, disposal, and production. The model structure is shown in Appendix B.

Figure 13: User Interface of the Zero Waste Model

UPSTREAM (Product Characteristics)

1. change in product lifetime (1=same, 3=3X) 1 [1] 3
2. waste in products and packaging (%) 30 [70] 90
3. recycled content in products (%) 0 [1] 100
4. product recyclability (%) 0 [80] 100

DOWNSTREAM (Consumer Behavior and Processing Capacity)

5. change in consumption (.5=half, 1=same) 0.5 [1] 1
6. consumer diversion rate (%) 0 [60] 100
7. processing capacity (tons/day) 22,0 [22,000] ,000

RESIDUAL

8. alternative disposal capacity (tons/day) 100 [100] ,500

Source: (Stave & Ph 2008)

The team built a user interface, shown in Figure 13, that presents eight strategic decision levers to be used – *'product durability, waste in products and packaging, recycled content of products, product recyclability, consumption, consumer diversion rates, diversion processing capacity, alternative disposal capacity'* – and six measures of output – *'waste sent to landfill, material diverted, diversion rate, relative greenhouse gas emissions, relative cost, and relative effort'.* The case in which the status quo is maintained leads to erosion of diversion rates. The greatest improvement is gained by reducing consumption, increasing product durability, and increasing recycled content of products.

The study concludes that:

1) It won't be possible for the City to achieve zero waste without some kind of intervention, and a strategy of no action would in fact lead to a reduction in the current landfill diversion rate.
2) Several scenarios could lead to zero waste but significant costs and tradeoffs in environmental impact and political/social effort would be required.
3) The largest cause of greenhouse gas emissions in this system is from use of virgin materials in the production of goods, so even small changes in parameters such as product durability, the recycled content of products, and consumption would have marked effects on GHG emissions.
4)

4.4 A SD Study of Solid Waste Recovery Policies in Phnom Penh City

Purpose	Effects of composting and informal recycling on diversion from landfill
Process focus	Downstream
Time focus	Present
Tools and methods	Stock and flow diagrams
Applicability to the UK waste system	Could be applied to council-run composting schemes that pick up from households, some aspects of informal recycling may exist in the UK

(Kum et al. 2005) created a SD model to try to answer the question of how much composting and informal recycling contribute to waste diversion in Phnom Penh, and to create a platform for discussion and learning.

The city has been running a low-technology pilot project for compost-making from domestic compostable waste, with the compost sold on to farmers. Although the quality of compost produced through the pilot project is quite high the market for the compost has remained small and is not stable, and because of this the local waste authority has been paying less and less attention to compost making from waste. Regarding recovery and recycling activities in the city, these are currently conducted in an informal ('*unregistered, unregulated, or casual'*) manner, primarily by waste scavengers in streets and on the dumpsite.

The model structure is that waste to landfill can be controlled in two ways: by the in-flow rate (collection) and the outflow rate (compost production and informal recycling). The compost production rate is assumed to depend on the demand for compost, which depends on the price buyers will pay and the quality of the compost (assumed high enough to be acceptable to the public). The model diagram is shown in Appendix C.

The simulation results, based on data collected in Phnom Penh city, indicate that without supporting policies, waste recovery through small-scale composting and informal recycling will not be able to contribute significantly to higher levels of waste diversion. The study concludes with the following recommendations:

- The waste authority should reconsider the present management system for compost making;
- The compost sale price should be lowered to promote composting;
- Compost making in the city may not be possible without subsidies from the Municipality and the Municipality should recognize the importance of the sector in overall waste management.
-

4.5 Model Conceptualization for Sustainable Waste and Resource Management Policy Design in Low and Middle-Income Countries

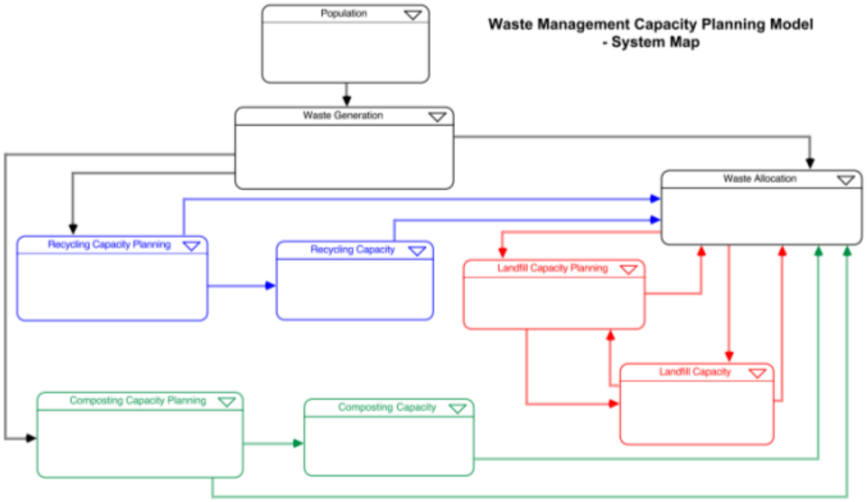
Purpose	Model concept to be used for planning a waste system in developing countries
Process focus	Population-driven waste generation, and downstream waste management
Time focus	Planning
Tools and methods	Stock and flow diagrams, not parameterised
Applicability to the UK waste system	Structure of model concept could be useful input to developing a large model for the UK; identification of various functions of the waste system interesting

(Escalante 2012) developed a high-level conceptual model of a waste system for planning purposes. The study was done as part of a research project to improve resource recovery from waste streams in large cities in developing countries; the project was first implemented in the Ethiopian capital, Addis Ababa. Modelling and simulation were chosen as tools to test potential effects of new decentralised waste treatment plants. Escalente first defines five primary functions that can be provided by a waste system: public health protection, value recovery, pollution control, resource conservation, and climate protection. These functions continuously interact with each other –e.g. capturing landfill gas contributes to climate protection; the treatment of leachate improves sanitation and public health conditions; commodity scarcity leads to the recovery of value from waste materials, strengthening resource conservation; increases in GHG emissions eventually lead to enhancements in climate protection strategies, influencing pollution control and resource conservation.

The paper presents the structure of a conceptual model, shown in Figure 14, intended to be a basis for discussions with stakeholders and decision makers. Within the model there are the basic physical infrastructure components of a planned waste system – waste generation, final disposal, and resource recovery. Population is the main driver of the system, determining the amounts of waste generated. Each sector, or module, in the planning model is a SD sub-model. The paper concludes that the model provides insights into the qualitative improvements that could be gained through the explored strategies.

Not considered were the financial, land, and human resources that would need to be allocated to enable capacity expansion and upkeep, because the decision rules that govern this type of expansion need to be *'elicited together with the people that make these decisions'*. The model is intended as a concept model for a class of systems to enable a model-based strategic planning process.

Figure 14: Waste Management Capacity Planning Model



Source: (Escalante 2012)

4.6 A Simulation Model Using SD for Construction and Demolition Waste Management in Hong Kong

Purpose	Better management of construction and demolition waste in Hong Kong
Process focus	Waste generation, sorting, mixing with MSW, public filling, landfill
Time focus	Retrospective, revealing current situation
Tools and methods	SD model, scenario testing
Applicability to the UK waste system	Specific modelling and understanding of waste from the building sector and its particular characteristics.

(Hao et al. 2007) developed a SD model to plan for better management of construction and demolition (C&D) waste in Hong Kong, which currently makes up over forty percent of solid waste and has become a serious environmental problem. C&D waste can be defined as *'the surplus materials arising from any land excavation or formation, civil or building construction, roadwork, building renovation or demolition activities.'* (ibid) The authors saw a need for an integrated model that could be used to simulate the highly complex and dynamic C&D waste management marketplace. They stress the importance of integrating C&D waste management into the management of construction projects so that the lifecycle environmental impact of buildings can be minimised. The overall system is divided into five components or sub-systems as follows: on-site sorting; C&D waste generation; municipal solid waste (MSW) generation; public filling; and landfill. The model includes around sixty variables, and historical data on MSW and C&D waste generation from 1986 to 2020. C&D waste increases by about six percent a year in the model, with four factors affecting it: waste management experience, environmental consciousness, site ratio impact, and landfill charges. The full model diagram is shown in Appendix D.

Simulation results compared different scenarios – for example, with and without government policies, and with different lifetimes for existing landfills. One finding was that existing landfills can be used up to 2020 but only if there is sufficient C&D waste management implemented, and only if enough public filling sites are found. As a communication tool, the SD model provides stakeholders with a means to better understand the challenges they face, and the model outputs can be used by waste managers to influence stakeholder viewpoints towards developing a shared vision for improving C&D waste management in Hong Kong. The model had not yet gone through a process of empirical validation or verification.

4.7 An Analysis of Household Waste Management Policy Using SD Modelling

Purpose	Evaluation of Flemish policy on household waste management
Process focus	Both upstream and downstream, relationships between them
Time focus	Historical (1991), to end of policy period (2015)
Tools and methods	SD modelling
Applicability to the UK waste system	Example of using historical data and validating model simulation data; relationships between waste prevention and waste to energy and landfill; takes into account EU directives on waste.

(Inghels & Dullaert 2011) studied the dynamic effects of household waste collection and disposal in Flanders through SD modelling. The model was used to evaluate current Flemish policy on household waste and was based on the principles of the waste hierarchy, or the Lansink ranking. Data for the model came from historical waste data from the period 1991–2006, literature reviews and interviews; it included both correlational and descriptive relationships, describing waste collection, reuse, recycling and disposal behaviour. The model provided insights into how GDP, population and selective collection behaviour have influenced household waste production and collection over time.

There are two main sections in the model: (i) household waste generation, prevention and collection; and (ii) household waste handling (reuse, composting, recycling, disposal) consisting of material waste handling and waste-to- energy flows. The simulation period was set to 25 years, starting in 1991 and ending in 2015 when the current household waste plan is set to end. The model was checked for structural validity and extreme conditions. A quantitative check of the goodness of fit between simulated and actual data was done using the Theil inequality statistics (Sterman 2000). R^2 values were all close to 1, indicating a good fit between simulation and original data; a high value of MAPE indicated a lack of fit in at least some of the variables, but the authors explain this difference as due to the seasonal differences in the collection of compostable waste. The model diagram is shown in Appendix E.

Model runs showed that *'Flemish household waste targets up to 2015 can be achieved by the current waste policy measures'* (ibid) and revealed the sensitivity of some key policy parameters such as prevention and reuse. The paper concludes that the model has been proven as reliable and capable of supporting the evaluation of integrated waste management issues, both for material waste and energy recovery issues. It was also effective in examining the effects of waste prevention initiatives. The authors state that they believe the model could be used in other EU countries, but users should first identify how EU directives are implemented within their own member state legislation, and replace model data with data from their own county. Not yet included in the model are CO_2 emissions or the trade-off between waste-to-energy and recycling waste.

4.8 A SD Modelling approach for Evaluating MSW Generation, Landfill Capacity and Related Cost Management Issues

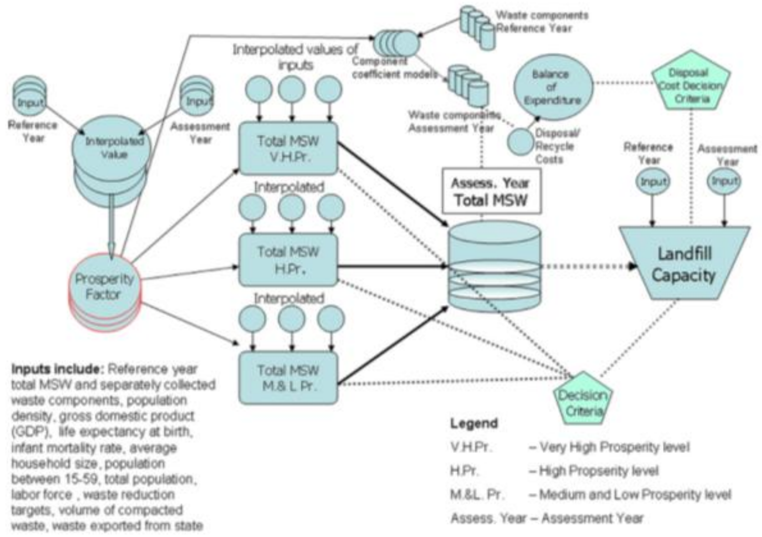
Purpose	Planning of MSW management
Process focus	Upstream economic factors and downstream processing of MSW
Time focus	Short term
Tools and methods	SD modelling
Applicability to the UK waste system	Importance of socio-economic factors and population to generation of MSW; relationships between recycling costs show economics of recycling needs to improve.

(Kollikkathara et al. 2010) used a SD approach to address achieving sustainable MSW management through modelling interconnected issues such as landfill capacity, environmental impacts and financial expenditure. The team created a model framework for the urban area of Newark, USA, and ran a forecast simulation. Representation of the complexity of the waste generation and management process was achieved by combining more simple sub-processes to form a whole system. Figure 15 shows the overall structure of the model, with three possible levels of prosperity driving the total amount of MSW.

The modelling process involved first identifying parameters determined to influence waste generation then adding these as inputs to the model. The city being modelled was specified to have a specific prosperity level, and this determined the total amount of MSW. The model considered recyclables, organic waste, and other discards including mixed and un-separated residual waste. Estimations of MSW amounts were based on analyses of the relationship between socio-economic and demographic conditions and the waste generation rate. Factors which were found to have a significant influence included per capita GDP, infant mortality rates, percent of population aged 15–59, household size, life expectancy at birth, and labour force in agriculture.

The paper found that the SD modelling provided *'a more comprehensive and sophisticated simulation method for integrated assessment of complex waste-management processes.'* (ibid) The simulation showed a general increase in the amount of MSW over the forecast period due to increasing population and changes in socio-economic conditions, and found that existing landfill capacity will be completely used up in nine years.

Figure 15: Schematic Diagram of MSW Generation Systems Model



Source: (Kollikkathara et al. 2010)

The model runs included the following details and results:

- Separate collection sector analysis provided values of uncollected waste fraction tonnages for each year showing an increasing trend in line with the change observed in the causal variables.
- Waste processing costs were shown to follow an increasing trend
- The cost of landfilling, in response to the decrease in landfill space, is shown to overtake that of recycling within eight years, making recycling the preferred option for the uncollected wastes
- Implementation of measures to increase recycling rates, initiated by a decision criteria based on remaining landfill space
- The authors recommend policy measures that would reduce the cost of recycling by increasing operation efficiencies and increase the market for recyclables.

5.0 Conclusion

This literature review provides a brief overview of a large body of literature on systems thinking and SD modelling. It is specifically aimed for policy makers at Defra and therefore provides commentary on and case studies of the use of these methods in the policy analysis and development field, specifically focused on waste.

Several themes emerged while reviewing the theory on systems methods used for policy making:

- The "wickedness" of public policy problems and the suitability of systems approaches to deal with that wickedness
- The need to include stakeholders in the process
- The benefits of creating "learning systems"

- The importance of concepts such as complexity, adaptivity, feedback, interconnectedness, and emergence
- The need to be able to model hierarchical systems (or systems of systems)
- The expected and unexpected (side) effects of policy interventions
- Iterative learning (model informs policy making, policies affect the system, real world evidence informs the model, etc.)
- Different options for the role of the modeller in relation to the modelled system.

Reviewing the eight case studies in using SD modelling to work with the waste system revealed many similarities in the approaches taken. Several models were hierarchical, linking modules representing different sub-sectors within the waste industry or in waste generation. Several studies linked upstream with downstream factors, expressed through mathematical functions. Only one study calibrated the model with the empirical data fed into it. None of the models covered a time frame long enough for one Sterman's double-loop learning, so it is not possible to say what effects the modelling has had in the real world;however, all of the case studies described the process of modelling as helpful and providing valuable insights. It is hoped that these case studies and various frameworks for working with large and wicked problems will be useful for Defra's experts and support their use of system thinking methodologies.

Finally, whenever engaged in systems thinking work it is important to remember the most commonly quoted statement about systems modelling: *'all models are wrong, but some are useful'*. (Box 1979)

6.0 References

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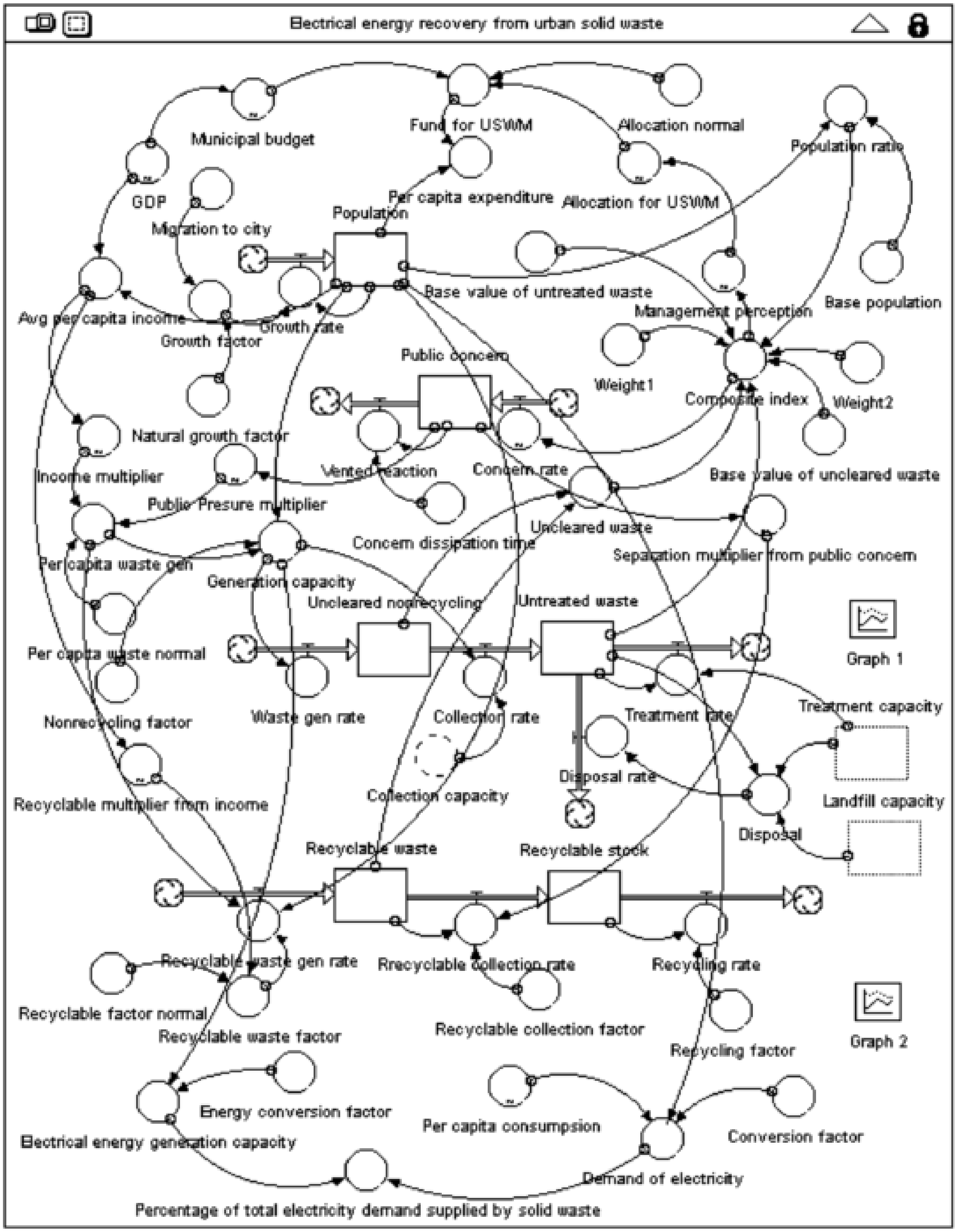
APPENDIX A: SD Model of Electrical Energy Recovery from Urban Solid Waste

The figure below shows an understanding of future growth in urban solid waste and potential for using that waste for electricity generation from (Sufian & Bala 2006).

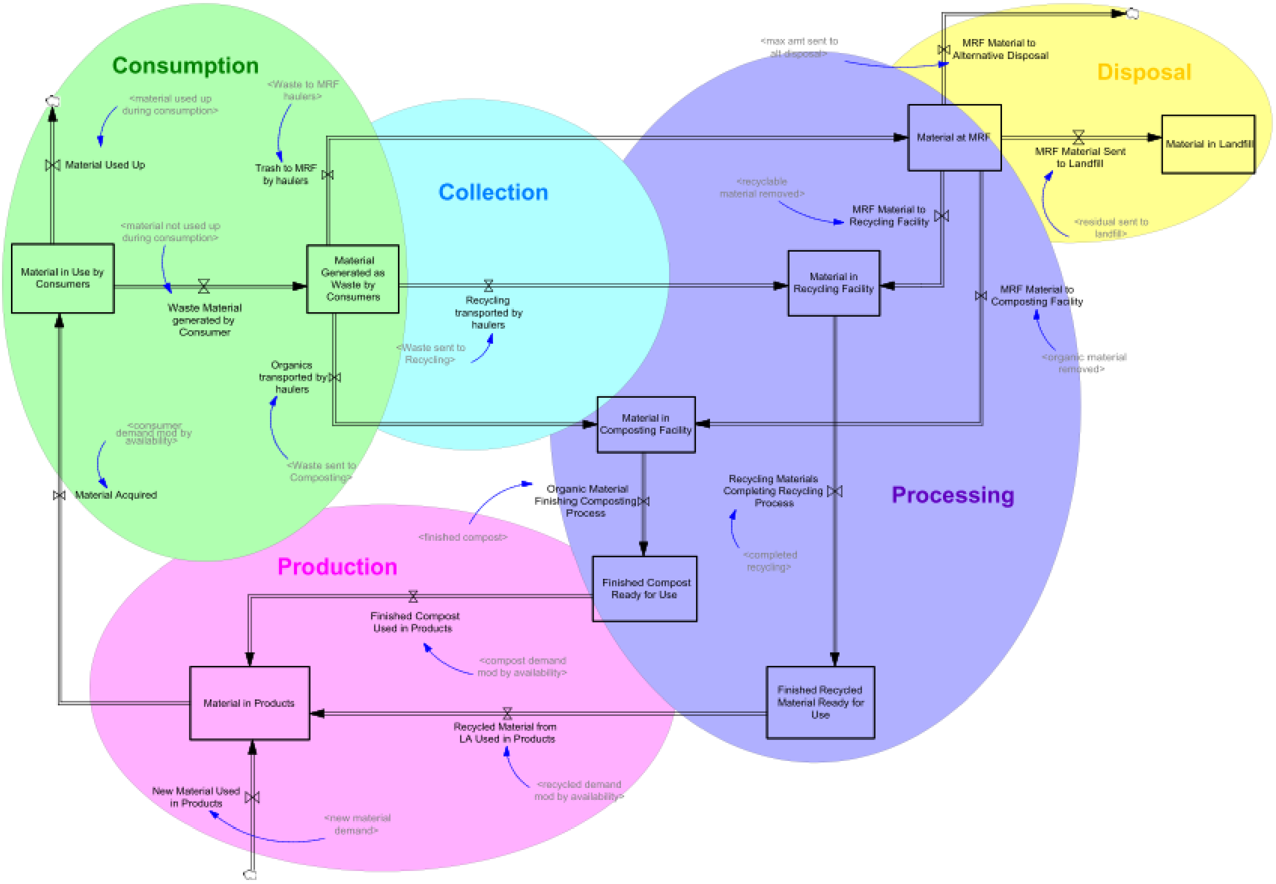


Source: (Sufian & Bala 2006)

APPENDIX B: Material Flows in the Backbone of the Zero Waste Model

The figure below shows material flows in Stave's zero waste model. The format is explained as:

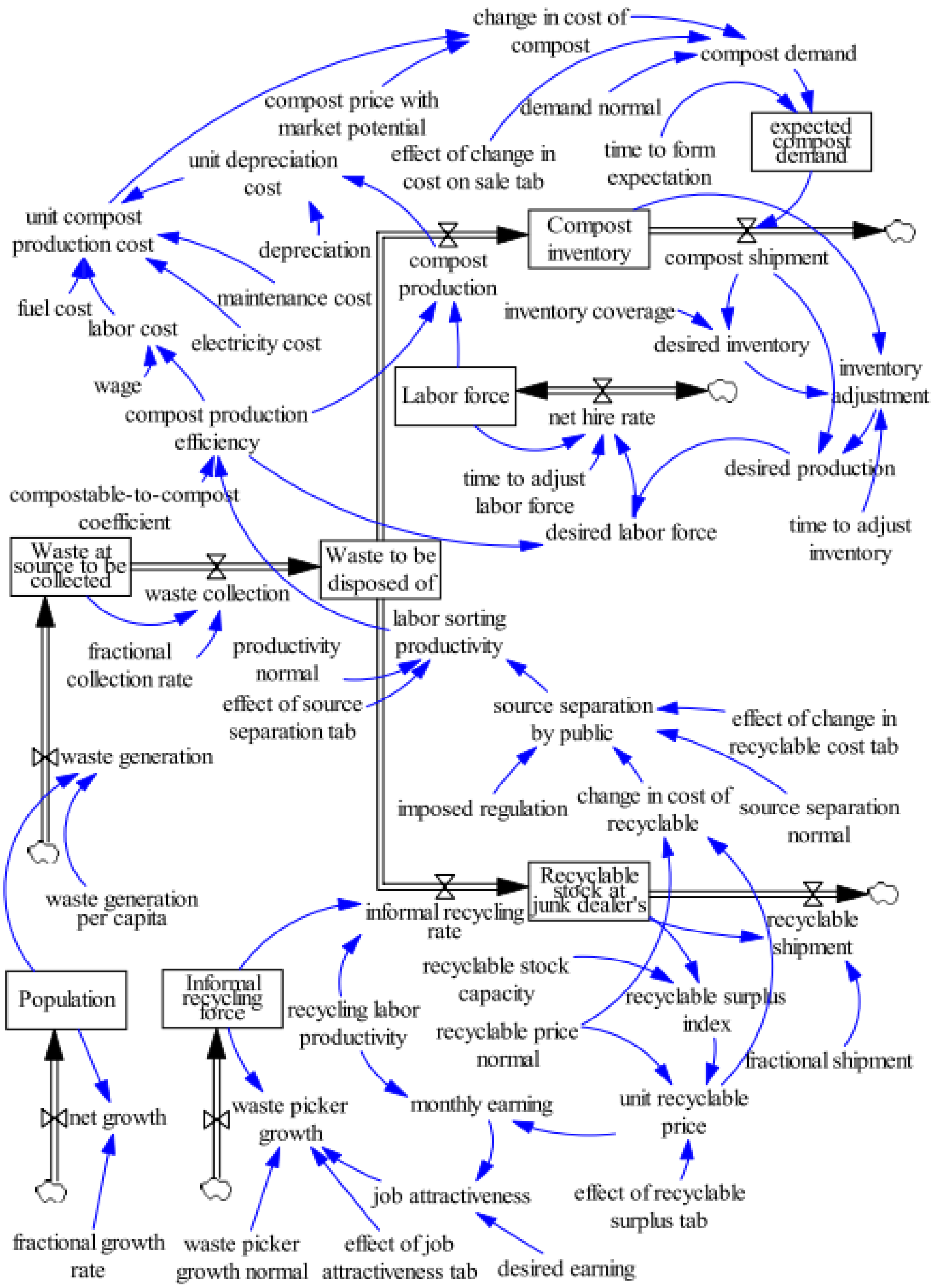
- *'The colored ovals indicate the sectors derived from Figure 1.*
- *New (virgin) material enters this stock-and-flow structure through the production, or manufacturing process in the lower left of the diagram, is transferred to consumers based on consumer demand, and, if it is not fully consumed, continues through the system when it is discarded by consumers.*
- *When consumers discard material, it enters one of three collection pathways: diversion to composting facilities, diversion to recycling facilities or transport to a transfer station or materials recovery facility (MRF).*
- *From the MRF, recoverable material can be diverted to composting or recycling facilities, or disposed in a landfill or alternative disposal facility.*
- *Material from composting or recycling facilities can continue back to the production sector to be reintegrated into new products.'* (Stave & Ph 2008)



Source: (Stave & Ph 2008)

APPENDIX C: Model of Waste System with Composting and Informal Recycling

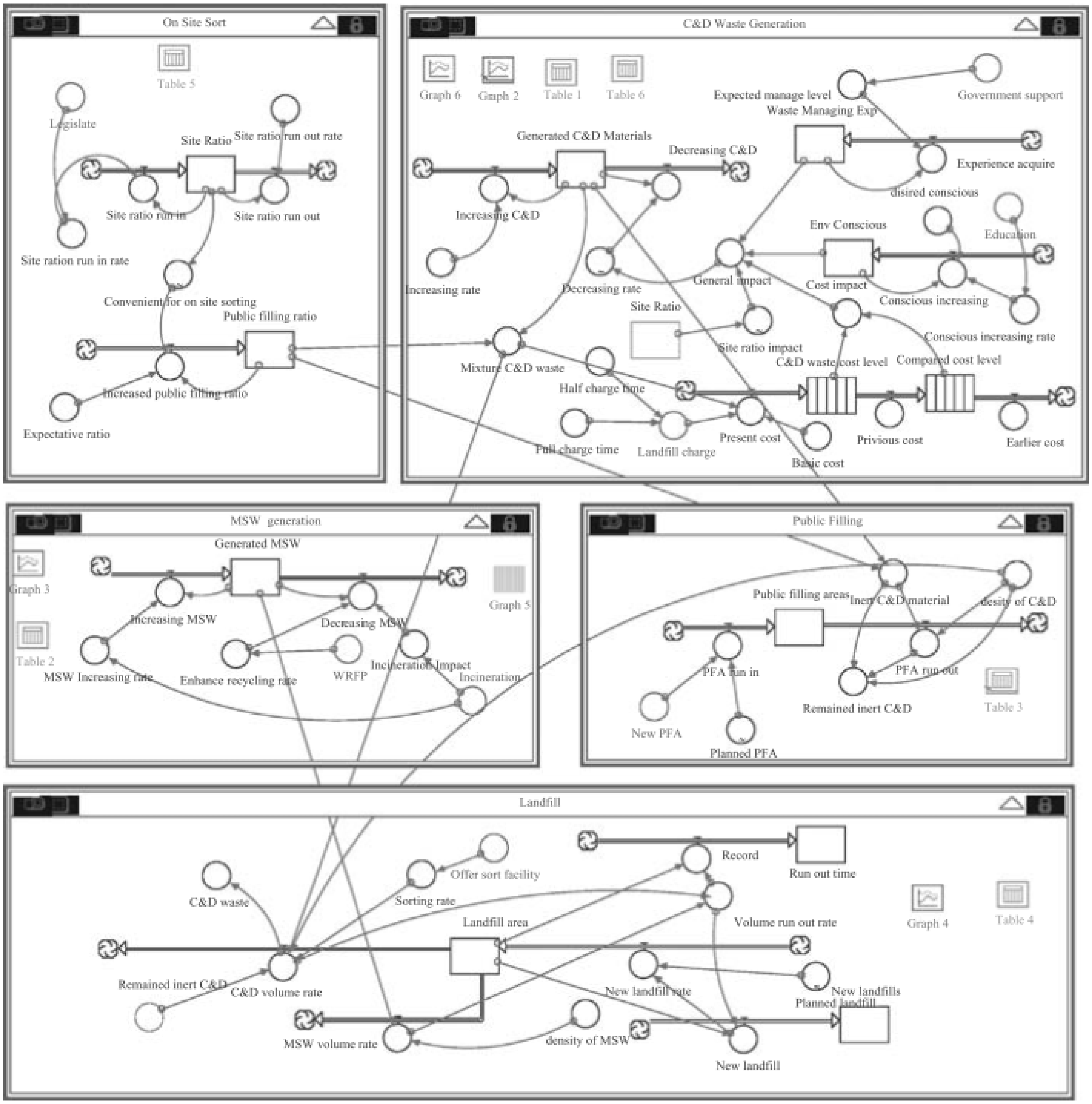
The stock and flow diagram by (Kum et al. 2005) shows the waste system, impacts of diverting waste for compost, demand for compost, and the effects of the informal recycling sector on the rest of the waste system in Phnom Penh.



Source: (Kum et al. 2005)

APPENDIX D: Construction and Demolition Waste Management in Hong Kong

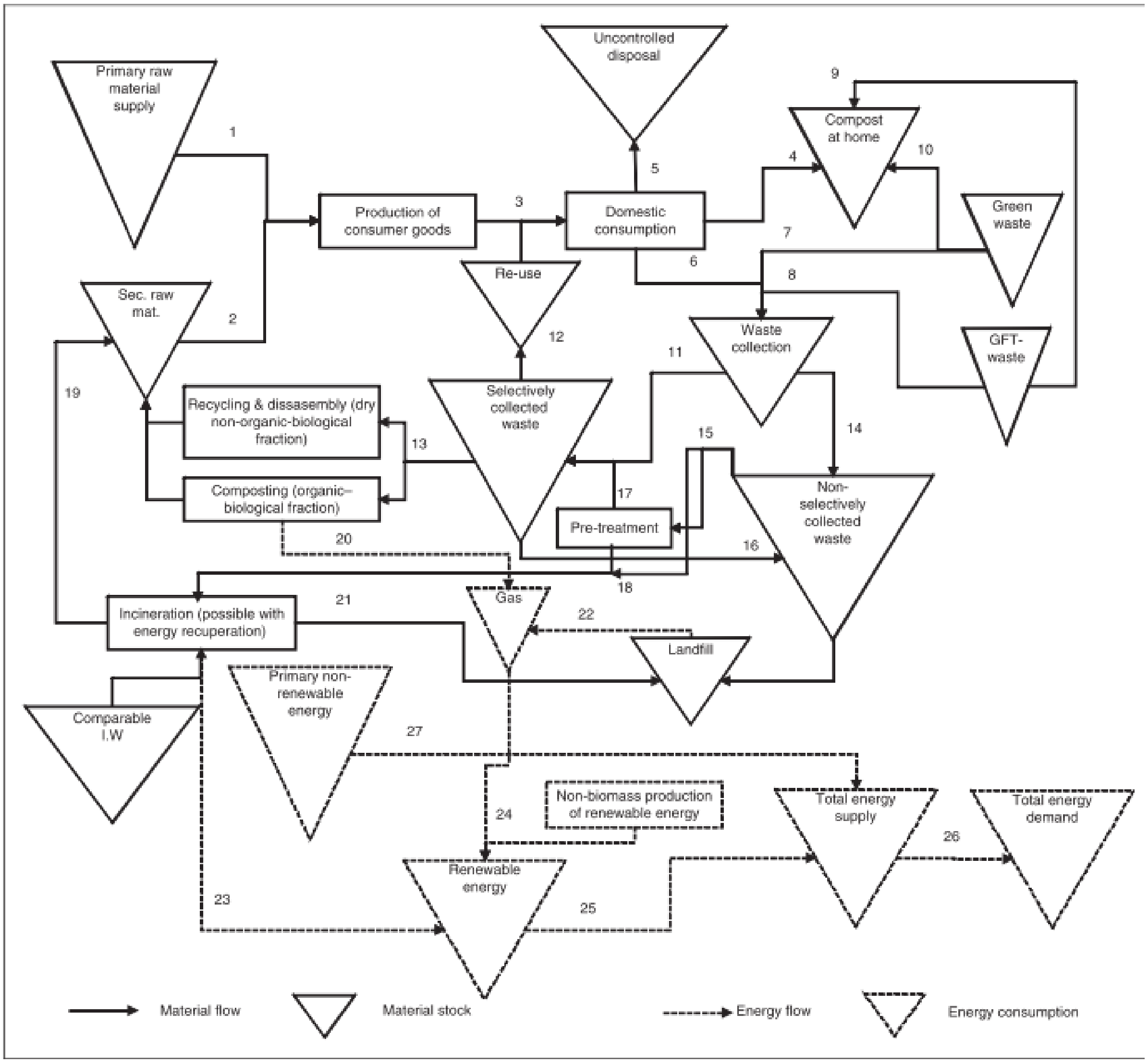
The diagram below shows a SD model from (Hao et al. 2007)for the management of construction and demolition waste in Hong Kong. There are five interrelated modules: landfill, MSW generation, public filling, C&D waste generation, and on site waste sorting.



Source: (Hao et al. 2007)

APPENDIX E: Evaluation of Household Waste Management Policy in Flanders

The diagram below shows a model from (Inghels & Dullaert 2011) of the dynamic effects of household waste collection and disposal in Flanders.



Source: (Inghels & Dullaert 2011)